SUMMARY OF "CYCLONE" PAPER "COMPARISONS AND PHYSICS BASIS OF TOKAMAK TRANSPORT MODELS AND TURBULENCE SIMULATIONS"

W. Nevins, LLNL
at DOE, October 1999

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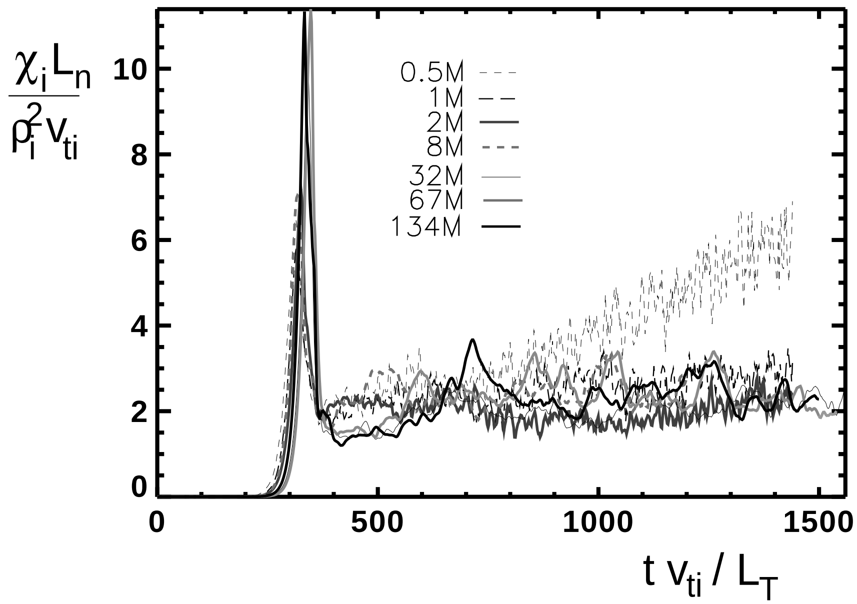
Careful linear benchmarking to ensure different codes had agreement on basic linear physics

Show Fig. 1 from paper.

Comment that good linear agreement was found. Linear growth rate and critical gradient depends on specific geometry (s-alpha vs. realistic aspect ratio), trapped electrons, etc.

of particles Varied Over a Very Wide Range to Demonstrate Convergence.



Typically need 2-4 particles per cell (1-2 M in this case), or more particles near marginal stability.

• Some people initially worried that variation of χ with $N_{\mathrm{particles}}$ might indicate convergence difficulties.

• But scan was eventually done over such a wide range of $N_{\mathrm{particles}}$ that, combined with the scrambling tests, it became clear that this was converged.

• Variations of χ with time and $N_{\mathrm{particles}}$ are now understood as resulting from a chaotic system with long time-scale dynamics (such as in zonal flows).

• Analogy: We are interested in time-averaged “climate”, averaging over random fluctuations of hotter and colder days...

Scrambling Tests Demonstrated that Particle Noise Was Not a Problem

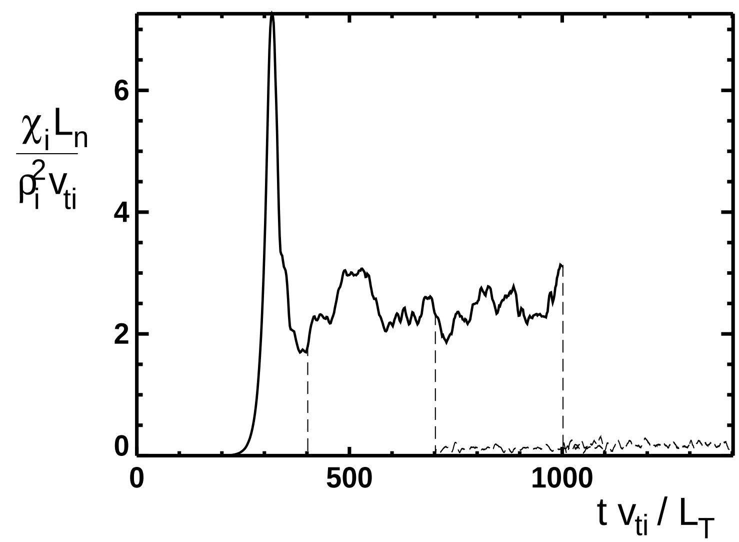
- Start with regular simulation that has reached nonlinear saturation

