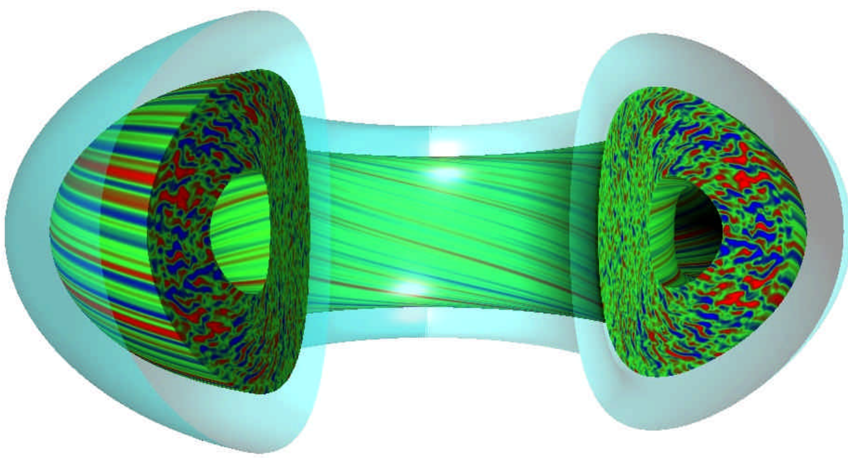
The Plasma Microturbulence Project



W.M. Nevins ( )

For the

Plasma Microturbulence Project Team

The Plasma Microturbulence Project

New this Year! Summit

Electromagnetic, Flux-tube PIC Code

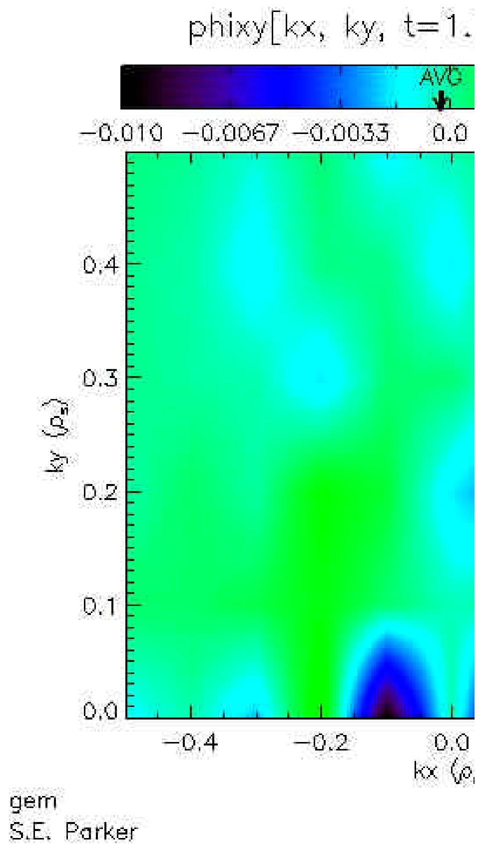
Our Goal:

Understanding plasma microturbulence through direct numerical simulation

Our Game plan:

- Enhance Fidelity of existing codes
- Develop new codes
- Develop shared code diagnostics
- Benchmark codes against each other
- Validate codes against experiment and theory
- Build a user community

Substantial progress on all fronts

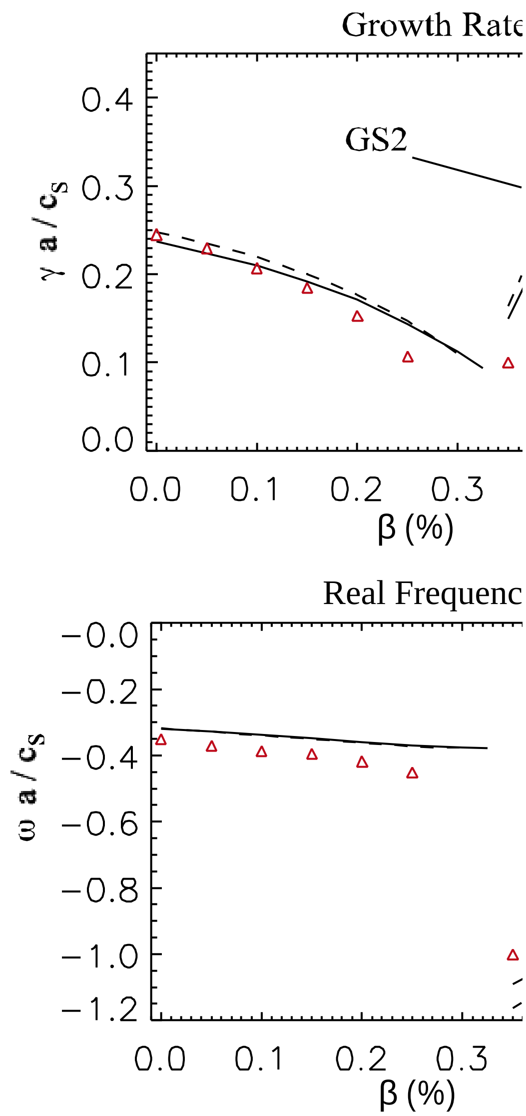


Benchmarking Summit against GS2 and GYRO

- Linear comparisons between GS2, GYRO and Summit with kinetic electrons and δB
- Kinetic electrons increase growth rate (trapped electron drive)
- Growth rate "goes through the roof" when kinetic ballooning threshold is crossed

Linear physics accurate at interesting values of β

A collaboration between PMP code development groups



GYRO/GS2 results from Candy & Waltz, JCP (2002)

