Intro Tokamak Turbulence I (overview)

Greg Hammett, Princeton Plasma Physics Lab (PPPL)
http://w3.pppl.gov/~hammett
Center for Multi-scale Plasma Dynamics Winter School
Jan. 3-7, 2005 UCLA

Acknowledgments:

Plasma Microturbulence Project

(General Atomics, U. Maryland, LLNL, PPPL,
U. Colorado, UCLA, U. Texas)

DOE Scientific Discovery Through
Advanced Computing

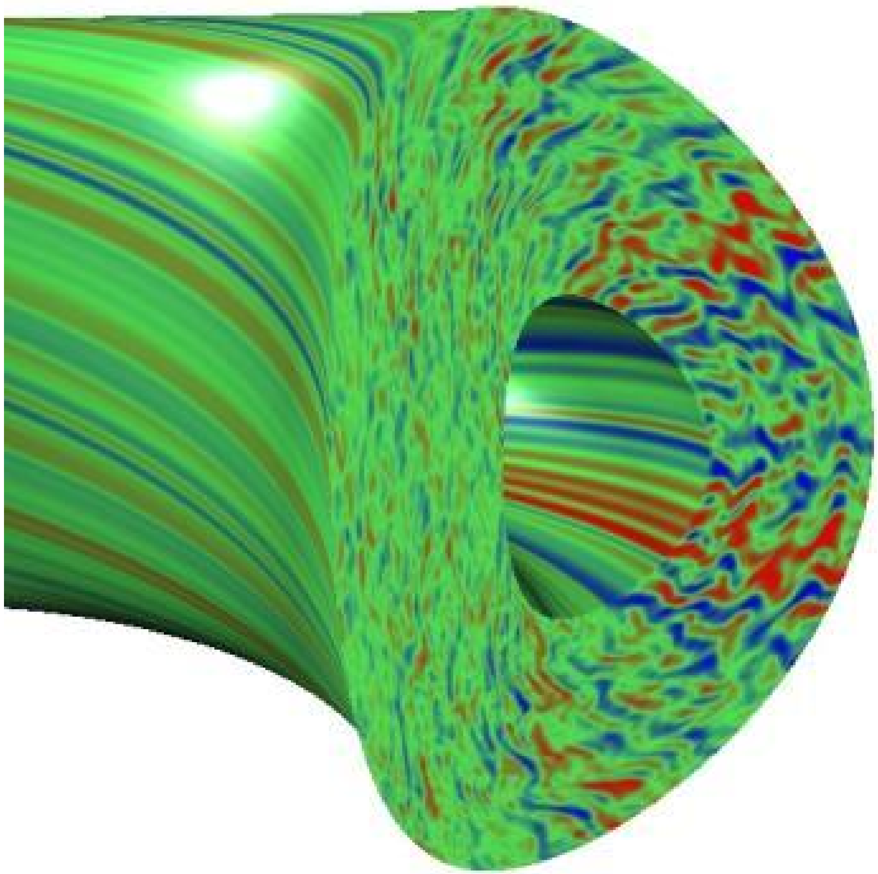
http://fusion.gat.com/theory/pmp

J. Candy, R. Waltz (General Atomics)

W. Dorland (Maryland) W. Nevins (LLNL)

R. Nazikian, D. Meade, E. Synakowski (PPPL)

J. Ongena (JET)



Candy, Waltz (General Atomics)

The Plasma Microturbulence Project

- A DOE, Office of Fusion Energy Sciences, SciDAC (Scientific Discovery Through Advanced Computing) Project

- devoted to studying plasma microturbulence through direct numerical sumulation

- National Team (& four codes):
  - GA (Waltz, Candy)
  - U. MD (Dorland)
  - U. CO (Parker, Chen)
  - UCLA (Lebeouf, Decyk)
  - LLNL (Nevins P.I., Cohen, Dimits)
  - PPPL (Lee, Lewandowski, Ethier, Rewoldt, Hammett, …)
  - UCI (Lin)

- They've done all the hard work …

Tokamak Turbulence Overview

- Motivation
- Simple physical pictures of tokamak plasma turbulence & how to reduce it (reversed magnetic shear, sheared flows, plasma shaping…)

- Simulation-based transport models (IFS-PPPL,…): stiff critical-gradient transport, sensitive to edge b.c.
- Worries about original ITER-96 design (problems with empirical fits, extreme density)
- Why recent designs are significantly better.

