Gyrokinetic Particle Simulations of Fusion Plasmas

Presented by

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Scientific Computing
National Center for Computational Sciences

Near-Term Priorities

Priority: 1
ITER

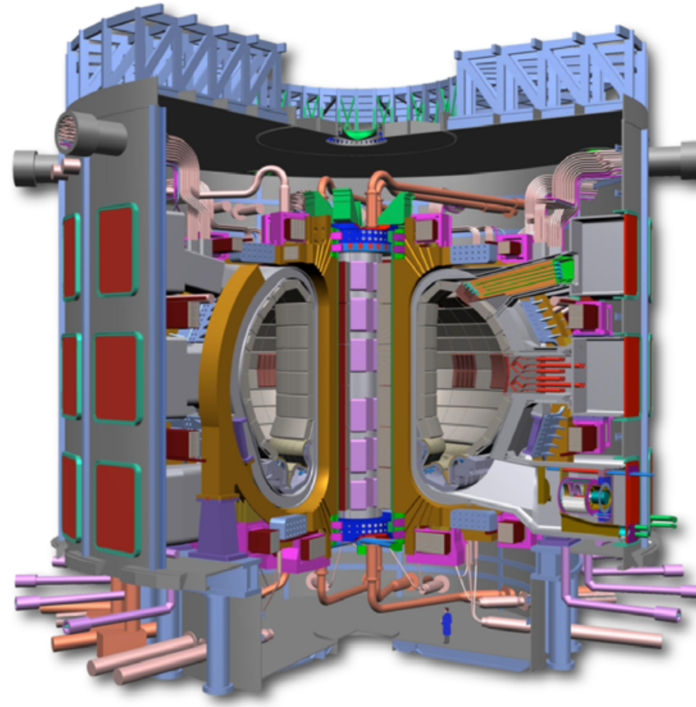
The Facility: ITER is an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction, called a "burning plasma." It is the next essential and critical step on the path toward demonstrating the scientific and technological feasibility of fusion energy.

Priority: 2
UltraScale Scientific Computing Capability (USSCC)

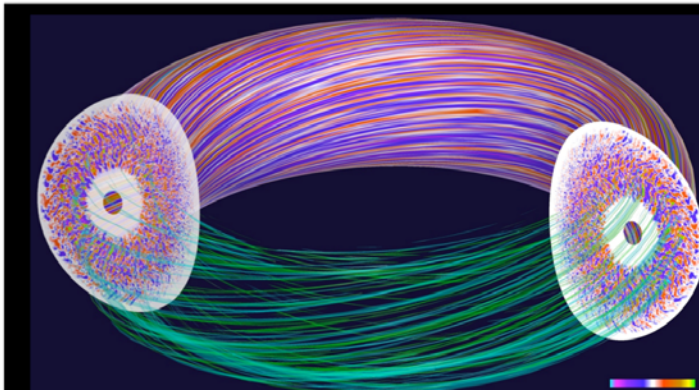
The Facility: The USSCC, located at multiple sites, will increase by a factor of 100 the computing capability available to support open (as opposed to classified) scientific research—reducing from years to days the time required to simulate complex systems, such as the chemistry of a combustion engine, or weather and climate—and providing much finer resolution.

November 2003

ITER is a donut-shaped device based on the tokamak magnetic confinement concept



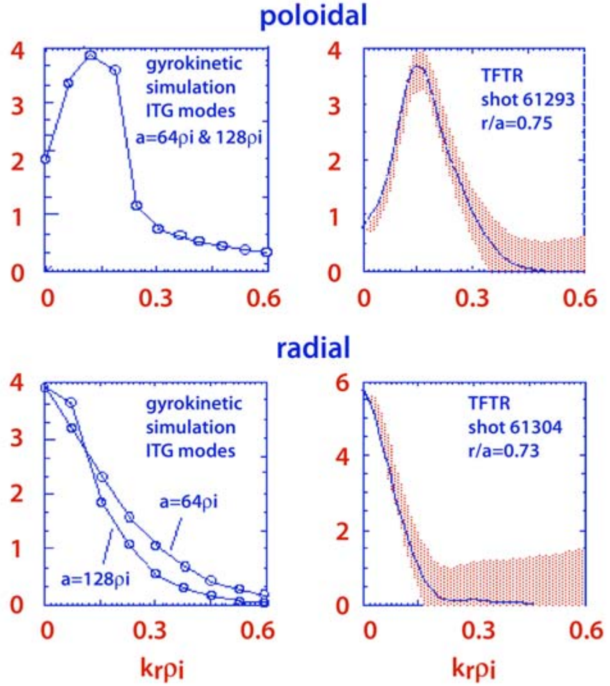
- Parameters:
  - Plasma major radius 6.2m
  - Plasma minor radius 2.0m
  - Ion gyroradius 2.0 mm
  - Electron skin depth 0.5 mm
- ITER is a dramatic step from today's 10 MW for 1 second with gain ~1 to 500 MW for 400 seconds with gain ~10
- ITER is the last step before a demonstration power plant, DEMO—a device of similar size and field, but with 2500 MW continuous operation with gain >30.
- ITER is an international project to be built in France with US, EU, PRC, Japan, ROK, India, Russia as partners.
- The first plasma is scheduled for 2016.