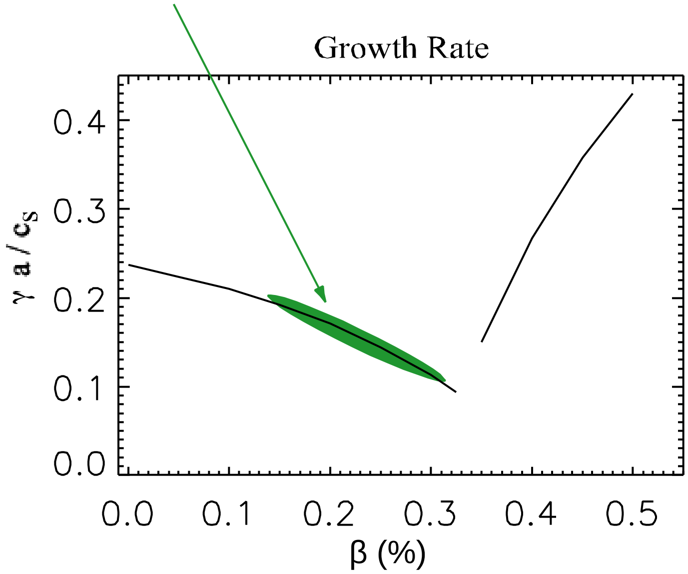
Summit shows a decrease in χ_i for increasing β when below ballooning limit

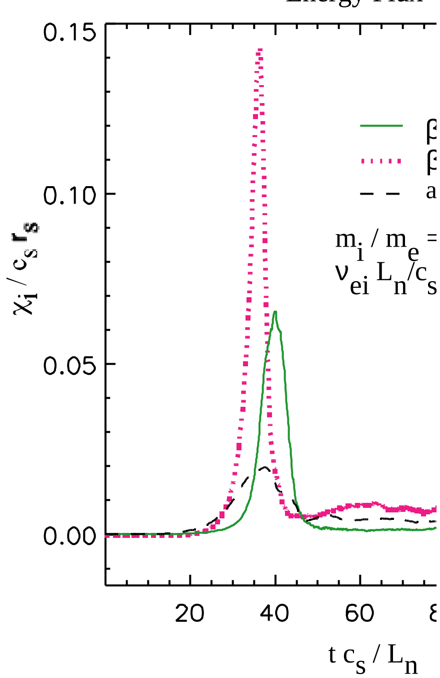
Puzzle: Why do turbulence simulations give transport levels that are greater than experimental values?
e.g. D. Ross Sherwood 1C47 (2002)

(possibly global effects, inaccuracies in profile measurements, sensitivity to critical gradients, etc.)

Plausible solution: Experiments operate in this low transport region just below the kinetic ballooning threshold

Summit Results:
Three-Dimen
Toroidal
Kinetic Elect
Electromagne
e-i Collisions

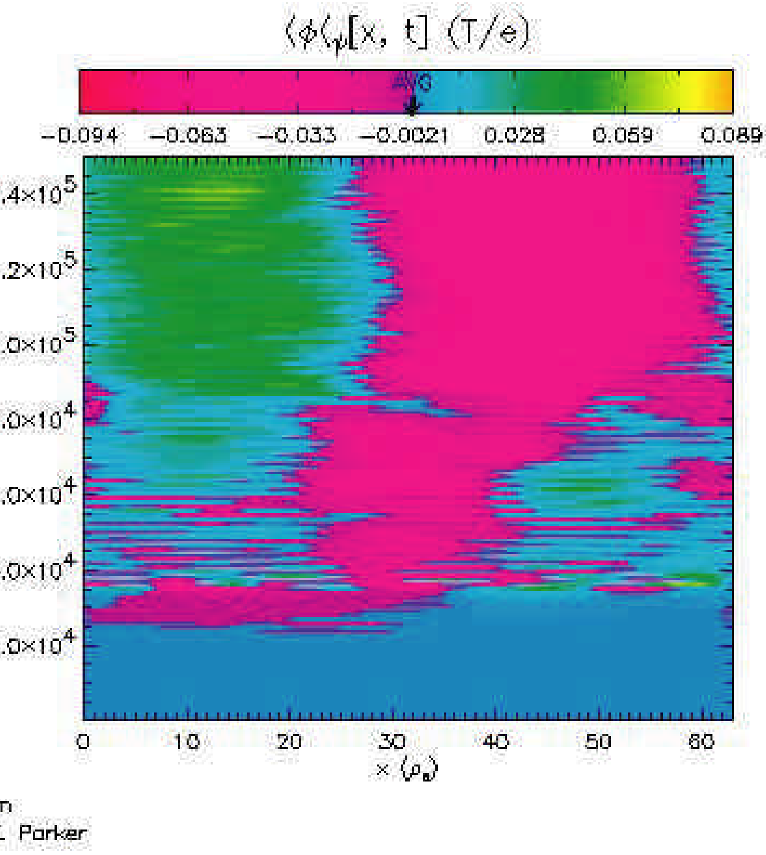




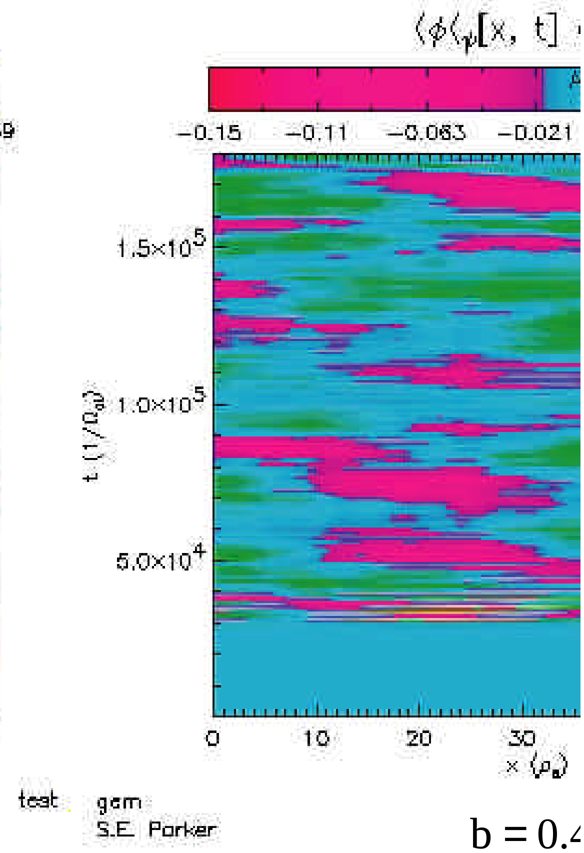
Zonal flows are not nearly as stationary in electromagn
(more a consequence of "kinetic electrons" th

Flux-surface-averaged φ(r,t)

Adiabatic



Electroma



b = 0.4

Global Gyrokinetic Toroidal Code (GTC)