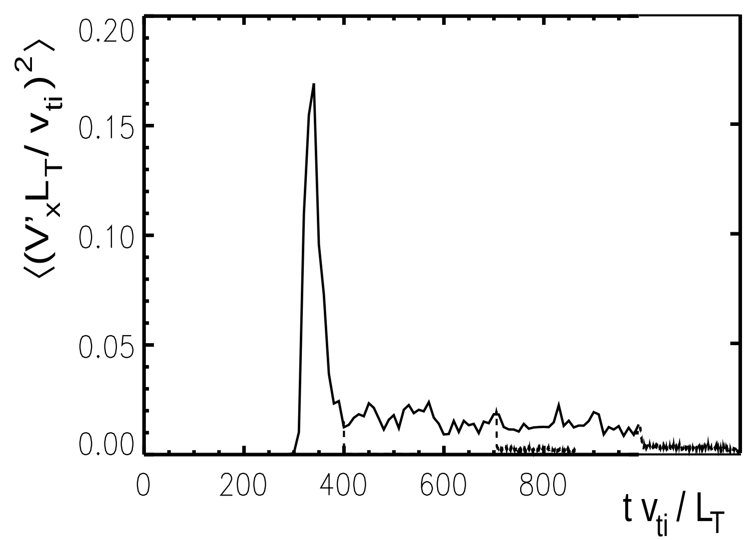
- Scramble all particle positions. Charge fluctuations should (almost) cancel out , left only with “noise” (vanish as $N_{\text{particles}} \rightarrow \infty$)

- Reduce ∇T_i below linear instability threshold and continue simulation

- Noise fluctuations cause very little χ. Noise shearing rate comparable to linear growth rate, but small compared to shearing rate during turbulence.

Scrambling test proposed by Kotschenreuther, modifications by Dorland, Hammett, Rosenbluth, implemented by Dimits et.al..





Why the large noise shearing rate is irrelevant

- **Several skeptics had questioned whether the particle codes had enough particles to be adequately converged (not just the IFS-PPPL/gyrofluid group, but also the Lausanne gyrokinetic group (Varenna98, EPS99)).**

- **Concerned that noise in zonal flows might suppress the turbulence & $\downarrow \chi$.**

- **In typical resolution cases, the noise-level of the zonal flows was found to have a shearing rate comparable to the linear growth rate.**

- **However, the turbulence-driven zonal flow was found to be even larger, so the noise component is ignorable by comparison.**

- **Usually, shearing rate $>$ growth rate would suppress turbulence. But as observed in gyrofluid simulations by Beer et.al., and explained in Hahm et.al. (Phys. Plasmas 1999), most of the apparent shearing**

$$\gamma_{shear} = \frac{\partial v_\theta}{\partial r} \propto [\sum k_r^4 \Phi^2]^{1/2}$$

is by high k modes, which rapidly fluctuate in time. They will start to shear an eddy, but then quickly reverse directions and unshear it...

Why the shearing rate is so large during the turbulence, and why $\langle\Phi^2\rangle$ isn't a sufficient measure

• Several skeptics had questioned whether the particle codes had enough particles to be adequately converged (not just the IFS-PPPL/gyrofluid group, but also the Lausanne gyrokinetic group (Varenna98, EPS99)).

• For example, although noise in zonal flows doesn't directly cause transport (zonal flows are in the θ direction, perpendicular to ∇T_i), some were worried that noise enhanced zonal flows could suppress the turbulence and thus reduce χ.

• However, the turbulence-driven zonal flow was found to be even larger, so the additional noise-driven zonal flow is usually ignorable.