Visualization by Klasky, Wang, Ethier

First microturbulence simulation on MPP platforms

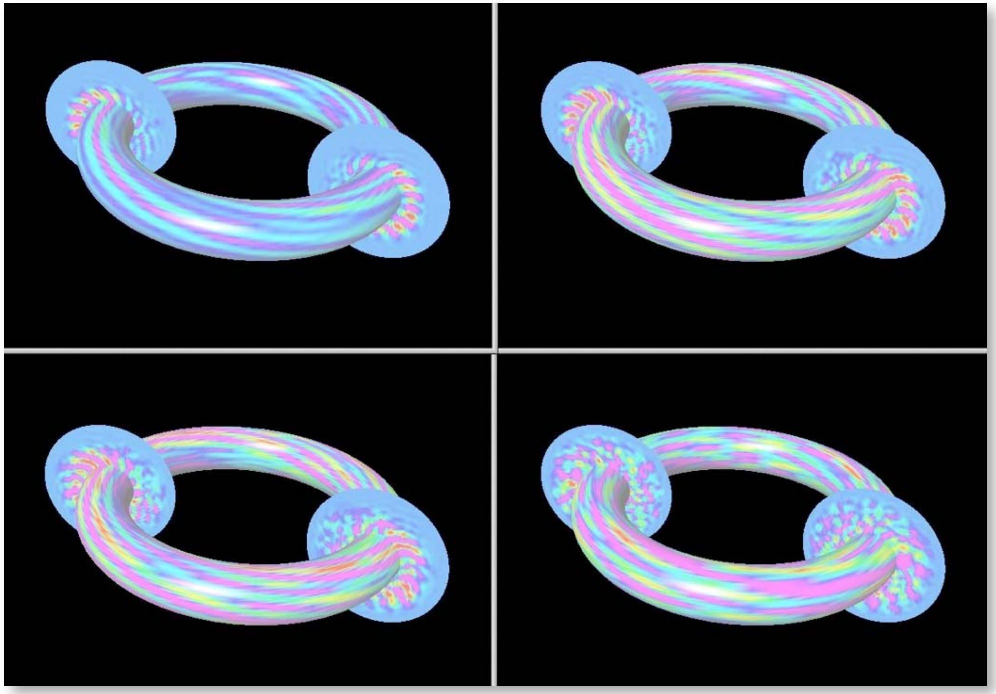
Turbulent spectra
in simulation and experiment:
$S(k_r)$ and $S(k_\theta)$ in arbitrary units



$\chi_i \propto 1/(k_\perp \rho_s)^2 (\rho_s/a)(cT_e/eB)$ -- Bohm vs. Gyro-Bohm

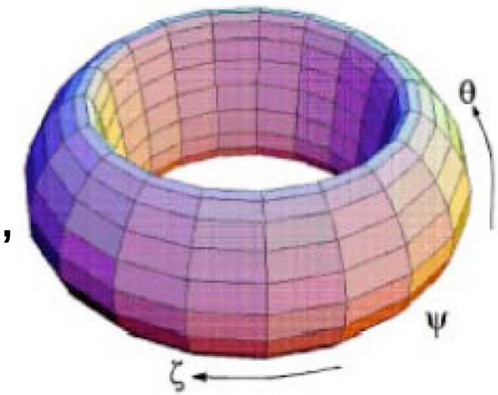
- TFTR BES Measurement
  Fonck, Crosby, Durst, Paul Bretz, Scott Synakowski, and Taylor, *Phys. Rev. Lett.* **70**, 3736 (1993)
- Gyrokinetic Particle Simulation
  Parker, lee, and Santoro, *Phys. Rev. Lett.* **71**, 2042 (1993)

- **These simulations and experimental observations established the fact that ion temperature gradient (ITG) drift instabilities are one of the main causes for turbulent transport in tokamaks.**
- **Using 1 million particles for minor radius (a)/gyroradius (ρ) = 64 - 128 on C_{90} at NERSC.**

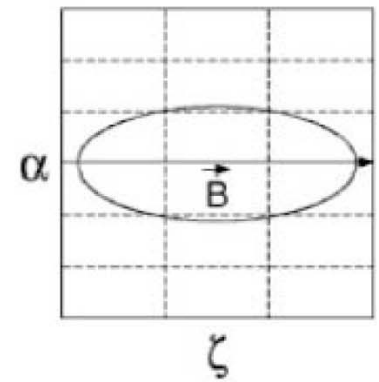


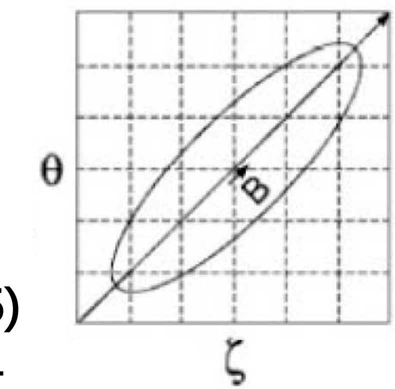
Parker, Lee, Santoro, 1993

Global gyrokinetic toroidal particle-in-cell codes



- Turbulence code with circular cross section GTC: Z. Lin et al., *Science* (1998)
- Magnetic coordinates (ψ,θ,ζ) [Boozer, 1981]
- Guiding center Hamiltonian [Boozer, 1982; White and Chance, 1984]
- Non-spectral Poisson solver [Lin andLee, 1995]
- Global field-line coordinates: (ψ,α,ζ) $\alpha = \theta - \zeta/q$
  - Microinstavility wavelength: $\lambda_\perp \propto \rho\lambda_{||} \propto qR$
  - With filed-line coordinates: grid $\# N \propto \alpha^2$: minor radius, $\Delta\zeta \propto R$
  - Without filed-line coordinates: grid $\# N \propto \alpha^3$, $\Delta\zeta \propto \rho$
  - Larger time step: no high $k_{||}$ modes
- Collisions: e-i, i-i, and e-e
- Neoclassical Transport Code in General Geometry: GTC-NEO, W. X. Wang (2004)
- Optimized GTC: S. Ethier et al., *J. Phys.*: Conf. Series 16, 1 (2005)
- Shaped Plasmas Code in General Geometry: GTC-S, W. Wang et al., *PoP* 13, 092505 (2006)