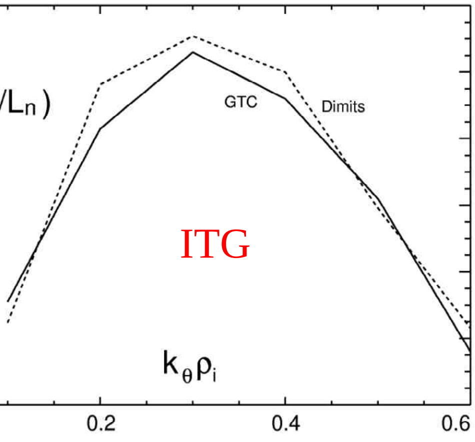
- Magnetic coordinates with field-aligned mesh
- GK ions on a charged ring for FLR effects, Guiding Center electrons
- Momentum/energy conserving collision operators
- MPI for 1-D domain decomposition & OpenMP for 2nd domain
- Interface with AVS for visualization
- Shaped plasmas (near completion)
- Global MultiGrid-MultiSolver for gyrokinetic Poisson's equation and Ampere's law (near completion)
- Three-dimensional numerical equilibrium (near completion)
- Electron dynamics, finite-β (in progress)

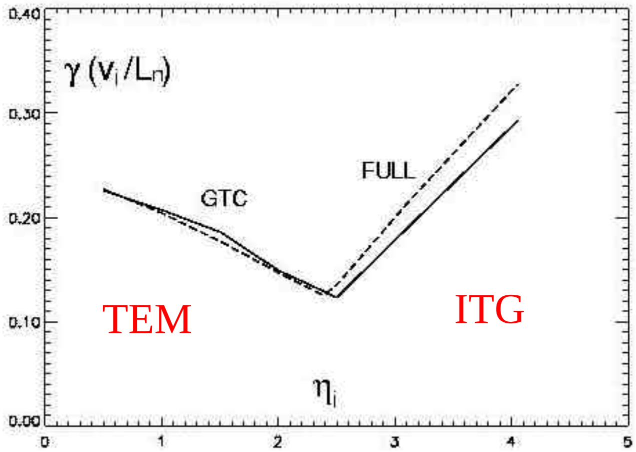
Special Features of GTC

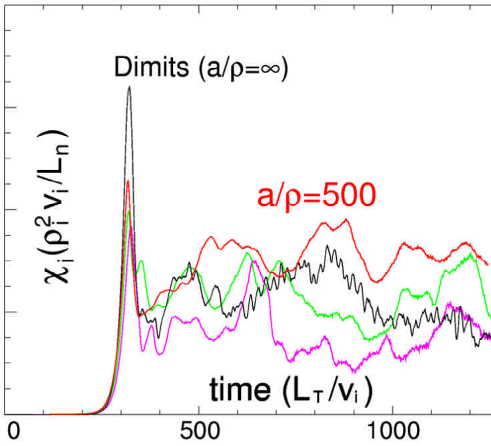
- A general purpose global particle code for studying neoclassical and (soon) finite-β turbulence physics. Will include
  - Non-circular cross section
  - small aspect ratio
  - 3D equilibria
- (Ultimately) Annulus, wedge, and flux tube will be subsets of this code
- Based on the split-weight scheme for electrons
  - Computing time ~ N_p (number of particles)
- The MultiGrid-MultiSolver for elliptic equations (*Lewandowski)*
  - Using magnetic & field-line coordinates with area-preserving mesh
  - Ideal for parallel architecture
  - Convergence rate is independent of N_g (number of grid points)
    Computing time ~N_g (number of grid points)

GTC: Global-Local and Global-Global Benchmarks

- Good agreement for linear growth rate between GTC and local codes:
  - adiabatic electrons (left panel)
  - kinetic electrons via fluid-kinetic model *[Lin and Chen, Phys. Plasma, 2001]*
  - TEM mode peaks at $k_\theta\rho_i$>1, a regime no TEM simulation has addressed
- Nonlinear benchmark for standard Cyclone parameters (right panel)
  - GTC global result χ_i=3.1 ***[Lin et al , IAEA, October, 2002]***
  - Dimits' local result χ_i=2.4 ***[Dimits et al, Phys. Plasma, 2000] (Cyclone standard)***
  - GYRO local result χ_i=1.9 ***[Candy and Waltz, JCP, April, 2003]***
- Benchmark with global GK code ***[Idomura et al, IAEA 2002]:*** good agreement for linear growth rate, nonlinear benchmark underway
- *Z. Lin*, *UC Irvine*, *G. Rewoldt* and GTC team, *PPPL*

