Center for the Study of Plasma Microturbulence

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Center for the Study of Plasma Microturbulence

- Scientific Goal:

  To develop a predictive understanding of plasma transport through an interplay between numerical simulations, experiment, and analytic theory
  (see http://www.scidacreview.org/0801/pdf/fusion.pdf)

- The CPSM supports this goal by supplying and exercising plasma microturbulence codes (GYRO, GS2, and GEM):
  - Optimized for high-performance computing
    (have demonstrated linear scaling to over 30k processors)
  - complementary algorithms for cross-checks: continuum (Eulerian) or PIC (Lagrangian), spectral / high-order upwind, …
  - High-fidelity
    (electromagnetic, multiple species, collisions, realistic geometry, …)
  - Convenient interactive data analysis (GKV, VUGYRO)
  - Support for 3rd party users
    (CPSM codes are widely used within the magnetic fusion community)

Supercomputing Boosts FUSION RESEARCH

Since the 1950s, scientists have believed that fusion—the nuclear reaction that powers our Sun—could one day be utilized to help meet humankind's ever-increasing demand for energy. But controlling the fusion reaction in order to cleanly and efficiently produce power is a complex and elusive endeavor. Researchers employing scientific computing have made great advances towards this goal, and as computational resources continue to grow and improve, the day when fusion power becomes a reality is drawing closer.

Fusion power plants would produce far less radioactive waste than fission plants, and none of it would be long-lived.

Today, more than 400 nuclear fission reactors operate in 31 countries, splitting heavy atomic nuclei to produce heat that drives steam turbines, which in turn produce the electricity humankind uses to power modern civilization. Generating next to no carbon, fission reactors contribute 6.5% of the world's energy and 15.7% of its electricity, according to the International Energy Agency. While reactor construction worldwide dropped over the two decades following the Three Mile Island accident in 1979, recent concerns about energy independence and global warming have rekindled investment in fission. But as populous China and India increase their standards of living and energy appetites, fission alone will not be able to meet the world's growing power needs. Even maintaining its proportionate contribution to world energy consumption would require construction of many more reactors—to replace decommissioned ones and meet increasing demand—as well as expanded solutions for dealing with radioactive waste. What's a world hungry for energy—and getting hungrier—to do?

The near-term answer is likely to be a buffet of energy solutions including nuclear fission, as well as power from biofuels, photovoltaic batteries, solar panels, hydrogen, wind, and more. One offering farther out on the horizon may come from doughnut-shaped reactors called tokamaks. These toroidal devices produce energy from nuclear fusion—the process that releases energy from hydrogen bombs, powers the sun, and produces elements in stars. In fusion, nuclei join to form heavier nuclei. If the fusing nuclei are heavier than iron or nickel, energy gets absorbed when they merge. But if the nuclei are lighter than these elements, energy gets released upon fusion.

Fusion reactors are fueled by isotopes of the lightest element, hydrogen. The isotopes are deuterium, isolated by distillation from sea water, and tritium, bred from plentiful lithium bombarded with neutrons from the fusion reactors themselves. The hydrogen isotopes combine at high temperatures to make isotopes of helium and neutrons. The neutrons carry the energy away, and lithium blankets outside the reactor wall capture it. In a future commercial reactor, the trapped energy would heat water to make steam to drive electric turbines. The process generates no greenhouse gases.

Fusion power plants would produce far less radioactive waste than fission plants, and none of

SciDAC Review, Spring 2008
www.scidacreview.org

CSPM Budget

Institution	Annual Budget FY08-FY10	Scientific Staff (~FTE)	Post Docs (FTE)
LLNL		0.4	1†
PPPL		0.33	
GA		0.4	
U of MD		0.45	
MIT			2/3*
U of CO		0.33	
TOTAL	~$800k		
*MIT will support 1 Post Doc for final 2 yrs of project			
†LLNL will support 1 post doc on internal funds for closely related work			

Code Fidelity:
the key to successful code validation

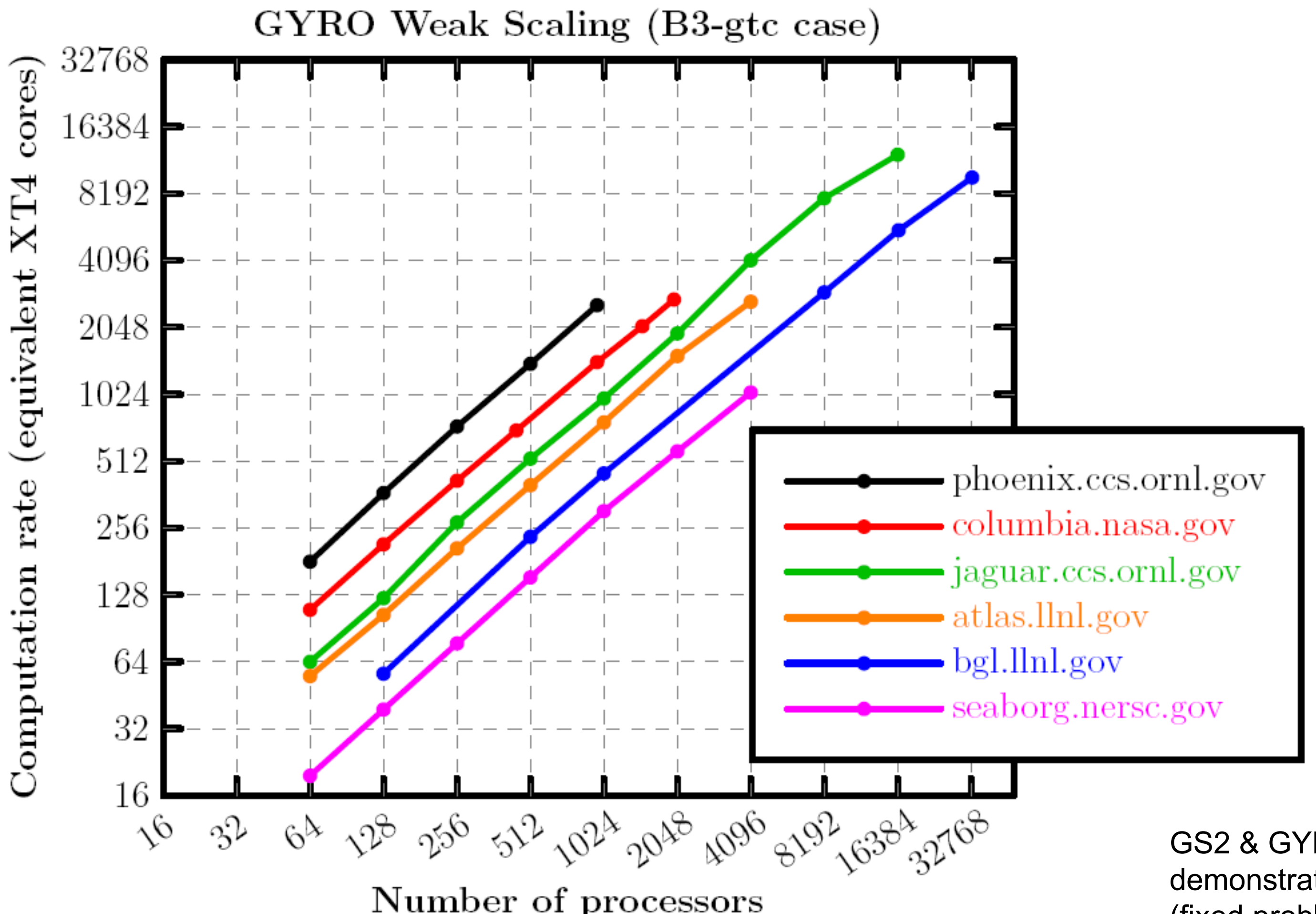
- Gyrokinetic code predictions change as physics is added [Ross, 2002; Candy, 2003b; Waltz, 2005]
- Successful code validation requires “high-fidelity” to the underlying physics, including
  - realistic magnetic geometry
  - multiple kinetic species
  - collisions
  - electromagnetic perturbations