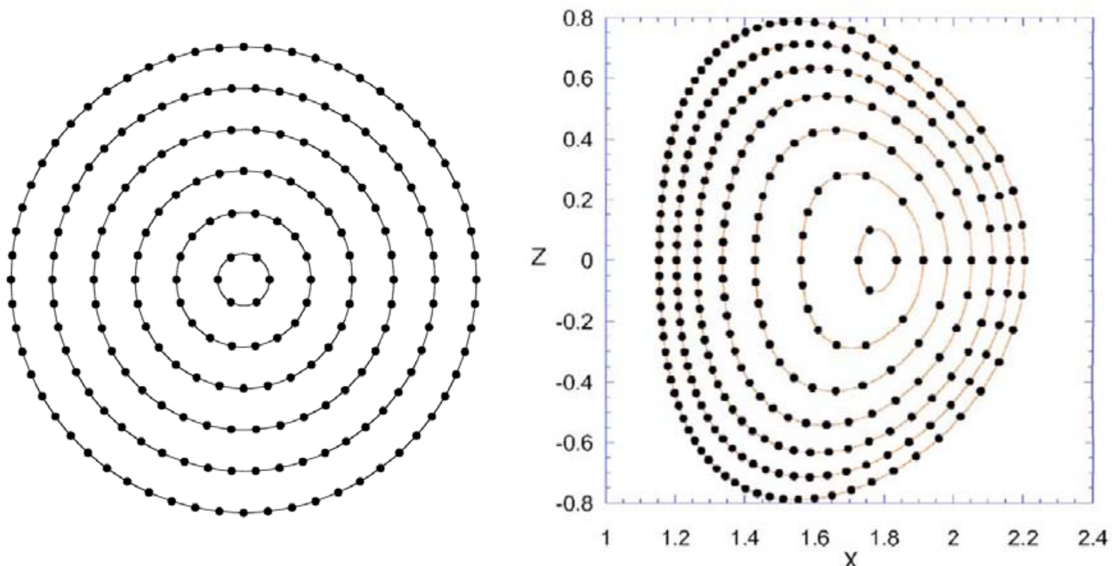




New grid follows change in gyro-radius with temperature profile

- Local gyro-radius proportional to temperature $\rho \propto \sqrt{T}$
- Evenly spaced radial grid in new ρ coordinate where

$$\frac{d\rho}{dr} = \sqrt{T_c / T_i(r)}$$

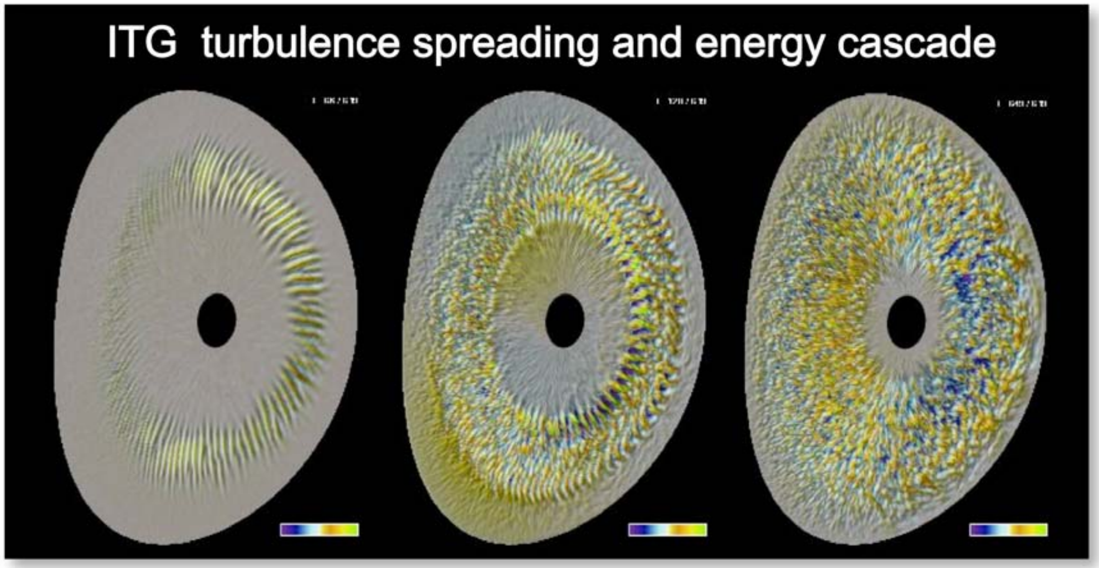


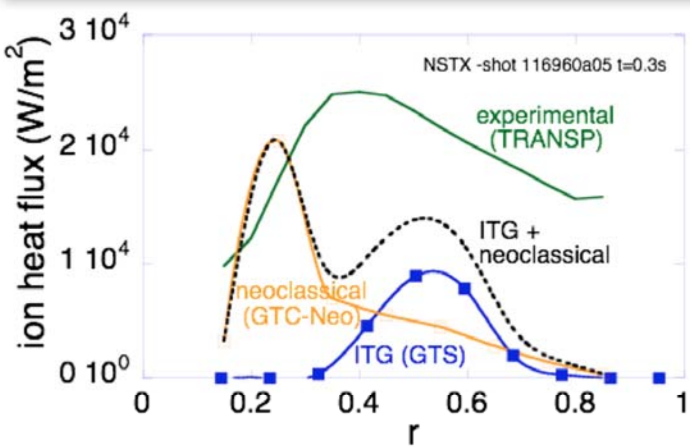
Original GTC circular grid with flat temperature

New GTC-S follows (r)

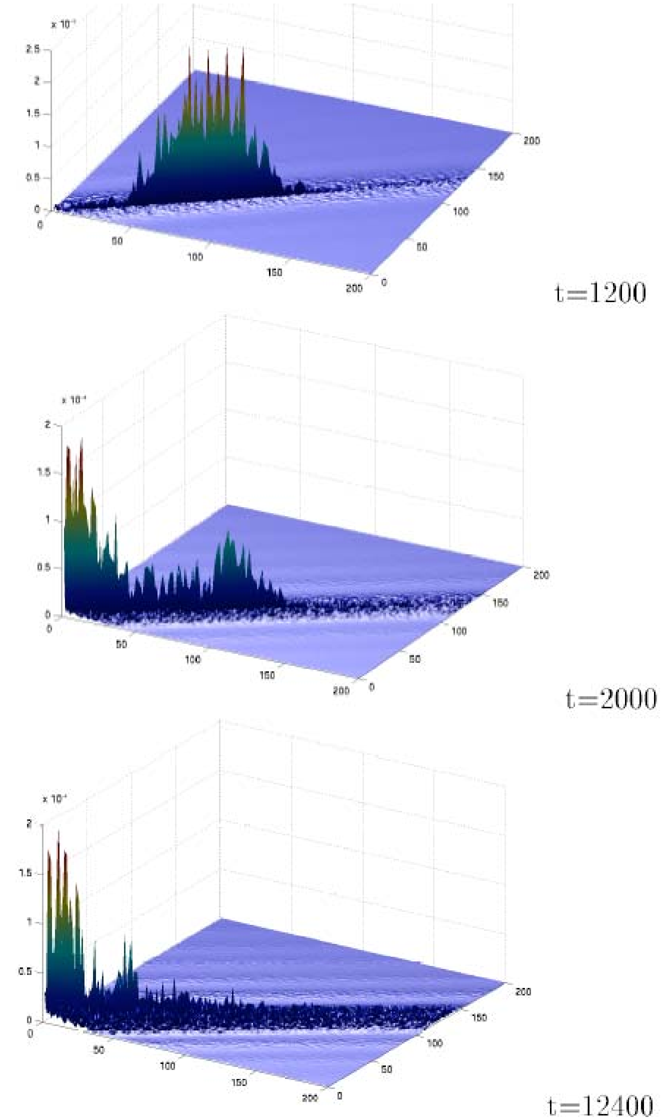
Verification and validation using GTC-S on MPP platforms (2006)