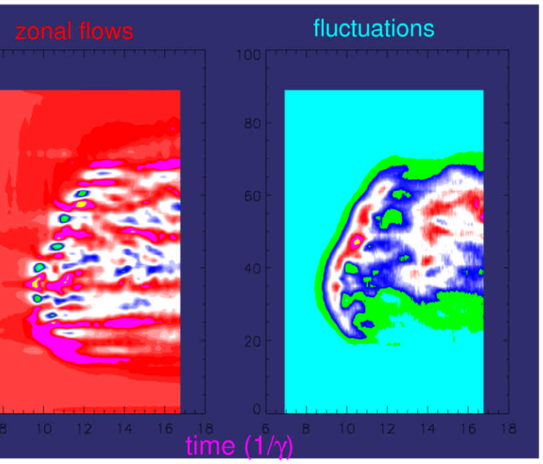


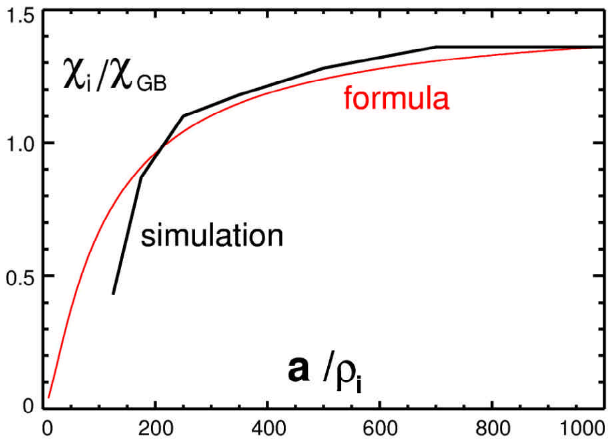


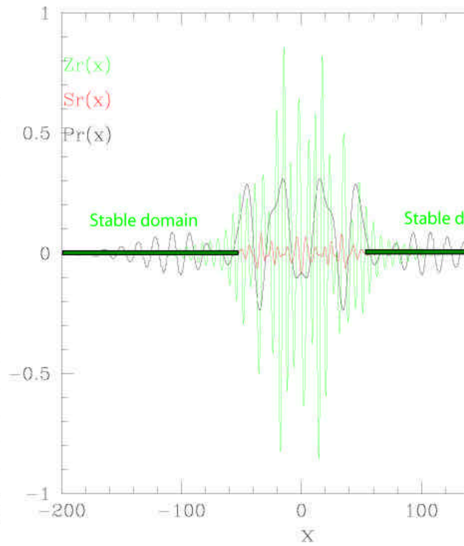


GTC Stimulates Theories for Turbulence Spreading

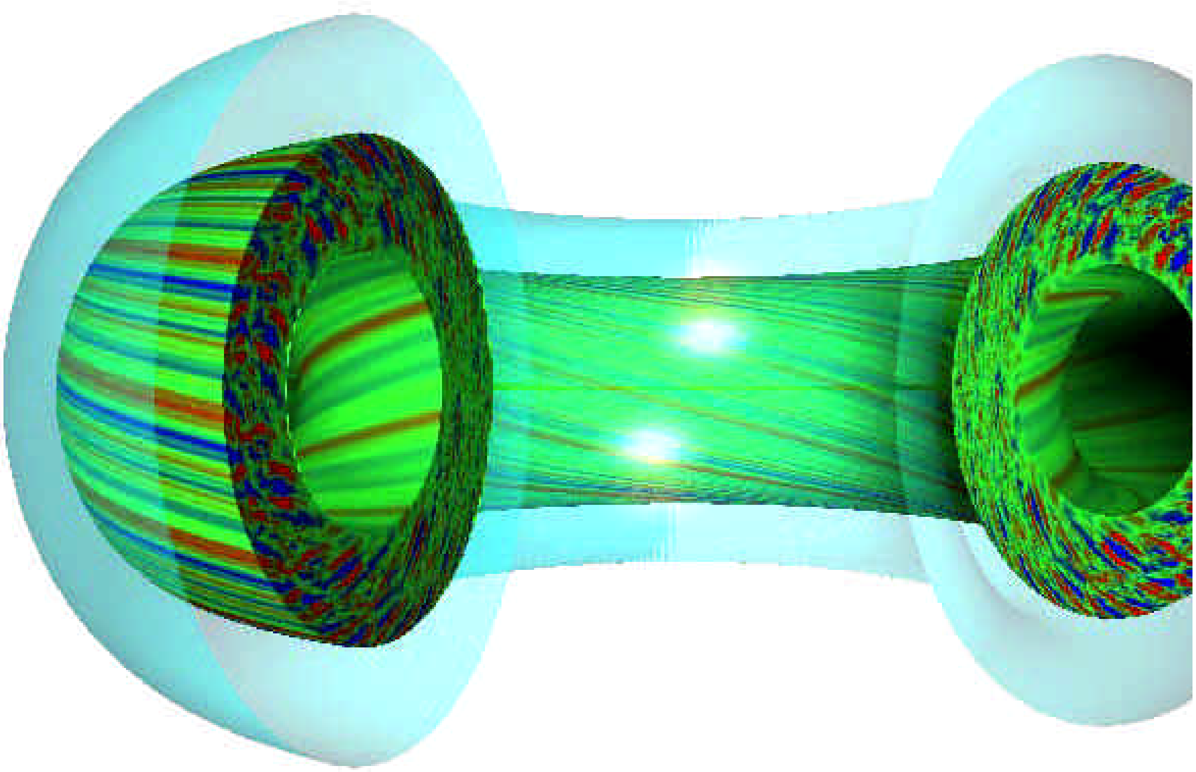
- Fluctuations spreading from unstable to stable regions is observed and postulated as a mechanism for Bohm to gyroBohm transition in GTC global simulations (left panel) ***[Lin et al, PRL, 2002]***
- Theory for nonlinear diffusion ***[Hahm, Diamond, and Lin, ITPA-OTB, 2002]***
  - balancing radial spread of front and local radial damping (center panel)
- Theory for radial propagation induced by zonal flows (right panel) ***[Chen, White, and Zonca, Sherwood talk, 2003]***
  - ***introduce radial profile to 4-mode modulational instability model of zonal flows generation [Chen, Lin, and White, Phys. Plasma, 2000]***
- Theories confirm key trend observed in simulations
- *Z. Lin*, *UC Irvine*, *T. S. Hahm* and GTC team, *PPPL*







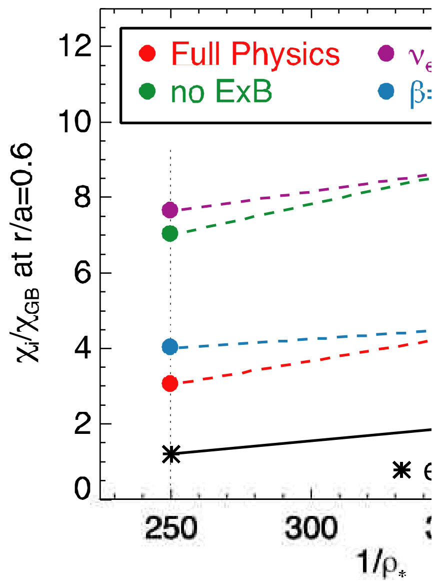
GYRO
A Global Continuum Code

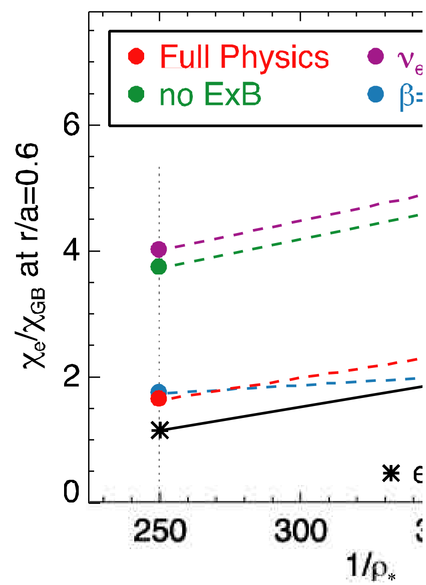


GYRO Progress

- Bohm scaling with full physics (particularly Exp. ExB shear)
  [Candy & Waltz, sub. to PRL (Sept. '02)]
  - Impurities → 2x reduction?
  - ETG not included (does it matter?)
- Core plasmas close to marginal
  "Stiff" — Small changes in parameters produce large changes in χ
- Small changes in T (within Exp. Uncertainty) can match simulation χ's or power flows to Exp.