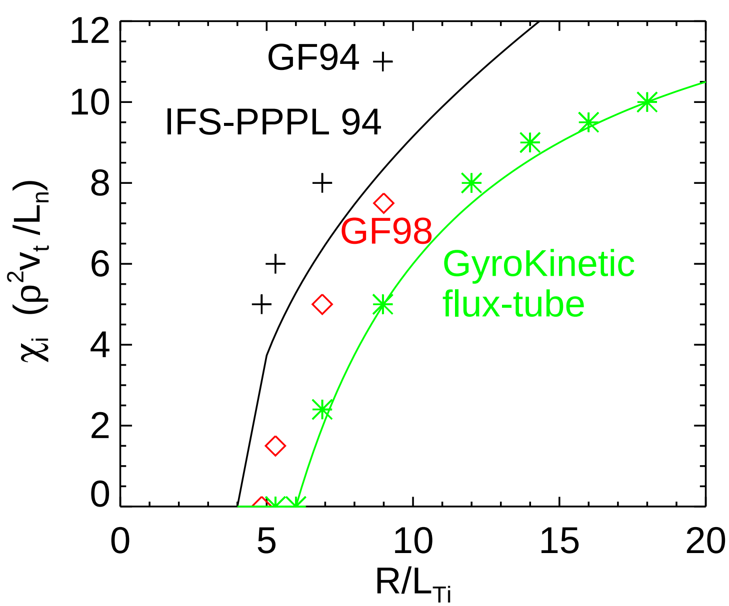
• Turbulence-driven zonal flow shearing rate is ~ 3 times larger than the linear growth rate. Usually this would correspond to stabilization of the turbulence. But as was observed in gyrofluid simulations by Beer et.al., and explained in Hahm et.al. (Phys. Plasmas 1999), most of the apparent shearing

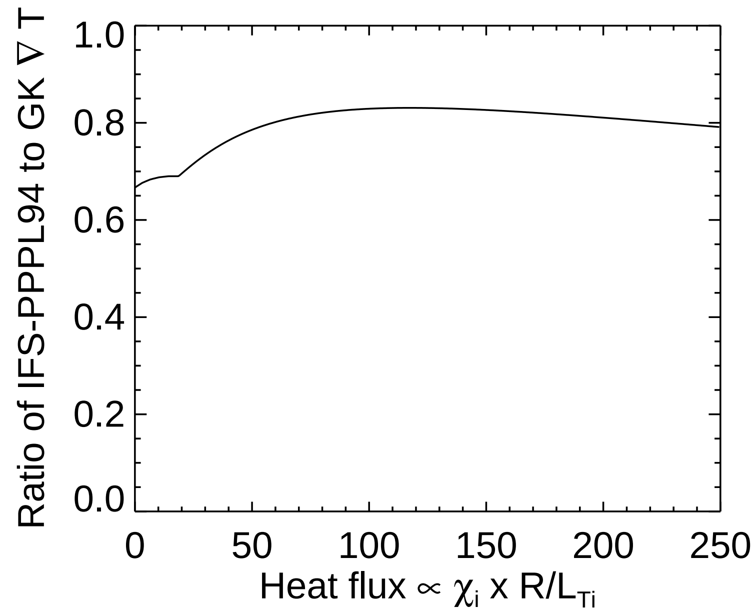
$$\gamma_{shear} = \frac{\partial v_\theta}{\partial r} \propto [\sum k_r^4 \Phi^2]^{1/2}$$

is by high k modes, which rapidly fluctuate in time. They will start to shear an eddy, but then quickly reverse directions and unshear it...

• Regarding $\langle\Phi^2\rangle$, it can be biased by large amplitude components of Φ at very low k_r which cause little physical effect.

Gyrofluid/gyrokinetic (GF/GK) simulation differences $\rightarrow$ 20-33% change in predicted temperature gradient