- Global turbulence dynamics in shaped plasmas
- Interfaced with TRANSP and JSOLVER and ESC



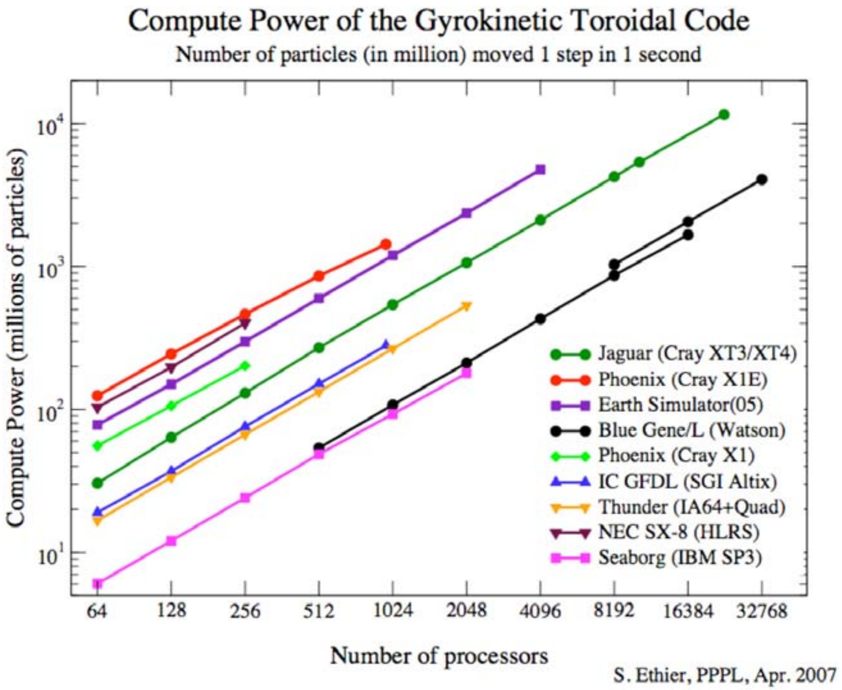


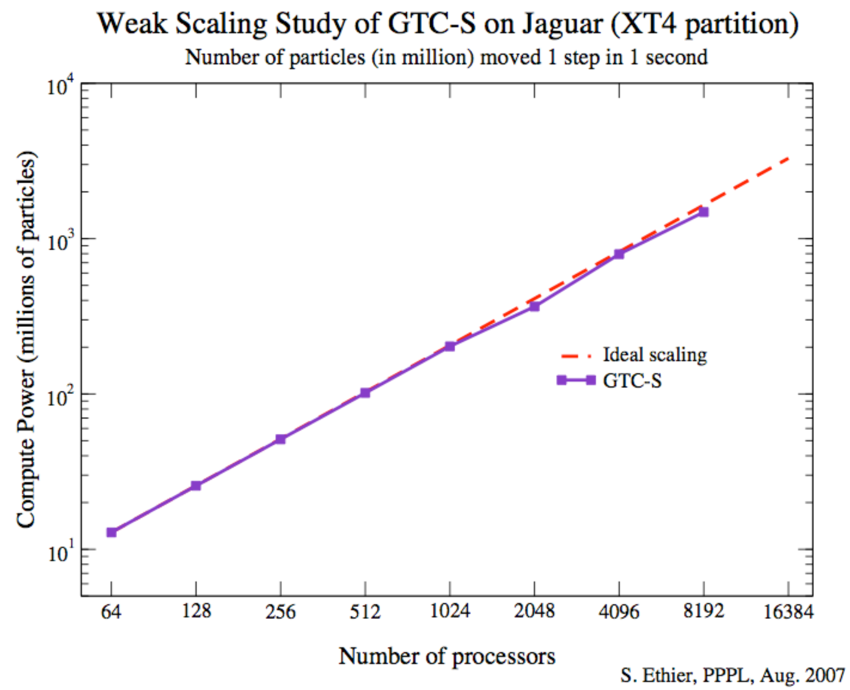
Comparison with NSTX plasmas



W. X. Wang et al. (2006)

Gyrokinetic PIC codes are most suitable for MPP platforms





- GTC is very portable, scalable and efficient on both cache-based and vector-parallel MPPs.
- 20 TF/sec performance has been achieved with 74 billion particles on Jaguar (ORNL) with 22,976 cores and 2.8 times faster than with 32,786 BG/L cores.
- Participation of GTC-S in Joule applications and 250 TF campaign at ORNL.
- The computing power above will increase by a factor of two for single precision runs.

(S. Ethier, 2007)