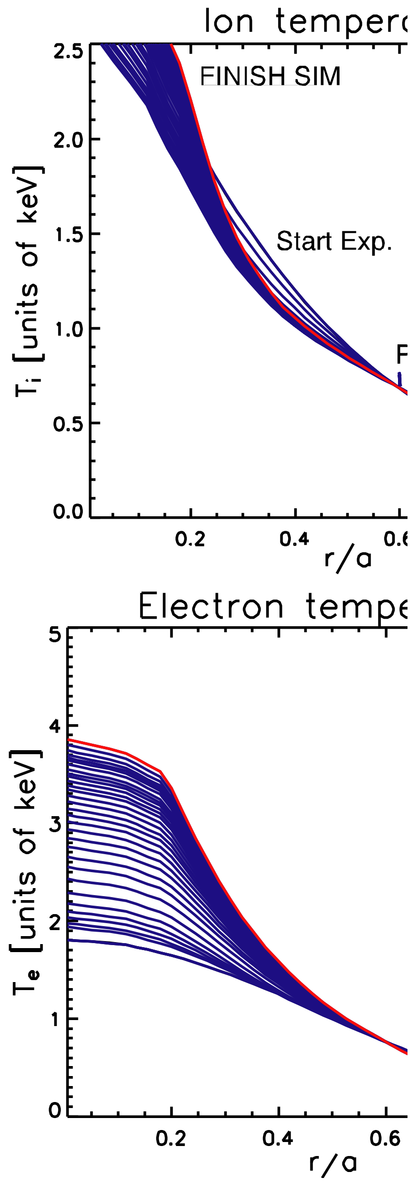
  Match power flows and use simulations to predict profiles





Simulations with fixed (Exp.) Power Flow

- Outer feedback loop added
  - Adjusts local gradient to match experimental power flows
  - Profiles obtained by integrating gradients from "pivot" point
- Steady-state solutions obtained after *1000-2000* (a/c_s)
  - Power flow in simulation matches experiment
  - Ion temperature profile similar to experimental profile
  - Electron temperature in simulation more peaked than experiment



GYRO Status and Plans

- GYRO can simulate nearly full radial slices of DIII-D with full physics
  - Bohm scaling for DIII-D L-modes with power flow similar to exp. And small adjustments to T (within experimental Uncertainty)
  - Moving on to understand gyroBohm scaling in H-mode shots
- Feedback loop ‘tunes’ profiles to match experimental power flows.
  - Predicts profiles of density, T_e, T_i, and toroidal momentum profiles
- Looking ahead to Fusion Simulation Project (Dahlberg last year)
  Fast restart capability allows feedback to/from external transport code
  - Steady-state transport solution in ~0.8 days w/ 2-mode toroidal spectrum
  - Same in about 6 days w/ 16 or 32 mode toroidal spectrum

    Steady-state transport solutions should be feasible with modest speed-up
- GYRO is building a user base —6-7 users at GA, PPPL, U Tx, MIT

Visit the GYRO web site http://web.gat.com/comp/parallel/ for literature and animations

GS2 — A Flux-Tube Continuum Code Fully Electromagnetic ($\delta B_\perp$ and $\delta B_{||}$)

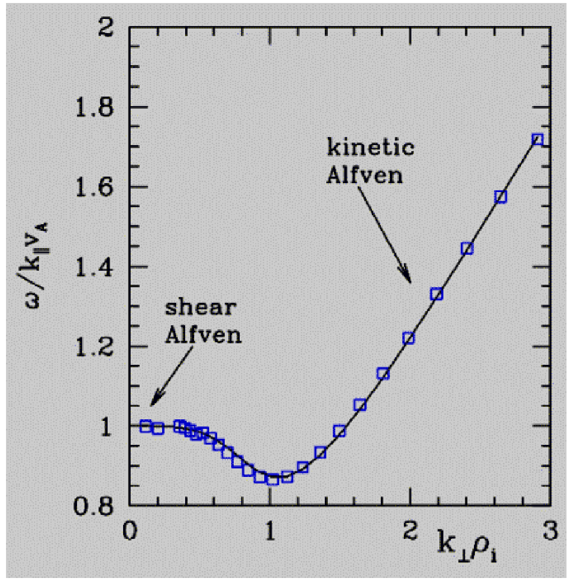
- GS2 effort is about building a user base and doing physics
  - 3-day training session at PPPL in January (GS2 is on PPPL cluster)
  - VERY widely used for linear stability studies
  - Widely used for non-linear microturbulence simulations
    (Nonlinear users include: D. Applegate, C. Bourdelle, R. Bravenec, R. Budny, D. Ernst, K. Hallatschek, F. Jenko, D. Mikkelsen, A. Peeters, T. Pedersen, M. Redi, and D. Ross)
  - Soon (July) to be available as part of the National Fusion Collaboratory
- GS2 is being used to study new physics
  - Particle and electron energy transport (esp. comparison with experiments)
  - Distinctly electromagnetic instabilities found in studies using exp. Profiles
  - Non-tokamak configurations (stellerators, dipoles, …)
  - Astrophysical turbulence, with $\beta >> 1$. Compressional terms ($\delta B_{||}$) important