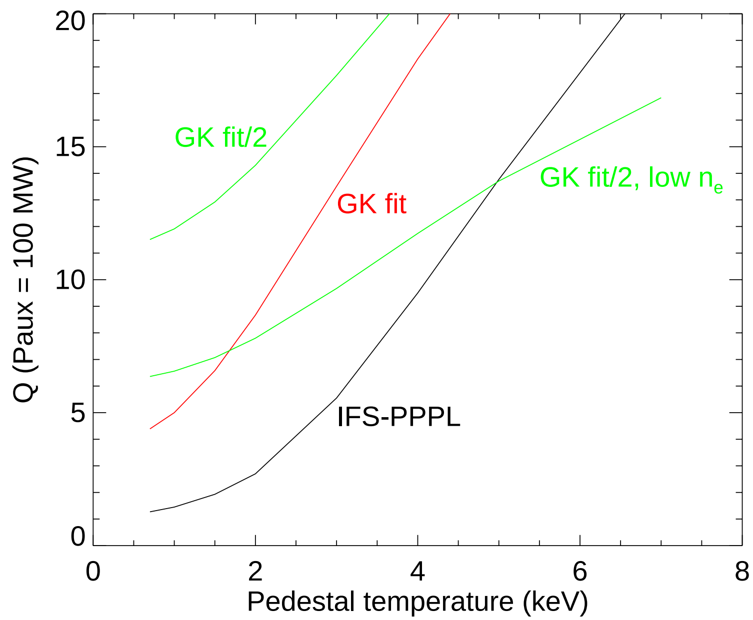
- **Dimits (LLNL): good convergence in his gyrokinetic particle simulations**

- **New neoclassical gyrofluid closure significantly improves GF/GK comparison.**

- **Turning this plot around, for a fixed amount of heat flux $\propto \chi\nabla T$, the temperature gradient predicted by the original gyrofluid-based IFS-PPPL model is 20-33% low. But $P_{fusion} \propto T^2$, and so may increase by $\times 2$ or more.**

- **Nonlinear upshift in critical gradient may depend on: Rosenbluth-Hinton undamped zonal flows $\uparrow$ with elongation (W. Dorland), $\downarrow$ with weak collisions (Z. Lin), $\downarrow$?? with non-adiabatic electrons [may limit inverse cascade that drives zonal flows (Diamond, Liang, Terry-Horton, Waltz, ...) and $\uparrow$ turbulent viscosity].**

Comparison of predictions of Q for ITER from original IFS-PPPL model, and from modified version to fit gyrokinetic simulations



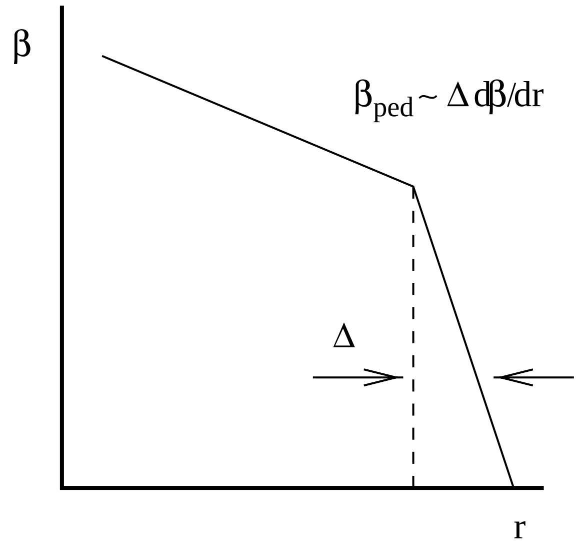
• Gyrokinetic-fit version causes predicted Q to rise some, but the original point remains that the results are sensitive to the assumed edge pedestal temperature, which is uncertain. There is a risk of low Q, particularly at low density.

• The uncertainties are large, and it may be that ITER's pedestal temperature and confinement would be acceptable for ignition. Other sources of uncertainty which need better treatment, in addition to a better understanding of the edge transport barrier and the achievable density and density peaking, include the effects of elongation and plasma shaping, plasma rotation, and fully electro-magnetic fluctuations with non-adiabatic electrons.

ITER-96 baseline scenario, $n_e = 1.3 \times 10^{20}/m^3 = 1.5\, n_{\mathrm{Greenwald}}$**,** $\tau_{He*}/\tau_E = 10$**.**

Edge pedestal scalings very uncertain, but most favor higher-field designs with stronger shaping...