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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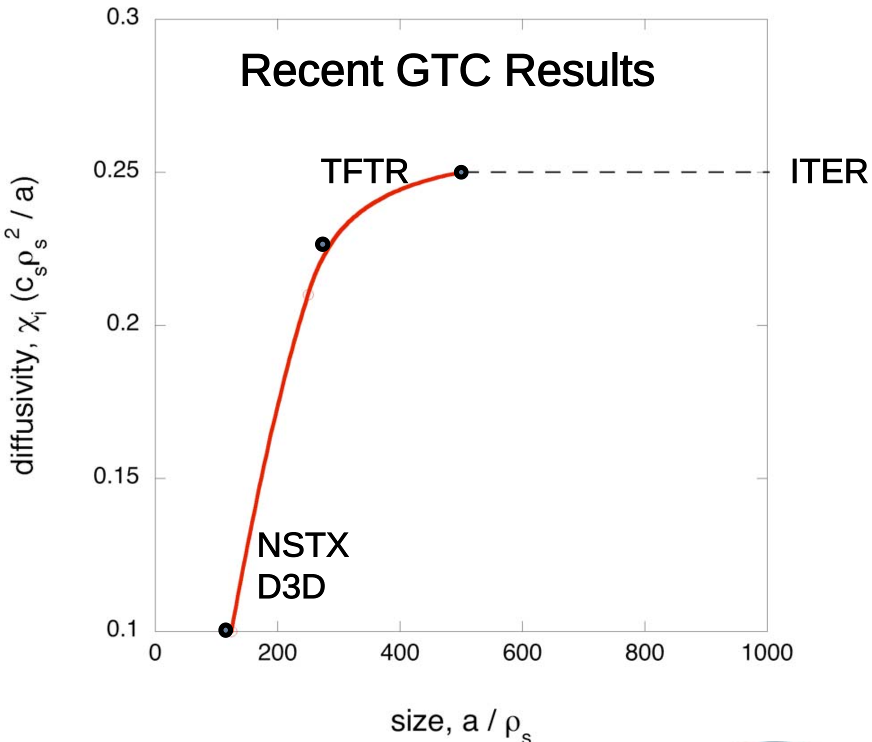
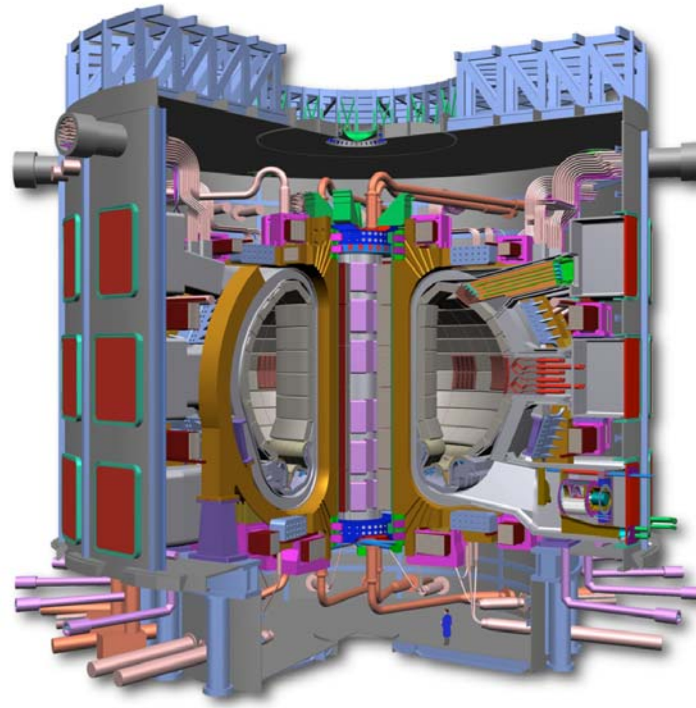
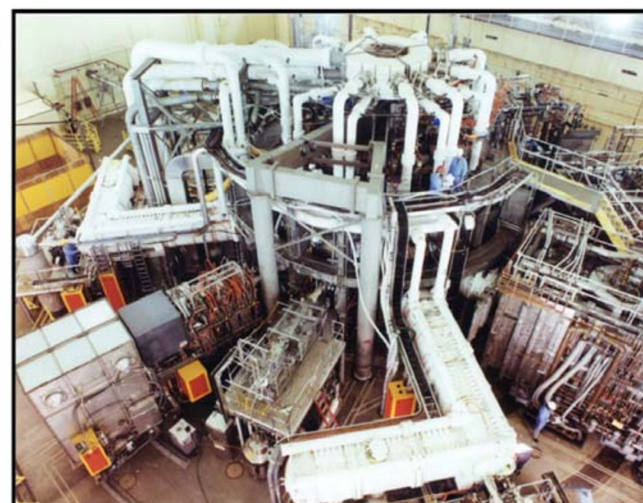
Petaflop computing is needed to understand scaling trend for ITER

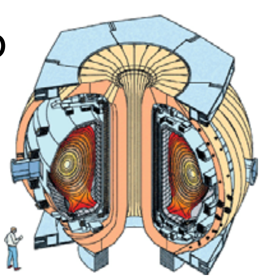




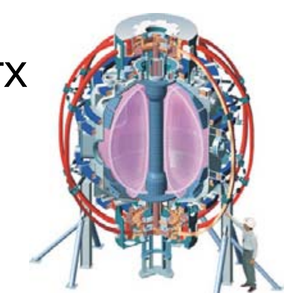
TFTR



D3D



NSTX



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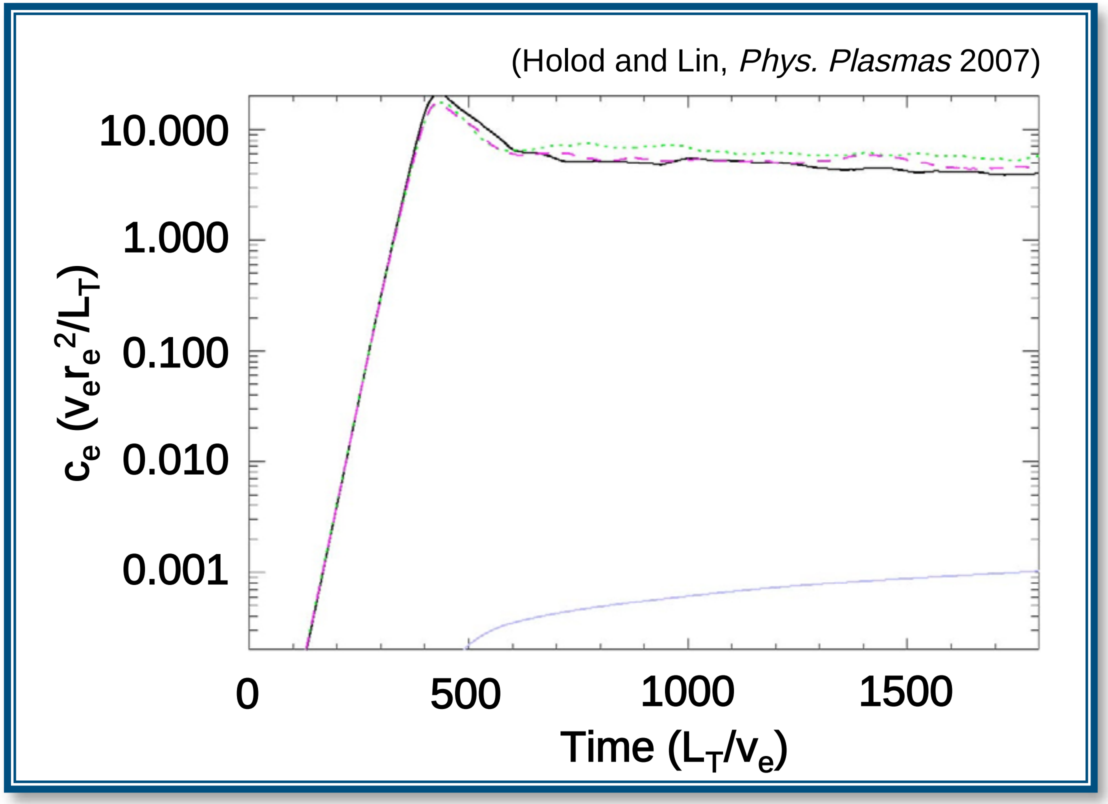
GTC nonlinear convergence in ETG simulation