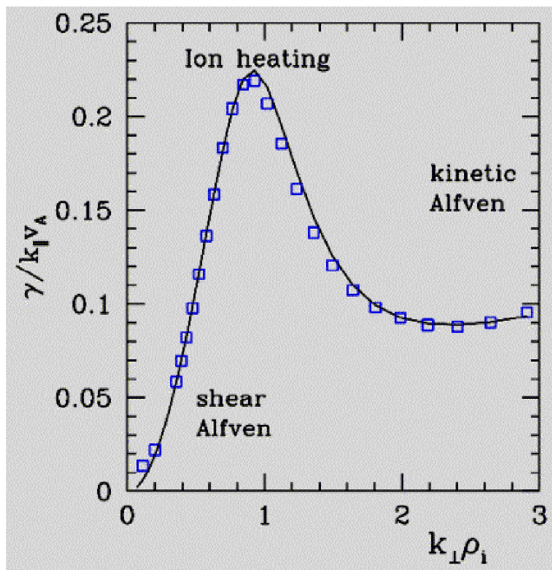
GS2 Simulations of Astrophysical Turbulence

- $\beta >> 1$ ($\beta = 10$ in figures to right)
- Issue is anomalous ion heating
- GS2 Simulates
  - MHD turbulence at long wavelength
  - Cascade to short wavelength
  - Shear and kinetic Alfvén waves with collisionless damping (see linear benchmark at right)

  Anomalous heating

See http://gk.umd.edu/GS_APS03a.htm for more details





Stabilization of ITG Modes at high β′

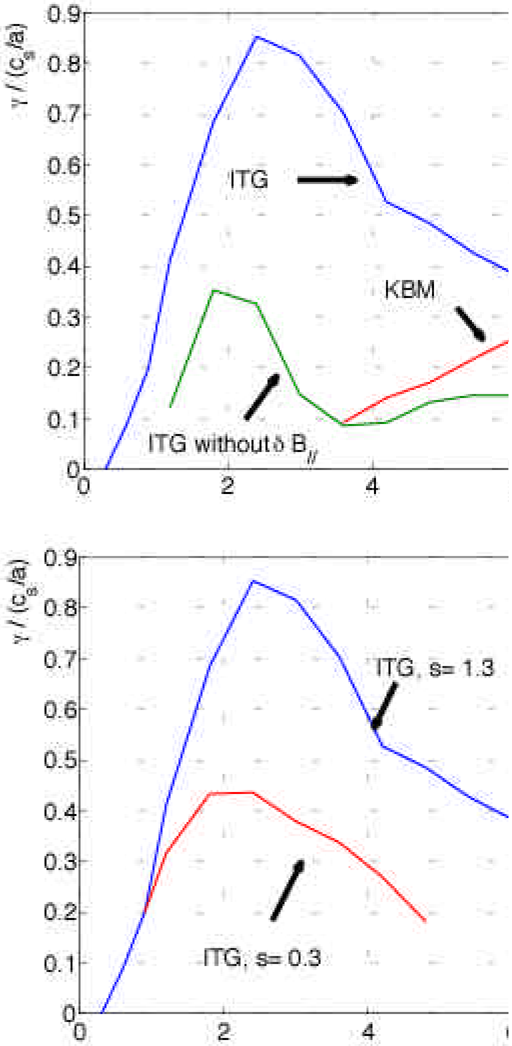
- Large gradients in β are stabilizing for ITG modes
- Compressional term ($\delta B_{||}$) important to this result
- Important for transport in low aspect ratio tokamaks

For details see

C. Bourdelle, et al, Phys. Plasmas (August, 2003)

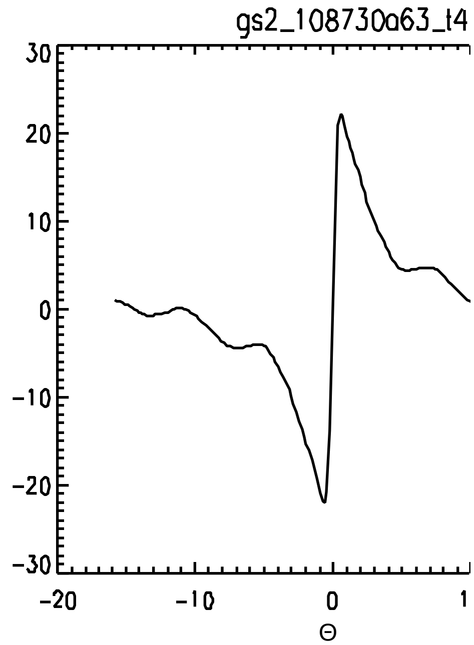
Or, on the web at

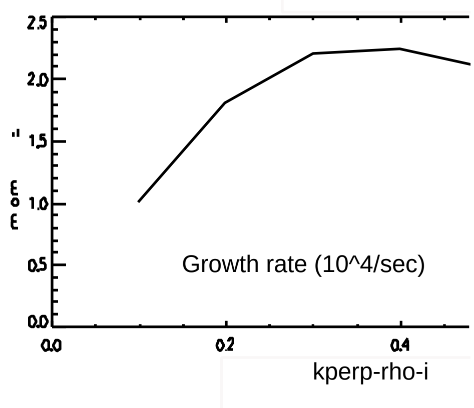
http://gk.umd.edu/bourdelle_2.pdf



Internal Transport Barrier Formation & Microtearing

- GS2 Simulations of transport barriers from C-Mod and NSTX experiments
  - ITB formation from
    - Geometry and profile effects
    - Precedes ExB shear layer
  - GS2 shows
    - Suppression of ITG
    - Reduced particle and ion heat transport
    - Appearance of microtearing modes (see Fig. to right) electron heat transport)





For more information, see M. Redi et al. at

http://gk.umd.edu/redi-sherwood-03.pdf

How the Questions in PAC Charge Are Addressed

•	Response to the 2002 PAC recommendations	→	**Coming up next. See "Response to 2002 PAC" viewgraph**
•	Progress on achieving its scientific targets *w.r.t.* stated timetable ending June of 2004	→	**Coming after that. See "Summary of Progress" viewgraph. Scientific progress was also in code viewgraphs**
•	How super-computing resources have enabled the achievement of the targeted scientific goals in the timeliest manner	→	**Coming real soon. See "SuperComputing Resources" viewgraph.**
•	What role have collaborative interactions within each project and also with other SciDAC activities played	→	**"Response to 2002 PAC" viewgraph (coming next) and 1st GS2 viewgraph**
•	What is the vision/scientific roadmap for the next 3-year phase (beyond June 2004)	→	**Save for discussion at end of talk**

Response to the 2002 PAC recommendations

2002 PSACI Comments on PMP
(nice words)

“Comprehensive and convincing benchmark comparisons of the spatial and temporal scales for turbulent decorrelation have been made using four different simulation codes. There’s also been encouraging initial work through the SUMMIT project on a common framework for developing future microturbulence codes. Productive physics applications were detailed in publications.”