- **Wide range of theory & expt. evidence:** $\Delta/R \propto \rho_{*\theta}$ **(JT-60U, JET),** $\rho_{*\theta}^{2/3-1/2}$**,** $\beta_{pol}^{1/2}\rho_*^0$ **(very interesting DIII-D evidence of a second stable edge, which would have a more favorable scaling to reactors)**



- **Making two assumptions:**

1. **Width** $\Delta \propto \sqrt{\epsilon}\rho_\theta \propto \rho q/\kappa\sqrt{\epsilon}$ **(scaling preferred by two largest tokamaks)**
2. **stability limit** $\partial\beta/\partial r \propto [1+\kappa^2(1+10\delta^2)]/Rq^2$ **(rough fit to JT-60U, Koide et.al., Phys. Plasmas 4, 1623 (1997), other expts.), get:**

$$T_{ped} \propto \frac{1}{n_{ped}^2}\left(\frac{B}{Rq}\right)^2 [1+\kappa^2(1+10\delta^2)]^2 \frac{A_i R}{\kappa^2 a} \approx \left(\frac{n_{Gr}}{n_{ped}}\right)^2 \left[\frac{1+\kappa^2(1+10\delta^2)}{1+\kappa^2(1+2\delta^2)}\right]^2 \frac{A_i R}{\kappa^2 a}$$

(Hammett, Dorland, Kotschenreuther, Beer, PPPL-3360 (1999))

Some of the new reactor designs may have significantly improved pedestal temperatures

Using this T_{ped} formula (with a $\Delta \propto \rho_\theta$ assumption), and other pedestal scalings also, to scale from JET to some proposed reactor designs:

	R m	a m	B T	I_p MA	n_{ped} $10^{20}/m^3$	$\frac{n_{ped}}{n_{Gr}}$	$\frac{n_{ped}}{\langle n \rangle}$	κ_{95}	δ_{95}	T_{ped} keV if $\Delta \propto \rho_\theta\sqrt{\epsilon}$	T_{ped} keV if $5\delta^2$	T_{ped} keV if $\Delta \propto \sqrt{Rq\rho}$
JET-norm	2.92	0.91	2.35	2.55	0.4	0.40	~ 1	1.61	.17	2.1	2.1	2.1
ITER-96	8.14	2.80	5.68	21.0	1.3	1.52	1	1.60	.24	0.20*	0.18*	1.5*
lower n_{ped}	8.14	2.80	5.68	21.0	0.6	0.70	.70	1.60	.24	0.94*	0.83*	4.2*
ITER-HAM	6.30	1.81	6.58	13.0	0.86	0.68	.8	1.58	.26	1.4	1.2	4.5
ITER-LAM	6.45	2.33	4.25	17.0	0.64	0.64	.8	1.70	.43	2.0	1.2	5.5
Aries-RS	5.52	1.38	7.98	11.3	1.4	0.74	.67	1.70	.50	3.4	1.9	7.7
FIRE	2.0	0.53	10.0	6.44	3.6	0.48	.80	1.77	.40	4.8	3.0	6.7

* should add $(nT)_{sol}/n_{ped}$ which could be as high as ~ 0.5 keV.