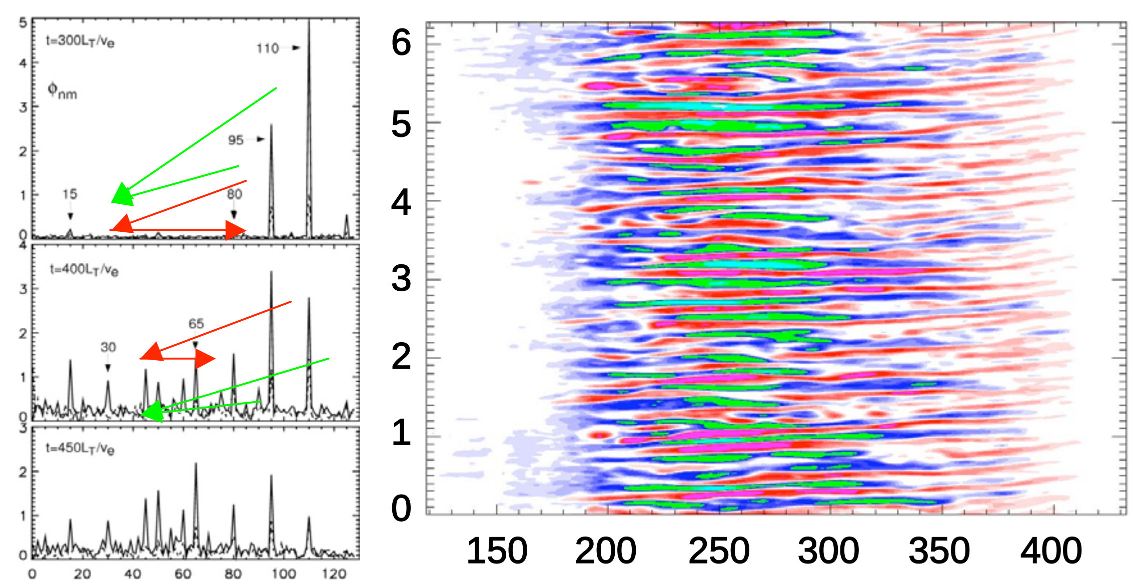
- Convergence from 400 to 2000 particles per cell.
  - Weak Cyclone case: $R/L_T = 5.3$, $s = 0.78$, $q = 1.4$, $a/r_e = 500$, $g{\sim}w_r/4$.
- Noise-driven flux is 4000 times smaller than ETG driven flux.
- Noise spectrum in ETG simulation measured. Noise-driven flux calculated and measured; both in good agreement.
- ORNL Cray XT4, 6400 PE, $4{\times}10^{10}$ particles.



Saturation and transport mechanisms in ETG turbulence

- **Global simulations using GTC find that electron temperature gradient (ETG) instability saturates via** nonlinear toroidal **coupling, which transfers energy successively from unstable modes to damped modes preferentially with lower toroidal mode numbers** [Lin, Chen, Zonca, *Phys. Plasmas* 12, 056125 (2005); Chen, Zonca, Lin, *Plasma Phys. Contr. Fusion* 47, B71 (2005)].

- **Comprehensive analysis of large dataset from GTC simulations finds that stochastic** wave-particle decorrelation **is the dominant mechanism responsible for electron heat transport driven by ETG turbulence with extended radial streamers** [Lin, Holod, Chen, Diamond, Hahm, Ethier, submitted to *Phys. Rev. Lett.*, 2007].



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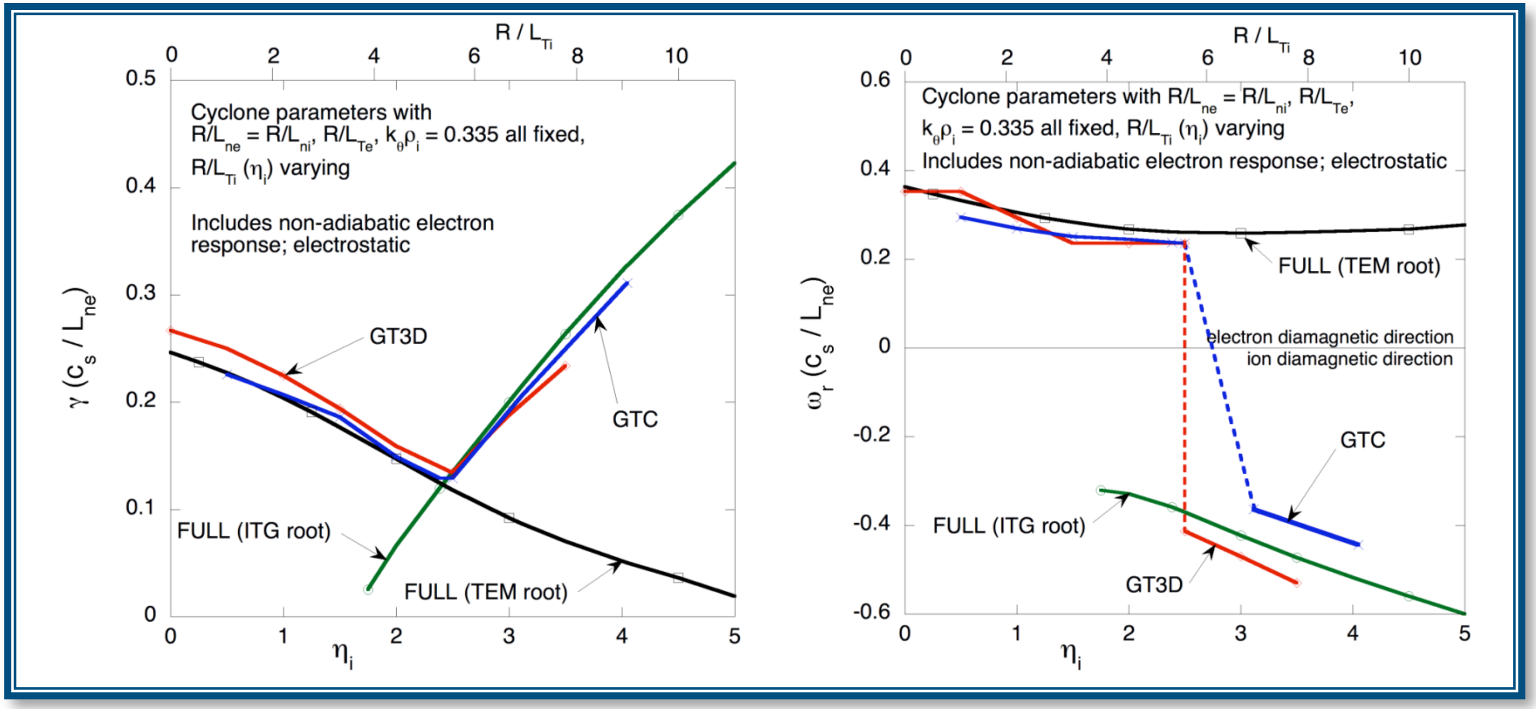
Global GTC simulation with kinetic electrons