And the PAC recommends:

- more analysis of the results of the codes (*e.g.*, the Bohm-gyroBohm transition)
  - “More analysis” Deploy GKV
    - Coupled GKV to all PMP codes plus
      - BOUT (edge turbulence)
      - C. Holland’s Hasagawa-Wakatani code
      - Some Expt. Data analysis
    - Lots of new GKV users
- Enhanced collaborations with CSET
  - Using the Fusion Collaboratory to make GS2 & GYRO available over the NET.
  - Working with PERC to characterize and enhance performance of PMP codes.
  - GTC, GYRO working with ORNL to optimize these codes for “Earth Simulator” prototypes.

Super Computing Resources (NERSC and ORNL) Have Enabled Our Physics Studies

NERSC

- FY '03 Allocation:
  4.78M node-hrs
  - 5M node-hrs Requested
    (as per 7/02)
  - 3.355M node-hours allocated
    (as per 10/02)
  - Increased to 4.78M node-hrs
    (as per 5/03—large GTC runs)
- Current usage:
  3.82 node-hrs
  - 74% of allocation
    (on target to use 4.78 node-hrs)

ORNL

- FY '03 "Allocation"
  2.0M node-hrs
- Current Usage:
  2.62 M node-hrs
  - 131% of allocation (!)
  - ORNL does not deactivate accounts when allocations are exhausted — just restricts maximum allowed priority
  - Anticipated FY '03 node-hrs
    ~3.5M node-hrs
    (and this is evidently OK)

- Plus substantial use of Linux Clusters at PPPL, GA, MIT and U of MD

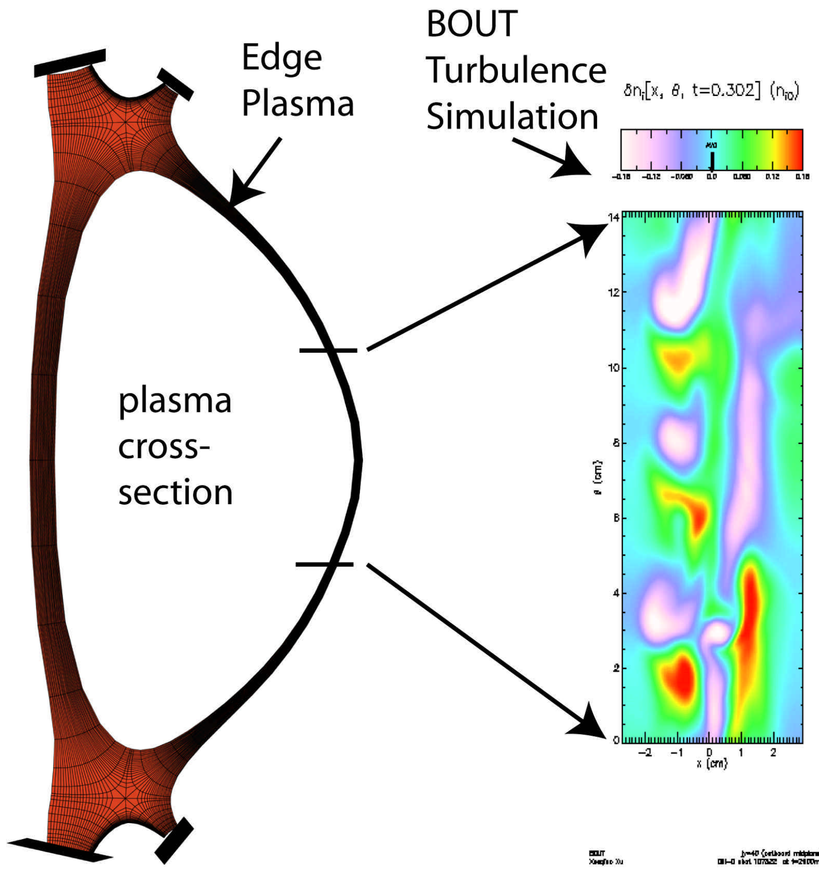
Summary of Progress on Achieving Scientific Targets *w.r.t.* Our Stated Timetable

- Context — Our 2001 SciDAC proposal asked for a substantial increase in funding. When the dust cleared our budget was about even.
- The PMP proposal promised:
  - A unified framework with
    - Four GK "kernels" (which we have — GS2, GYRO, Summit, and GTC)
    - A common front end (we'll complete this for GS2 and GYRO this year)
    - A common back end (which we have — GKV)
    - And users beyond the code development groups (which we've done)
  - Kinetic electrons and (at least) $\delta B_{||}$ in all four codes
    - Have $\delta B_{||}$ and δB in GS2 now, will be in GYRO by June '04
    - Have $\delta B_{||}$ in Summit now, hope to have it in GTC by June '04
  - To do LOTS of good science with our codes (which we've done)

If you stopped the clock today, and the PMP would a success

And We've Done MORE …
by Providing a Home for Edge Turbulence

- BOUT
  - 3-D edge turbulence model
    - Braginskii fluid equations
    - Realistic magnetic geometry
  - Benchmarked against exp't
    - DIII-D L-mode
    - C-Mod QC-mode
    - Density limit
- The PMP has provided BOUT
  - Data analysis with GKV
  - Node-hrs (at ORNL)
  - Access to PERC for code optimization



Two Paths Need to Be Followed Next

Core Turbulence

(mainly doing physics with the codes we have)

- We've developed the tools. They need to be exercised!
  - Understanding ITG and ion heat transport,thermal barrier formation, etc.
  - Understanding electron dissipation (TEM, ETG)
    - Electron heat transport
    - Particle transport
    - Momentum transport

We've made progress, but much remains to be done!