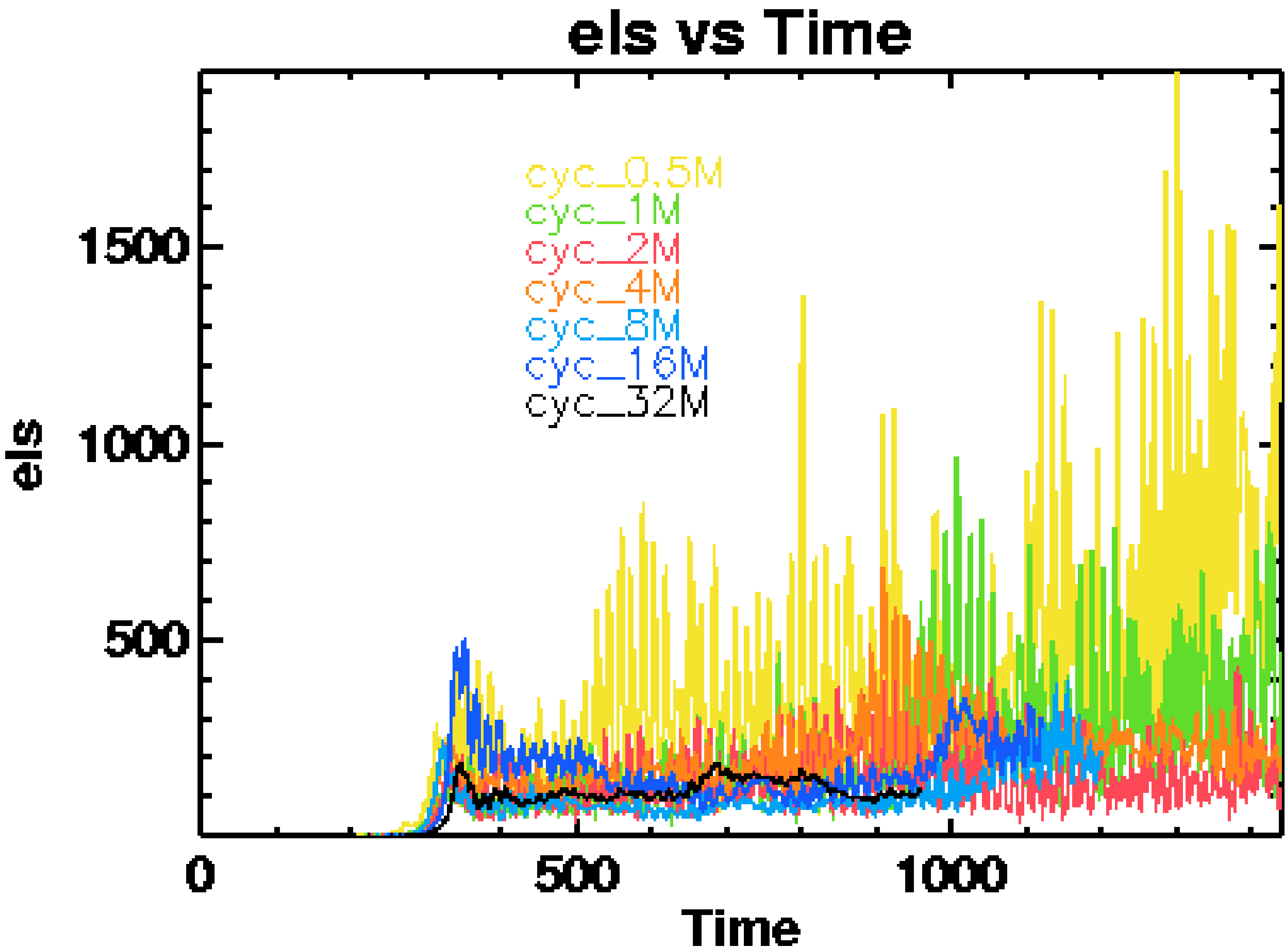
FESAC97: "While, given the present state of knowledge, we cannot provide a reliable estimate for the pedestal parameters in ITER . . ., a pedestal temperature less than 1500 eV, perhaps much less, is a distinct possibility."

Encouraging that even with the pessimistic pedestal scaling ($\Delta \propto \rho_\theta$), it may be possible to get high pedestal temperatures by going to stronger plasma shaping, higher field, smaller size, and modest density peaking.

(Hammett, Dorland, Kotschenreuther, Beer, PPPL-3360 (1999))

The rest of this is leftovers from previous vugraphs or very rough notes.

$\langle \Phi^2(t) \rangle$ did not show clear convergence with $\uparrow N_{\text{particles}}$, but later scrambling tests showed this wasn't relevant



THEORY-BASED MODELS OF TURBULENCE AND ANOMALOUS TRANSPORT IN FUSION PLASMAS

I. Simple picture of plasma microinstabilities

Inverted pendulum $\rightarrow$ Rayleigh-Taylor $\rightarrow$ Magnetic curvature instability.

Difference between MHD and micro-instabilities/drift-waves.