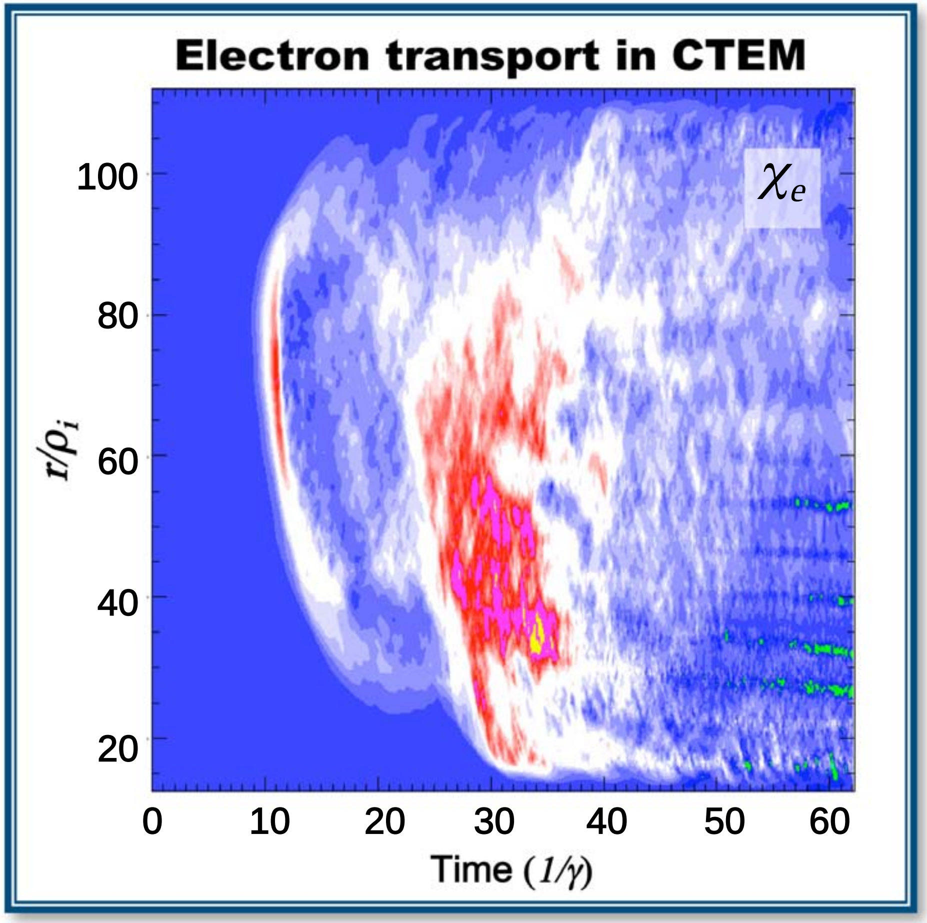
- **Electron response expanded using $\varepsilon = (m_e/m_i)^{1/2}$** [Lin and Chen, *PoP* 2001].
- **Approximation: re scales; no inductive $\delta E_{//}$ ($k_{//} = 0$).**
- **Model treats rigorously all other $k_{//} = 0$ modes: electrostatic δE, magnetic δB, zonal flows/fields, all ideal and resistive MHD modes.**
- **Model optimal for drift and Alfvenic turbulence on ρ_i scales.**
- **Electrostatic ITG/CTEM benchmark** [Rewoldt, Lin, and Idomura, *Computer Physics Communications* 2007].



Nonlinear bursting in CTEM turbulence

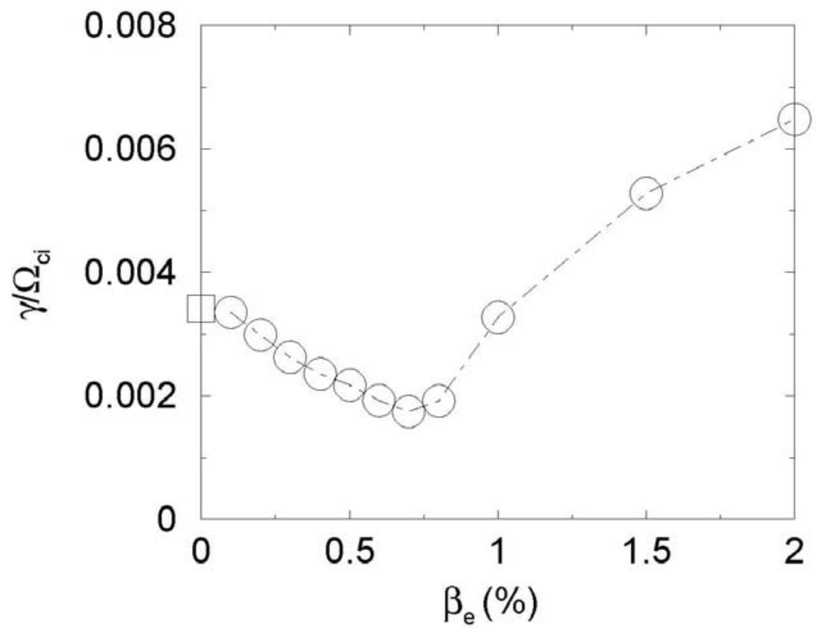
- **GTC simulations of collisionless trapped electron mode (CTEM) turbulence finds a nonlinear bursting of fluctuation and transport, which propagates ballistically both inward and outward** [Lin et al., EPS invited talk 2007].