  [Candy, 2003b; Ernst, 2004; Estrada, 2006; Waltz, 2006a; Waltz, 2006b]
- Code validation also requires code support for 3rd party users to provide:
  - Expertise in experimental analysis
  - Unbiased comparisons
  - Additional man (and woman) power

Capability	GYRO	GS2	GEM
Gyrokinetic ions (electrons) for ITG (ETG) physics	[Waltz, 2002]	[Dorland, 2000a]	[Parker, 1993]
Nonlinear gyrokinetic impurities	[Estrada, 2005]	[Dorland, 2000b]	[Chen, 2007]
Trapped and passing electrons for ITG/TEM physics	[Candy, 2003]	[Dorland, 2000b]	[Chen, 2001]
ρ_i- and ρ_e-scale turbulence, simultaneously	[Nevins, 2006]		
Axisymmetric shaped geometry (parameterized)	[Candy, 2003b]	[Dorland, 2000b]	
Axisymmetric shaped geometry (numerical)		[Dorland, 2000b]	[Chen, 2007]
Stellarator geometry		[Belli, 2001]	
Transverse magnetic perturbations	[Candy, 2003]	[Jenko, 2001]	[Chen, 2003]
Compressional magnetic perturbations		[Kotschenreuther, 1996]	
Equilibrium parallel velocity shear	[Candy, 2003b]	Unpublished	[Parker, 1996]
Equilibrium sheared rotation	[Candy, 2003b]	[Hammett, 2006]	[Parker, 1996]
Equilibrium parallel velocity	[In press]		[Parker, 1996]
Electron pitch-angle collisions	[Candy, 2003]	[Kotschenreuther, 1995]	[Chen, 2003]
Ion pitch-angle collisions	[Candy, 2006b]	[Kotschenreuther, 1995]	
Energy-diffusing collisions		[Navkal, 2006]	
Input of full experimental profiles	[Candy, 2003b]	[Ernst, 2000]	[Rewoldt, 2006]
Finite- ρ_* effects (profile shear)	[Candy, 2003b]		[Parker, 1993]
Turbulent momentum transport	[In press]		Unpublished
Turbulent particle transport, including electrons	[Estrada, 2005]	[Ernst, 2004a]	[Chen, 2001]
Turbulent heating diagnostics	Unpublished	[Howes, 2006]	
Synthetic fluctuation diagnostics	[Holland, 2007]	[Ernst, 2006a]	[Parker, 1993]
Open source, with documentation and training	Since 2002	Since 1999	Since 2003

CPSM Code Capabilities

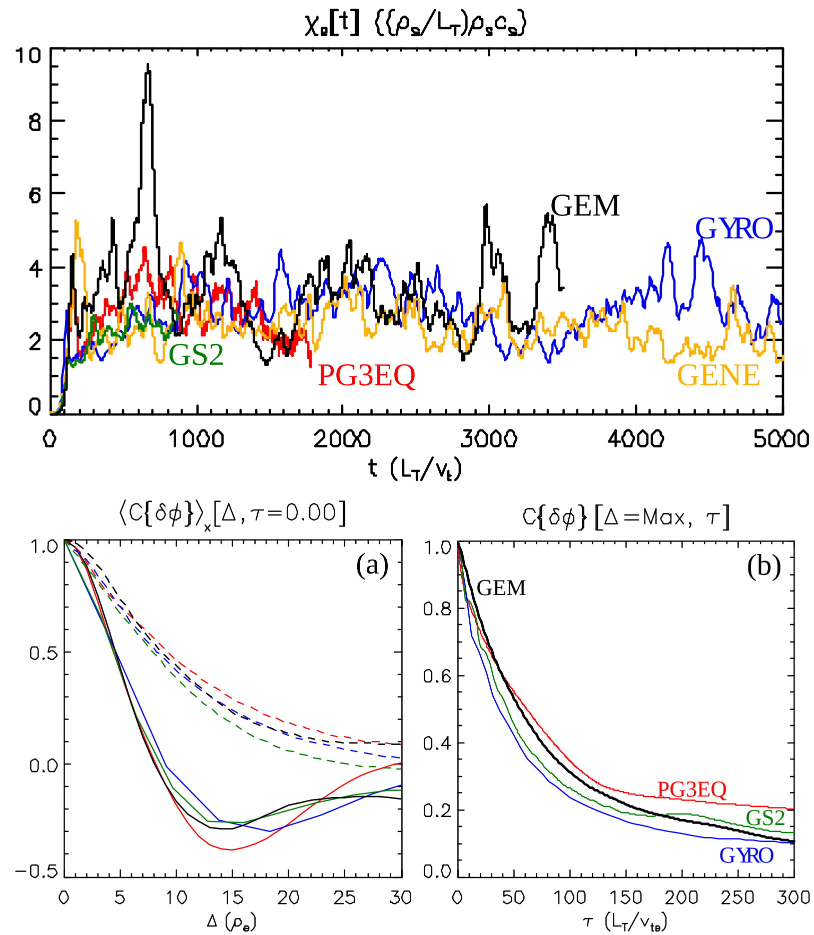
5-D continuum codes show excellent scaling to over 10^4 processors



GS2 & GYRO have also demonstrated strong scaling (fixed problem size) over a factor of 1000 processors.