Edge Turbulence

(mainly code development)

- Key problem —understanding the structure of the H-mode pedestal. This requires a kinetic edge code
  - $\rho_p/L \sim 1$ in experiments
  - $\ell_{mfp} \geq \frac{B_T(0)}{B_p(0)} R$ in many experiments
- Computational difficulty similar to core turbulence (?) but
  - $e\varphi/T$, $\delta n/n \sim 1$ (because $\rho_p/L \sim 1$)

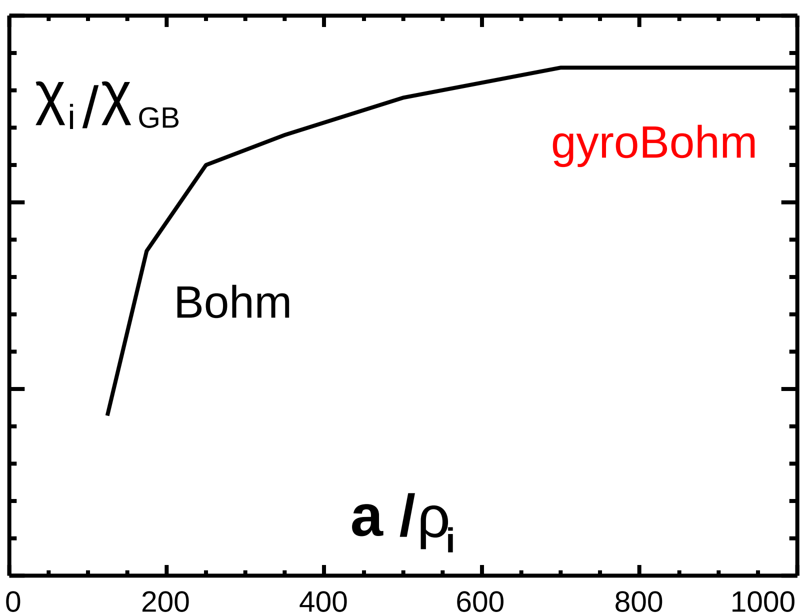
    Need new ordering for an edge kinetic equation

A major code development effort!

Talk ends here
The following are
Backup Slides

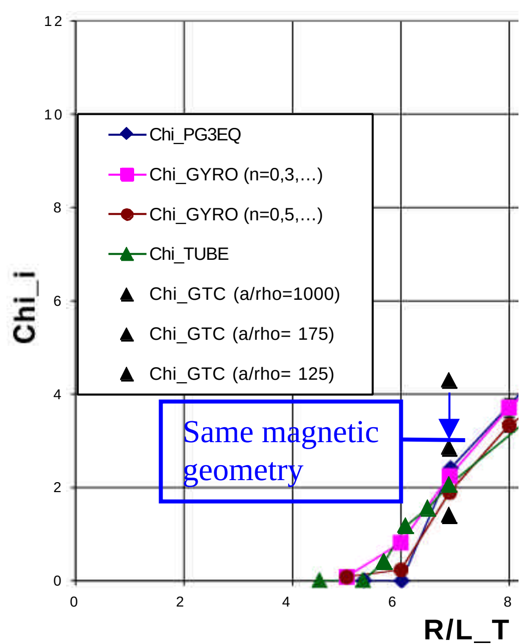
GTC vs. GYRO: This is about Bohm vs. GyroBohm (an important issue) rather than actual value of χ_i

GTC sees transition from Bohm to gyroBohm scaling



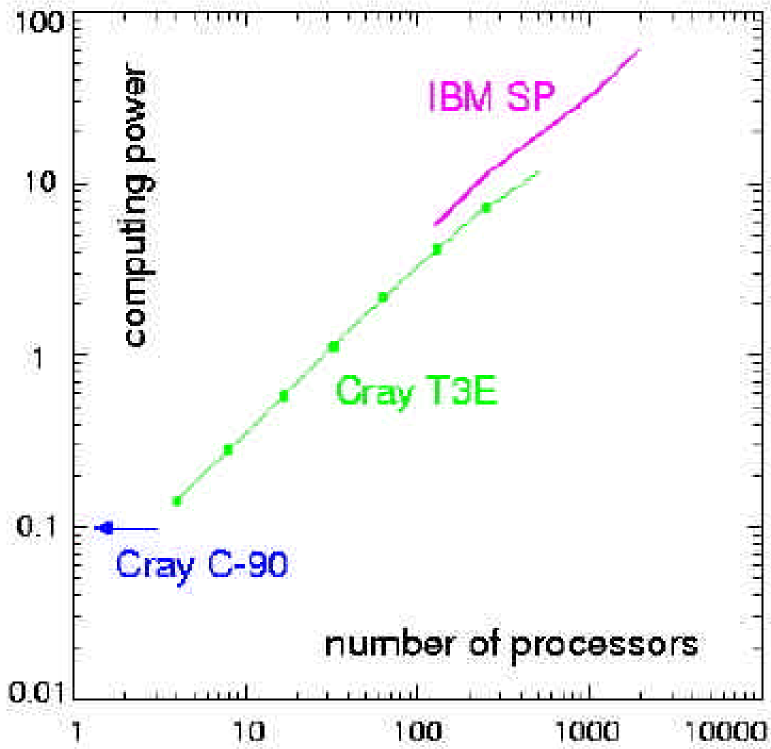
From T.S. Hahm, et. als., "Gyrokinetic Simulation of Transport Scalings and Turbulence Structure" APS/DPP Invited Talk (Nov. 2001).

GYRO sees gyroBohm scaling for this problem



From A. Dimits et als., Phys. Plasmas **7**, 969 (2000); J. Candy (private communication); T.S. Hahm (*op.cit.)*; Z. Lin (2002 IAEA Mtg.)

GTC Scalable to a Large Number of processors



Y-axis: the number of particles (in milions) which move 1 step in 1 second

Single Processor Performance

Processor	Max speed (Mflops)	GTC test (Mflops)	Efficiency (real/max)	Relative speed (user time)
Power3 (Seaborg)	1,500	173.6	12 %	1
Power4 (Cheetah)	5,200	304.5	6 %	1.9
SX6 (Rime)	8,000	715.7	9 %	5.2

Progress Against our Initial Vision for Four Plasma Turbulence Codes