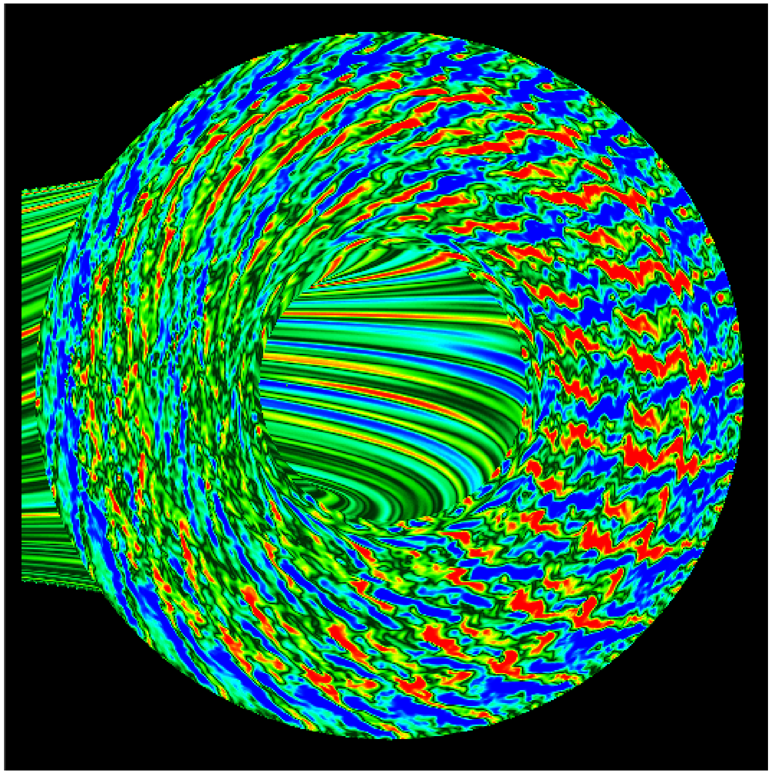
II. Complexity and challenge of plasma turbulence

nonlinear, chaotic, wide-range of space and time scales

theoretical and computational advances made in tackling these problems.

III. Comparisons with experiments, remaining challenges.

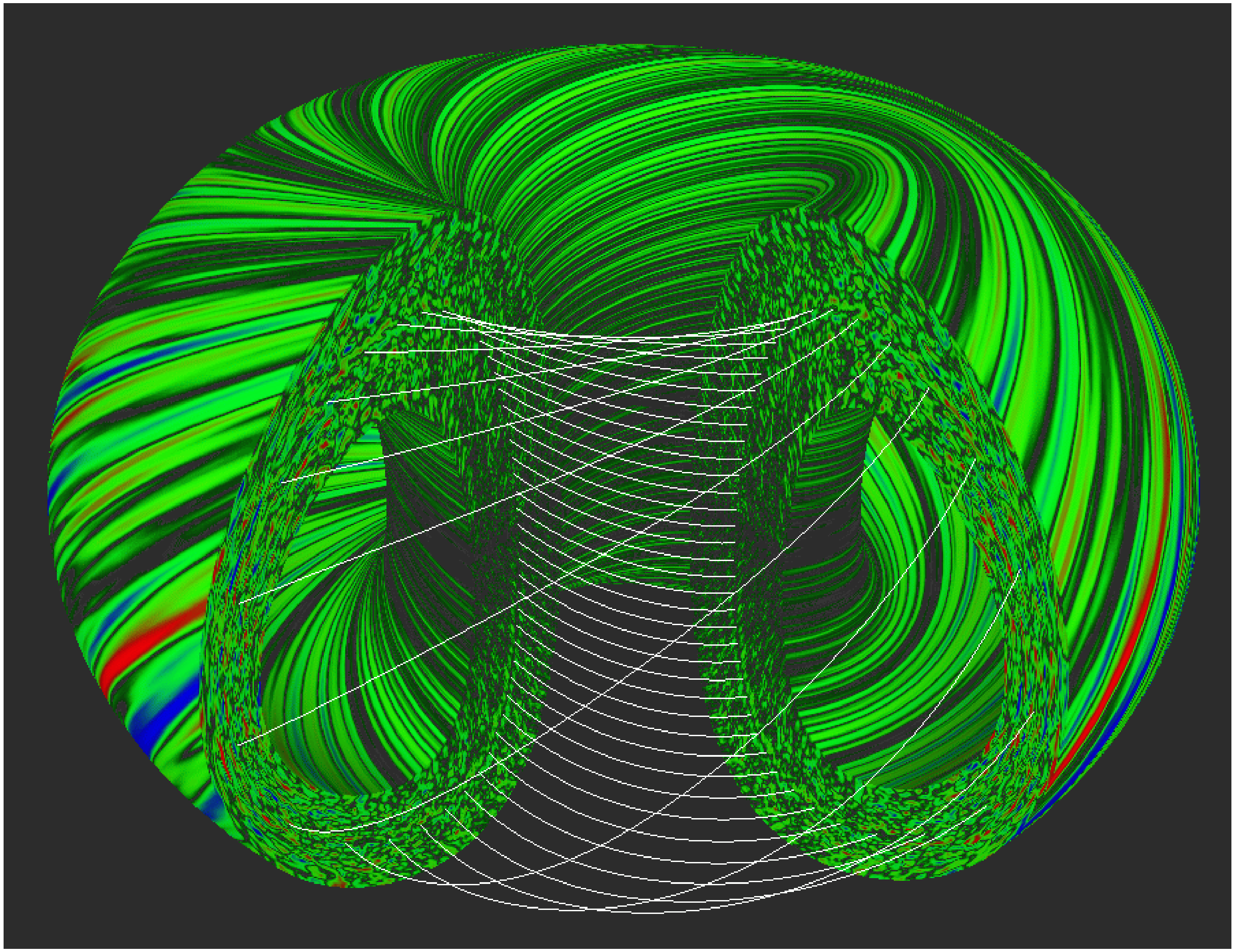
Simulations of Tokamak Plasma Turbulence