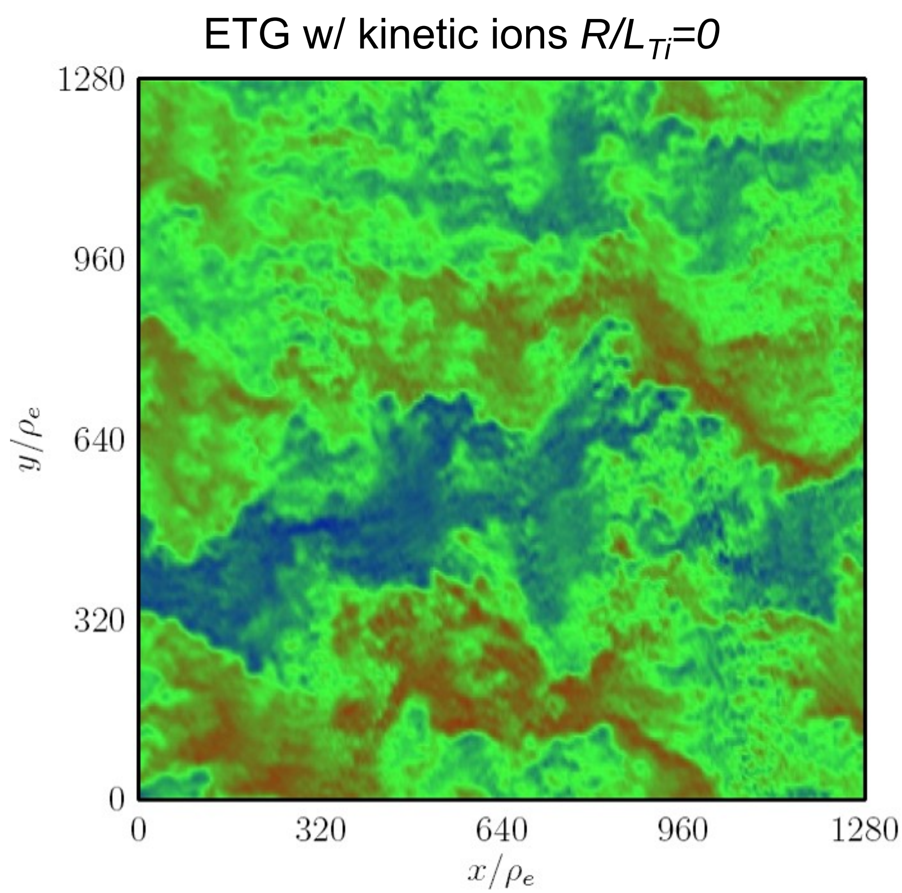
Recent accomplishments: Electron-Scale Turbulence

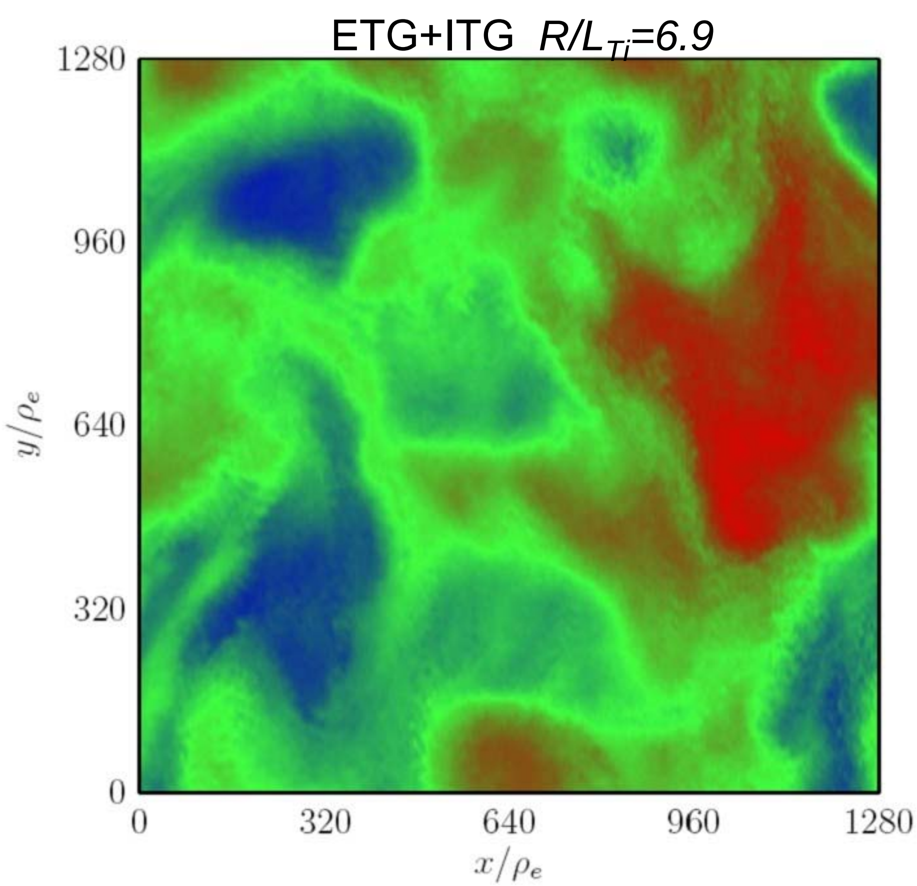
- Successful benchmark of ETG Turbulence simulations using
  - PIC (GEM and PG3EQ) and
  - Continuum (GYRO, GS2, GENE) codes
- Reproduced both
  - heat transport (top frame)
  - fluctuation structure (bottom frame)
- Demonstrated kinetic ions prevent dramatic increases in ETG transport at large magnetic shear
- This work published as
  Nevins et al, Phys. Plasmas **13**, 122306 (2006)
  Nevins et al, Phys. Plasmas **14**, 084501 (2007)



Largest GYRO simulations used to study interaction of ITG & ETG Turbulence

- 1280 ρ_e x 1280 ρ_e x 10 parallel pts/half-orbit x 8 energies x 16 $v_{||}/v$ x 2 species
- electrons + kinetic ions, $m_i/m_e = 20^2 - 30^2$
- 5 days on DOE/ORNL Cray X1E w/ 720 Multi-Streaming Processors (X1E: 1024 MSPs, 18 TF)