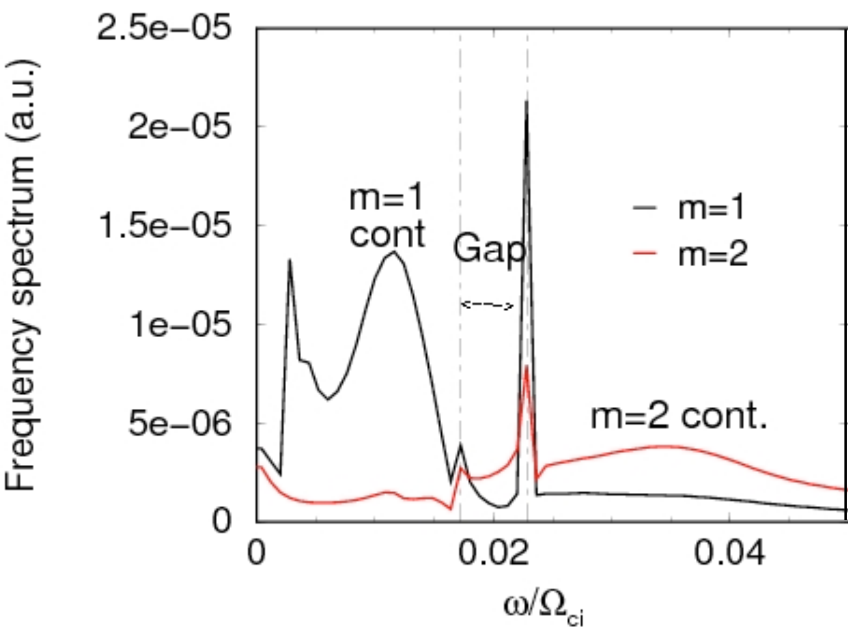
- **GTC simulations of ITG turbulence with kinetic electrons find that the electron thermal and particle transport are much smaller than the ion thermal transport and that small-scale zonal flows are generated through nonlinear interactions of the trapped electrons with the turbulence** [Lin, Nishimura, Xiao, Holod, Zhang, Chen, *Plasma Phys. Contr. Fusion*, 2007].



GTC electromagnetic simulation

- **Global GTC electromagnetic simulations demonstrate finite-β stabilization of ITG and excitation of KBM/AITG, Alfven wave propagation in tokamak, continuum damping via phase mixing, and existence of toroidal frequency gap** [Nishimura, Lin, Wang, *Phys. Plasmas* 2007].
- New Science: **Nonlinear evolution of micro-meso multiple scales turbulence of toroidal Alfenvic eigenmodes driven by energetic particles using fully self-consistent, global, gyrokinetic GTC simulations.**





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New physics direction for GTC simulation

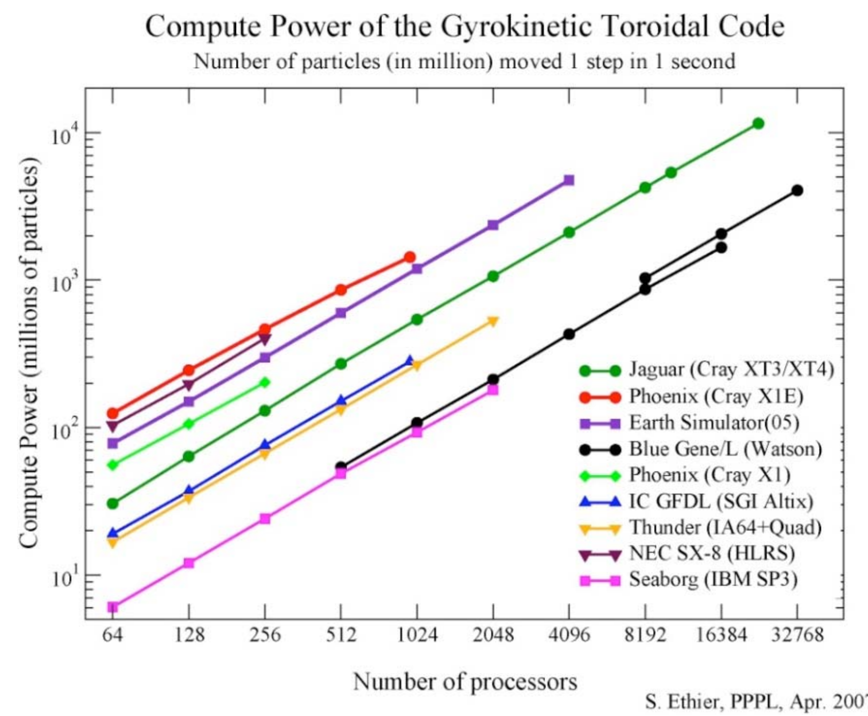
- SciDAC Center for Gyrokinetic Particle Simulation of Turbulence and Transport in Burning Plasmas has been renewed (2007-2010) with new PI (P. H. Diamond of UCSD).
- New physics direction for GTC simulations:
  - Momentum transport and intrinsic rotation
  - Strong resonant nonlinear interaction in CTEM
  - Meso-scale dynamics and nonlocality

GTC code development in new GPSC

- Object-oriented GTC version for collaborative code development and for integrating kinetic electron, electromagnetic, multiple ion species, collisions, and MHD equilibrium with general geometry.
- Advanced code capability for long time simulation:
  - Full-f simulation for noise mitigation
  - Flux-driven turbulence
  - Realistic heat/particle sources

GTC code development in new GPSC

- Only fusion code selected for early applications on 350 TF ORNL computer
- Parallelization and optimization
- Advanced data management
- Diagnostic and data analysis



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