- **Realistic simulations made possible by advances in plasma theory, experimental insights, and parallel supercomputers.**
- **Fundamental science: fascinating physics of plasma turbulence.**
- **Applications: studying ways to reduce turbulence and the cost of a fusion energy power plant.**

General Atomics (San Diego), NERSC (Livermore/Berkeley), PPPL (Princeton), IFS (U.Texas, Austin), ACL (Los Alamos), part of the Numerical Tokamak Project, a DoE/HPCC Computational Grand Challenge.

Simulations can handle realistic non-circular geometry



Turbulence can be reduced by strong plasma shaping in advanced tokamaks, spherical tori, etc.

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IFS-PPPL Transport Model

Kotschenreuther, Dorland, Beer, Hammett '94

• **Based on nonlinear gyrofluid simulations of ITG turbulence to map out structure of ion thermal conductivity χ_i, & on linear gyrokinetic calc of growth rates and critical gradients.**

$$\chi_i = \rho_i^2 \frac{v_{ti}}{R} \left(\frac{R}{L_T} - \frac{R}{L_{T,crit}(p_j)} \right)^{1,1/2} F(p_j) \underbrace{\left(1 - \frac{\overbrace{\gamma_{shear}}^{\text{Hahm-Burrell ExB shear}}}{\gamma_{lin}} \right)}_{\text{Waltz gyrofluid fit}}$$

$$p_j = \left(\frac{R}{L_T}, \frac{R}{L_n}, \frac{T_i}{T_e}, q, \hat{s}, Z_{eff}, \nu_*, \frac{r}{R}, \ldots \right)$$

$\chi_e / \chi_i =$ **quasilinear**

• **Brought together scalings from many analytic theories into a single formula. Comprehensive enough to explain many observed trends in standard tokamak operating regimes, including some improved confinement regimes (given edge B.C.'s)**

IFS-PPPL transport model represented a significant advance. But a more complete model is needed:

- **advanced tokamak regimes (negative shear, high β, strong shaping)**
- **internal transport barriers: suppress χ_i & D_e, but large χ_e ??!!**
- **particle and momentum transport (presently just heat transport)**
- **edge turbulence**
- **better shear in equilibrium $E \times B$, $\omega_*(r)$, $\eta_i(r)$**
- **better zonal flows, gyrofluid/gyrokinetic diffs**

CONCLUSIONS

Major progress has been made during the past 10 years in direct 3D simulations of plasma turbulence and in reduced transport models.

Reasonable agreement with core temperature profiles ($\sim$30%) in many cases, but more work needed to resolve significant uncertainties (edge turbulence, zonal flows, electron dynamics, ...).

Relatively complete simulations should be achievable soon...†

Also: many ways to reduce turbulence and improve performance (sheared flows, IBW, edge beams, density peaking, high beta advanced tokamak designs with strong Shafranov shift and shaping, ...)

†**But needs a lot of hard work, more complete physics in codes, and new generation of computers.**