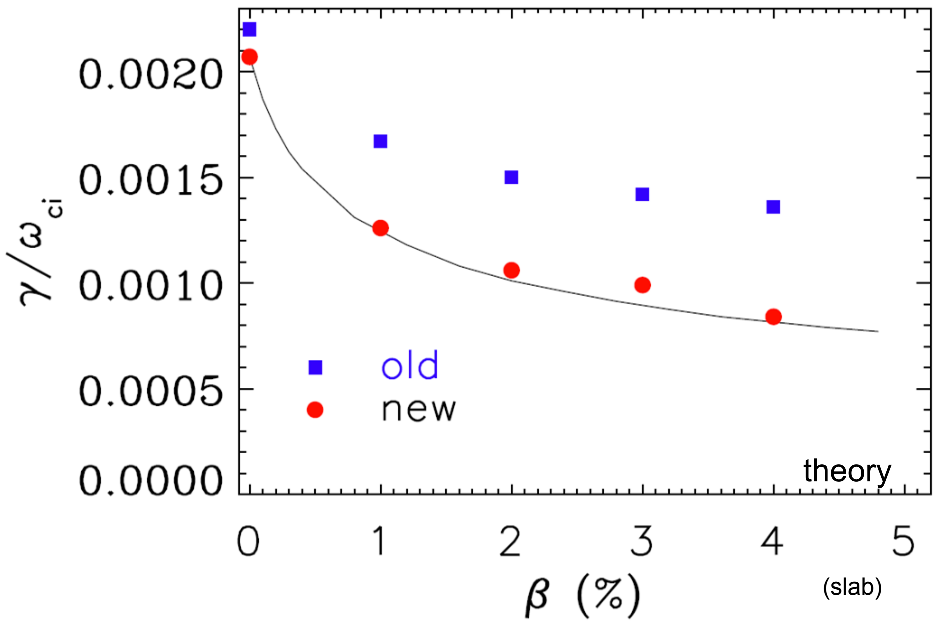


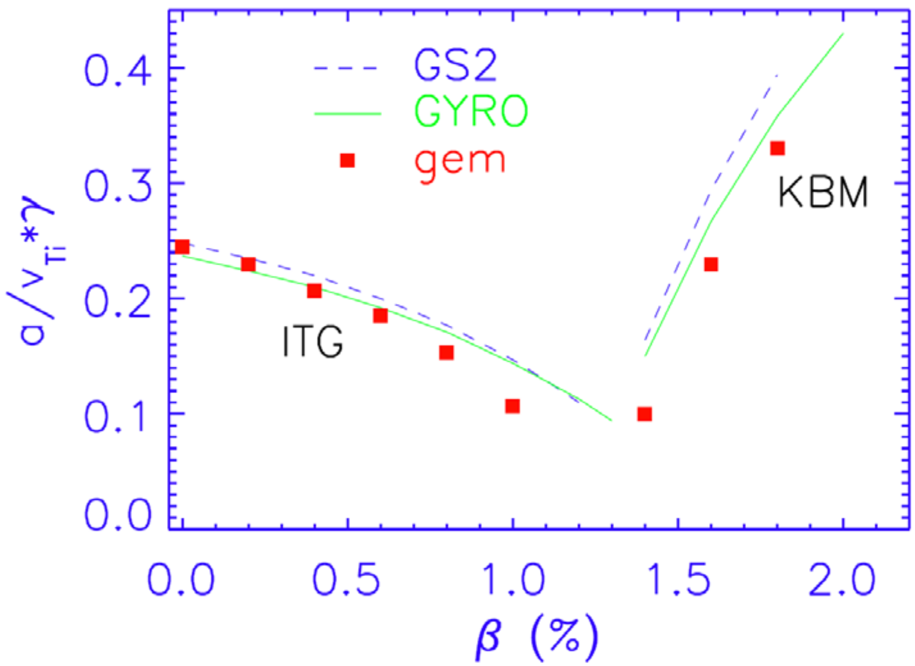


http://fusion.gat.com/theory/Gyromovies

Candy, Waltz, et al. SciDAC 2007, J. Physics Conf. Ser.

GK PIC breakthrough: working algorithm for magnetic fluctuations





- Long standing "high-β" problem in GK PIC codes, first observed by Cummings ('94).

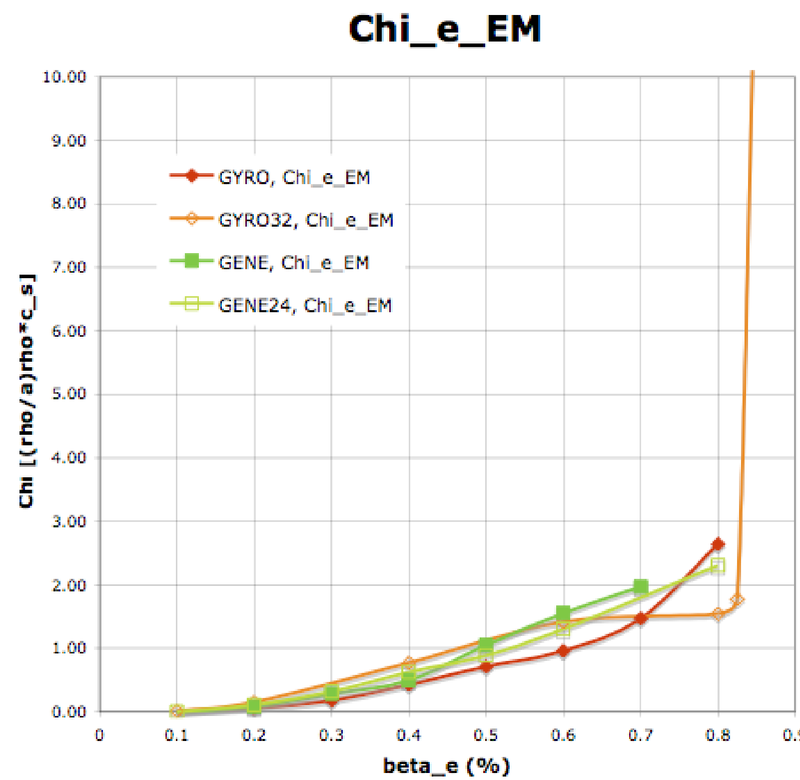
- Does not affect GK continuum codes.

- Y. Chen & S. Parker (JCP 03) fixed by careful treatment of two large terms (arising from canonical momentum transformation) that nearly cancel

Benchmark 3 independent PIC & continuum codes

Code Verification: Electromagnetic Plasma Microturbulence

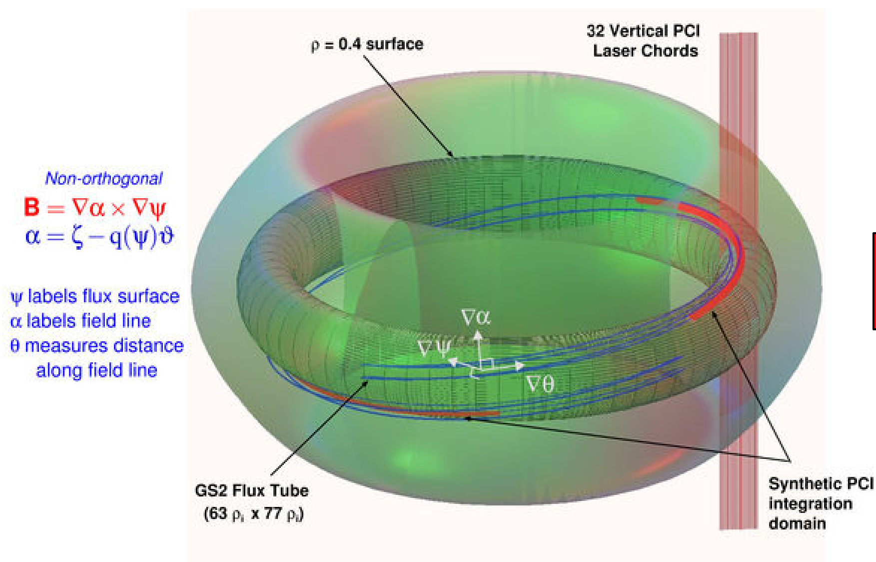
- ITER (and fusion reactors) expected to operate near ideal MHD β-limit
- Electromagnetic GK-codes sometimes experience difficulties at $\beta \approx \beta_{MHD}/2$
- CSPM has initiated code benchmarking effort
  - Including GYRO, GS2, GEM and GENE (an IPP Garching EM GK Code)
  - Results to be reported at 2008 APS/DPP Meeting



Electron thermal conductivity from "magnetic flutter" vs. β (ideal limit is β=1.6%) showing agreement between GYRO and GENE

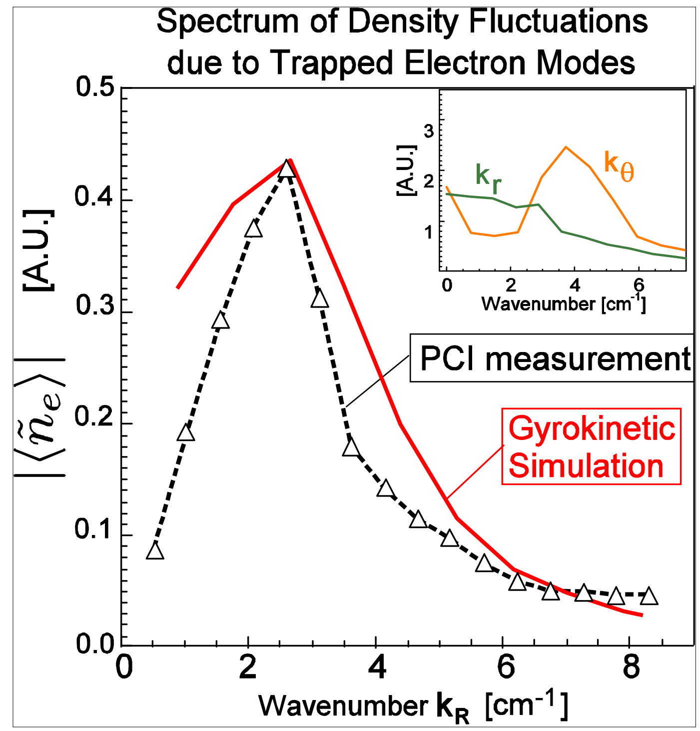
Code Validation Example:
Trapped Electron Mode turbulence on C-Mod

Synthetic phase contrast imaging diagnostic in GS2 [Ernst, IAEA06].



- Transform $k_R = (\nabla R \cdot \nabla\psi/|\nabla\psi|)k_\psi + (\nabla R \cdot \nabla\alpha/|\nabla\alpha|)k_\alpha$
- Instrument function: Gaussian beam, finite aperture, reference beam k_R~0

Direct observation of TEM turbulence:

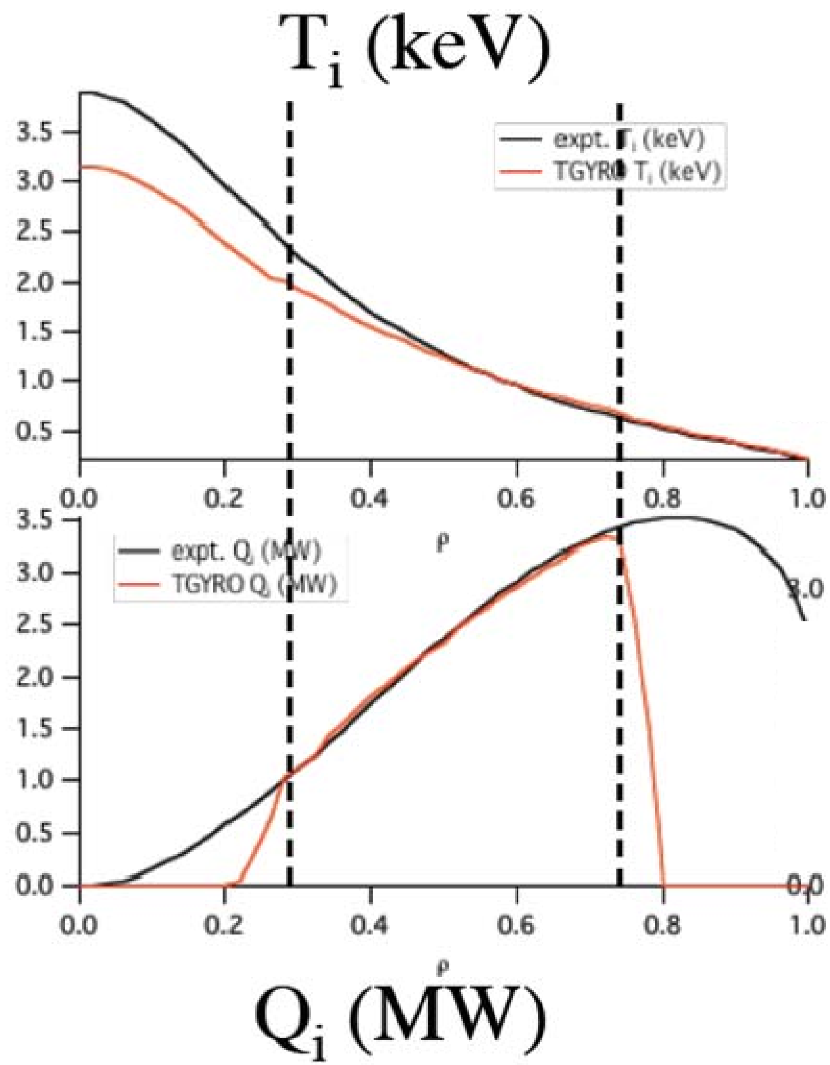


Nonlinear GS2 simulations, with synthetic diagnostic, reproduce wavelength spectrum from phase contrast imaging in Alcator C-Mod ITB [Ernst-IAEA06].

other experimental tests and synthetic diagnostic work: DIII-D, NSTX, JET

Modeling ITER & Present Experiments

- new: TGYRO, a steady state gyrokinetic transport code (Fahey/Candy, yesterday)
- also GS2 profile-prediction mode, APS07
- Two ways to use GK turbulence codes:
  - – chi-prediction mode:
    Given temperature profiles, predict turbulent fluxes and chi's
    ("analysis mode", like TRANSP)
  - – profile-prediction mode:
  - – Given heating profiles, predict temperature profiles
    ("predictive mode", like TSC/ASTRA)
  - ⇒ Use for validation tests comparing with experiments
  - ⇒ Eventually, predict ITER performance
- Initial TGYRO results at 2008 TTF
- Preliminary ITER results to be at APS08



(fig: Holland, TTF08 http://fusion.gat.com/theory/Gyropubs)

Efficient 3-D plus time data analysis
(current state-of-the-art within OFES is 2-D plus time)

- Fundamental technical issue is the memory available on desktop workstations (or to individual processors)
  - 2-D plus time data set:
    (4 bytes/word)(~10^4 grid points)(~10^4 time-slices) ~ 400 Mbytes
  - 3-D plus time data set:
    (4 bytes/word)(~10^6 grid points)(~10^4 time-slices) ~ 40 Gbytes
- Best solution:
  - Break dataset into manageable subsets with several correlation lengths/times in each dimension:
    - Data subset:
    (4 bytes/word)(~10^5 grid points)(~100 time slices) ≥ 40 Mbytes
  - Data subsets can be processed in parallel

  ⇒ This reduces required memory per processor
  40 GB/processor → 40 MB/processor

  ⇒ Enables efficient data processing on massively parallel computers

We expect two Strategic Application Partnerships to be funded in FY08

Visualization and Analysis
in support of Fusion Science

(VACETS: Visualization and Analytics Center for Enabling Technologies)

- Comparative visualization and analysis in support of model validation and code verification
  - ⇒ realization-independent characterization of turbulence
- Topological analysis of magnetic fieldlines
  - ⇒ magnetic reconnection and the integrity of magnetic surfaces

Scientific Data Management
to accelerate fusion scientific discovery

(SDM Center)

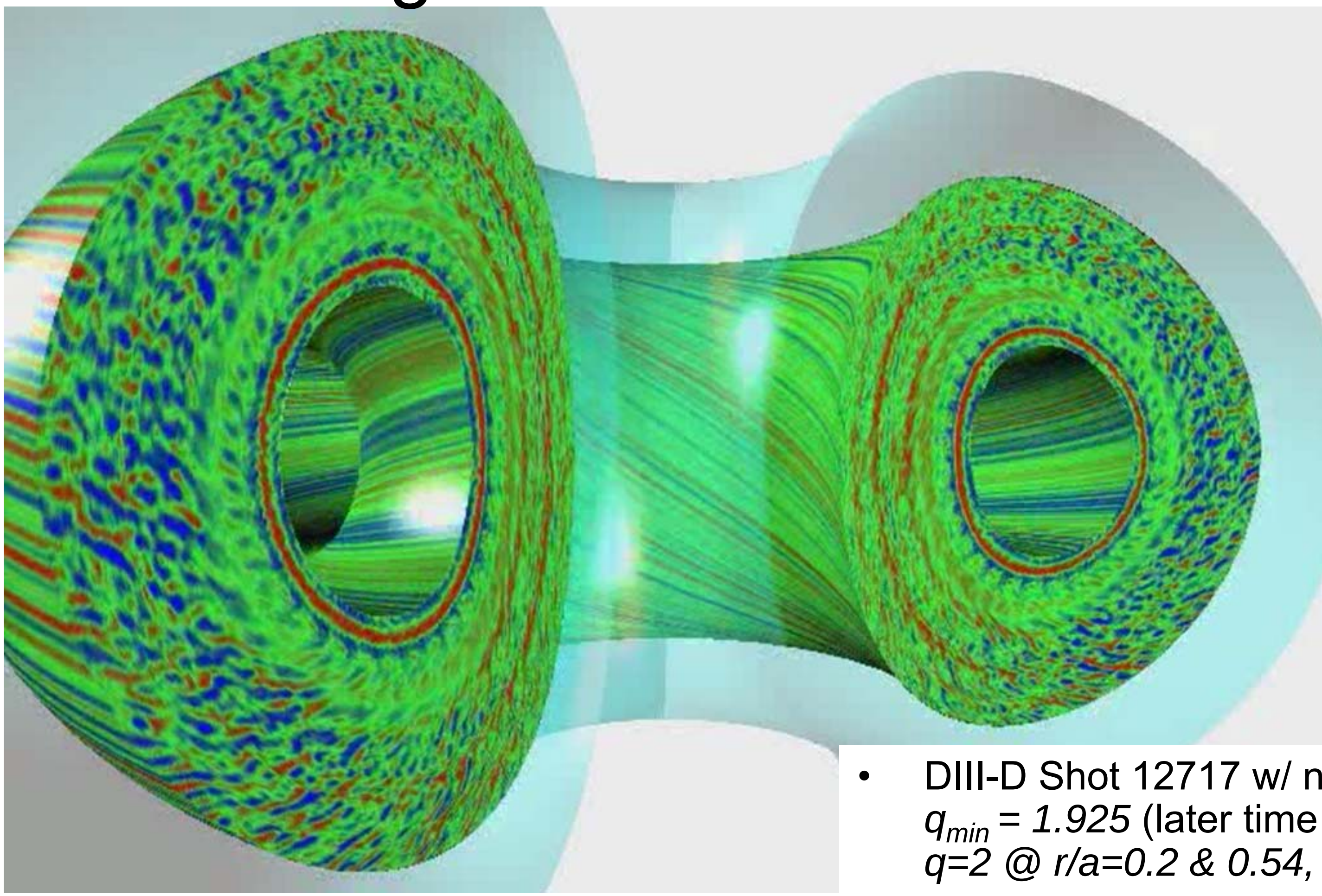
- Parallel and scalable algorithms for analysis of 4D data sets
- Explore the use of ‘dashboards’ and ‘workflows’ for
  - Automated data analysis
  - Automated data archiving

Project Milestones

- Near Term (2008 DPS/APP and IAEA meetings):
  - Initial TGYRO simulations of projected ITER discharges
  - Initial EM plasma microturbulence studies
  - TEM mode turbulence studies
- Medium term (FY09)
  - 3D plus time data analysis (in collaboration with SDM)
  - Magnetic surface diagnostic (in collaboration with VACETS)
  - Code validation studies (DIII-D, NSTX, C-MOD)
- Long term (FY10)
  - Projection of the steady state performance of ITER burning plasmas

BACKUP SLIDES

Full-physics GYRO simulation of Negative Central Shear DIII-D case

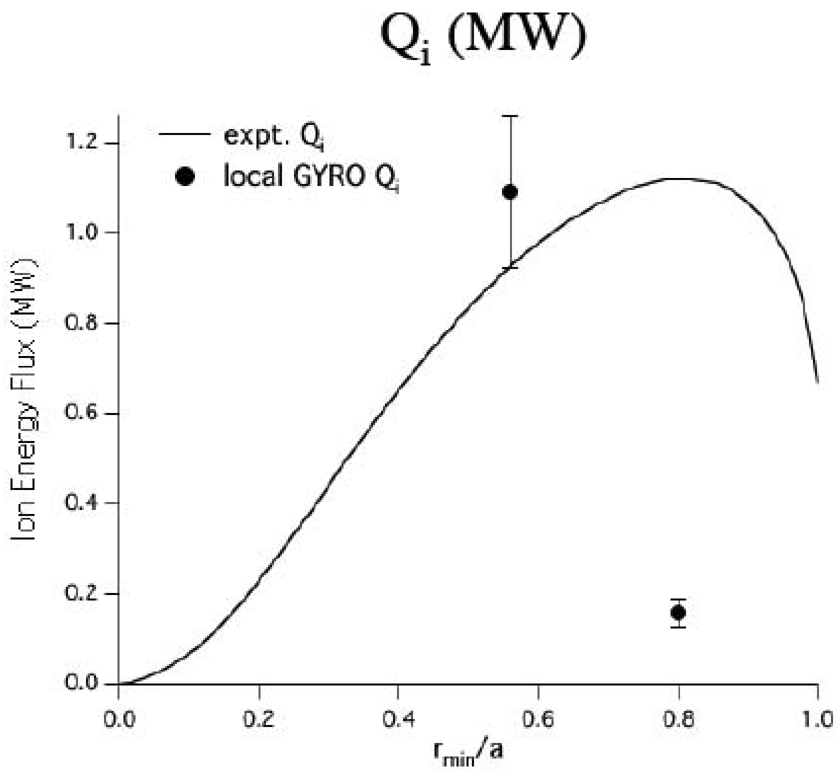


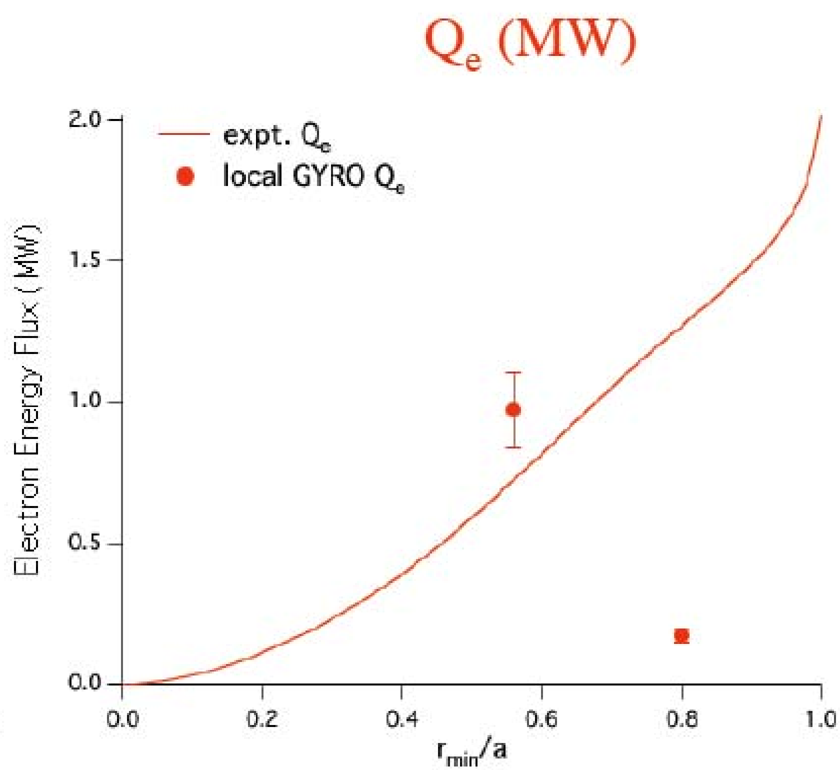
Movie of density fluctuations from GYRO simulation
http://fusion.gat.com/THEORY/images/0/0f/N32o6d0.8.mpg
from http://fusion.gat.com/theory/Gyromovies

- DIII-D Shot 12717 w/ negative central shear, q_{min} = *1.925* (later time than cases in paper), *q=2 @ r/a=0.2 & 0.54,* $\rho_*/a=0.003$
- experimental *grad(T)* used, but reduced ExB shearing rate by 20% to get finite turbulence
- 500 radii x 32 complex toroidal modes (96 binormal grid points) x 10 parallel points along half-orbits x 8 energies x 16 $v_{||}/v$, 12 hours on ORNL Cray X1E with 256 MSPs

Waltz, Austin, Burrell, Candy, PoP 2006

Local Fixed-Gradient Sims Match Energy Fluxes and RMS Fluctuation Levels at ρ = 0.5, Underpredict ρ = 0.75





DIII-D NATIONAL FUSION FACILITY SAN DIEGO

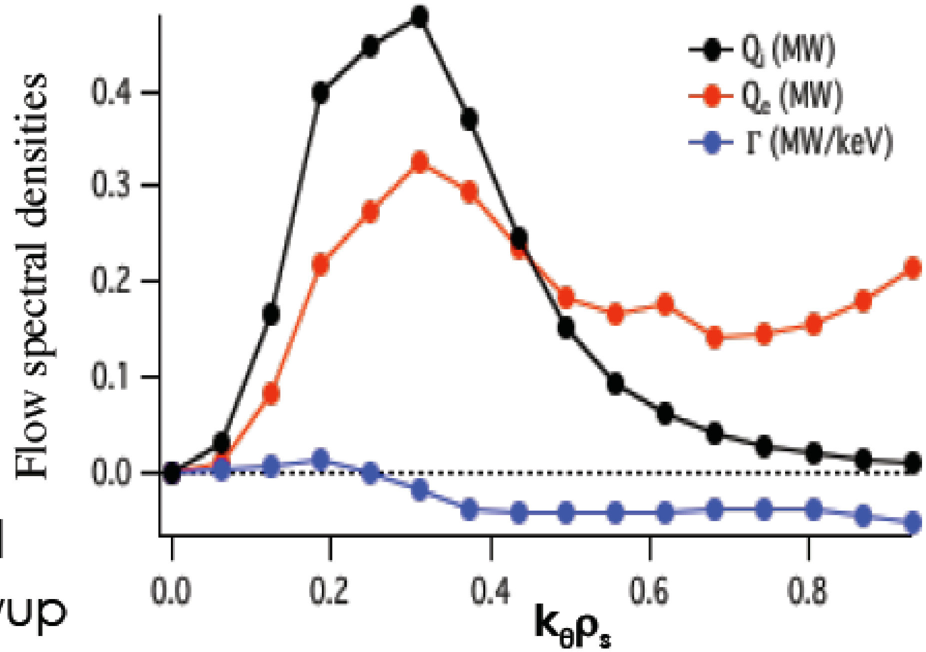
UCSD

(Holland, TTF08 http://fusion.gat.com/theory/Gyropubs)

Electron Energy and Particle Flux Under-Resolved in $k_\theta \rho_s$ at $\rho = 0.75$

- **Significantly stronger TEM/ETG drive at $\rho = 0.75$ (relative to $\rho = 0.5$) appears to drive significant short(er) wavelength electron transport**
  - Ion flux remains well resolved

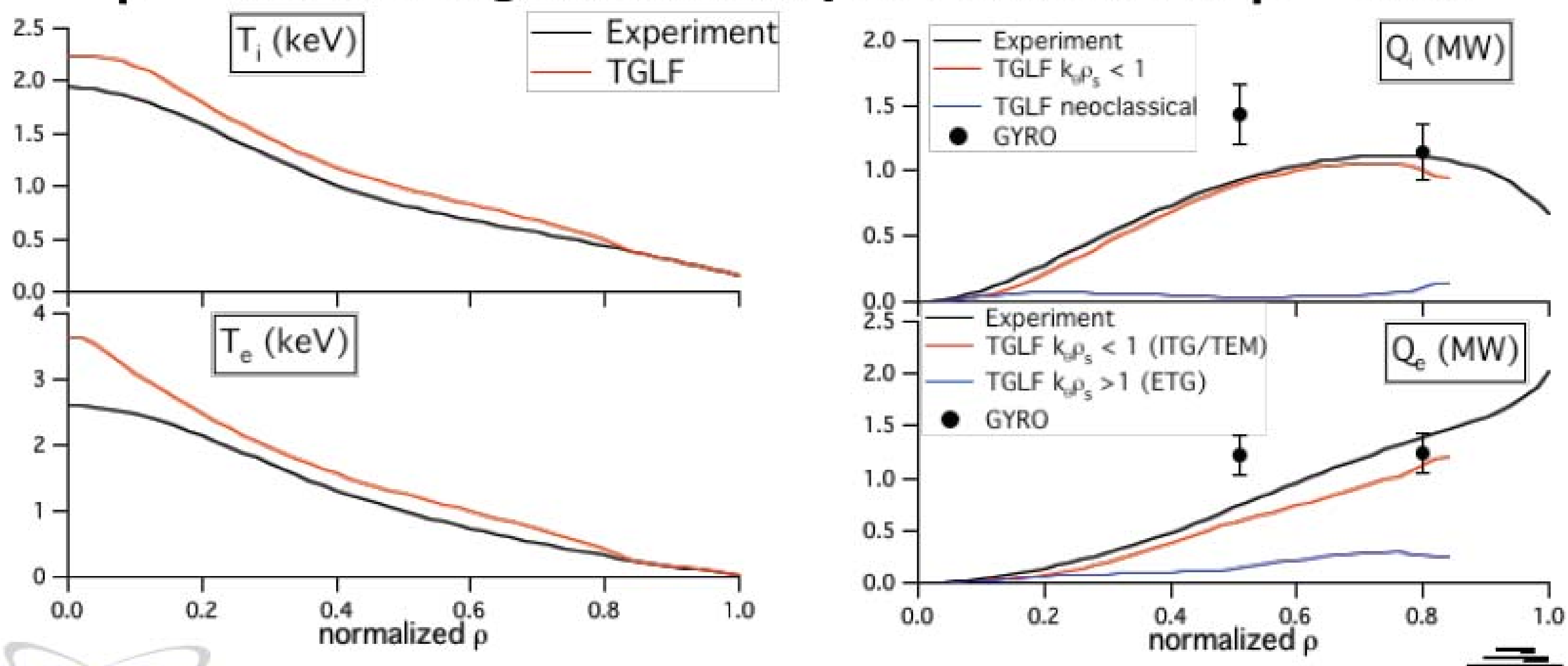
- **Attempts to date to increase maximum $k_\theta \rho_s$ while maintaining box size and resolution have been unsuccessful**
  - Sims exhibit high-k blowup even without ExB shear



(Holland, TTF08 http://fusion.gat.com/theory/Gyropubs)

Preliminary Result: GYRO Simulation Using TGLF Profiles Exhibits Much Better Agreement at ρ = 0.75

- **Local GYRO simulations using the TGLF profiles show moderate disagreement in heat fluxes at ρ = 0.5, but significant improvements at ρ = 0.75**



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