- Impressive progress with comprehensive 5-dimensional computer simulations being developed to understand plasma turbulence & optimize performance

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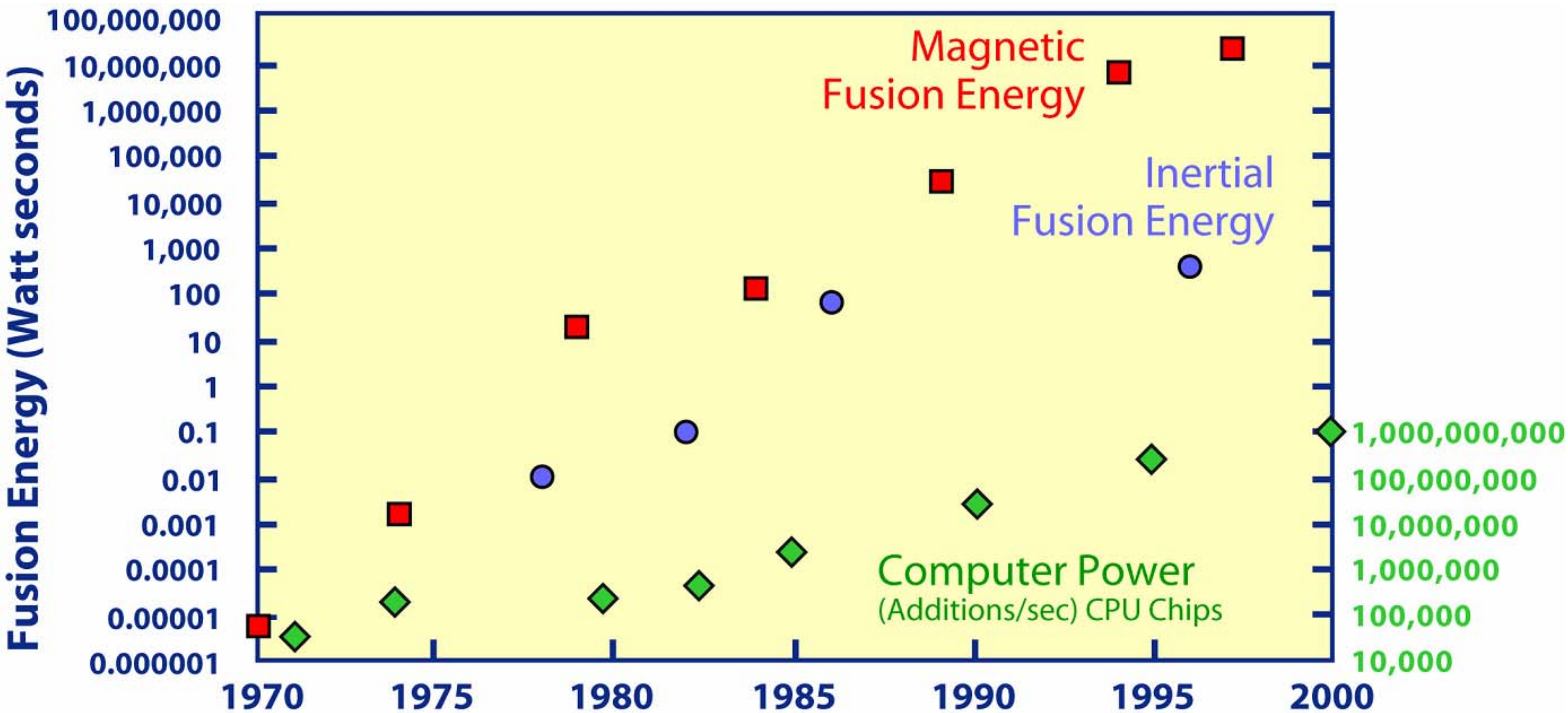
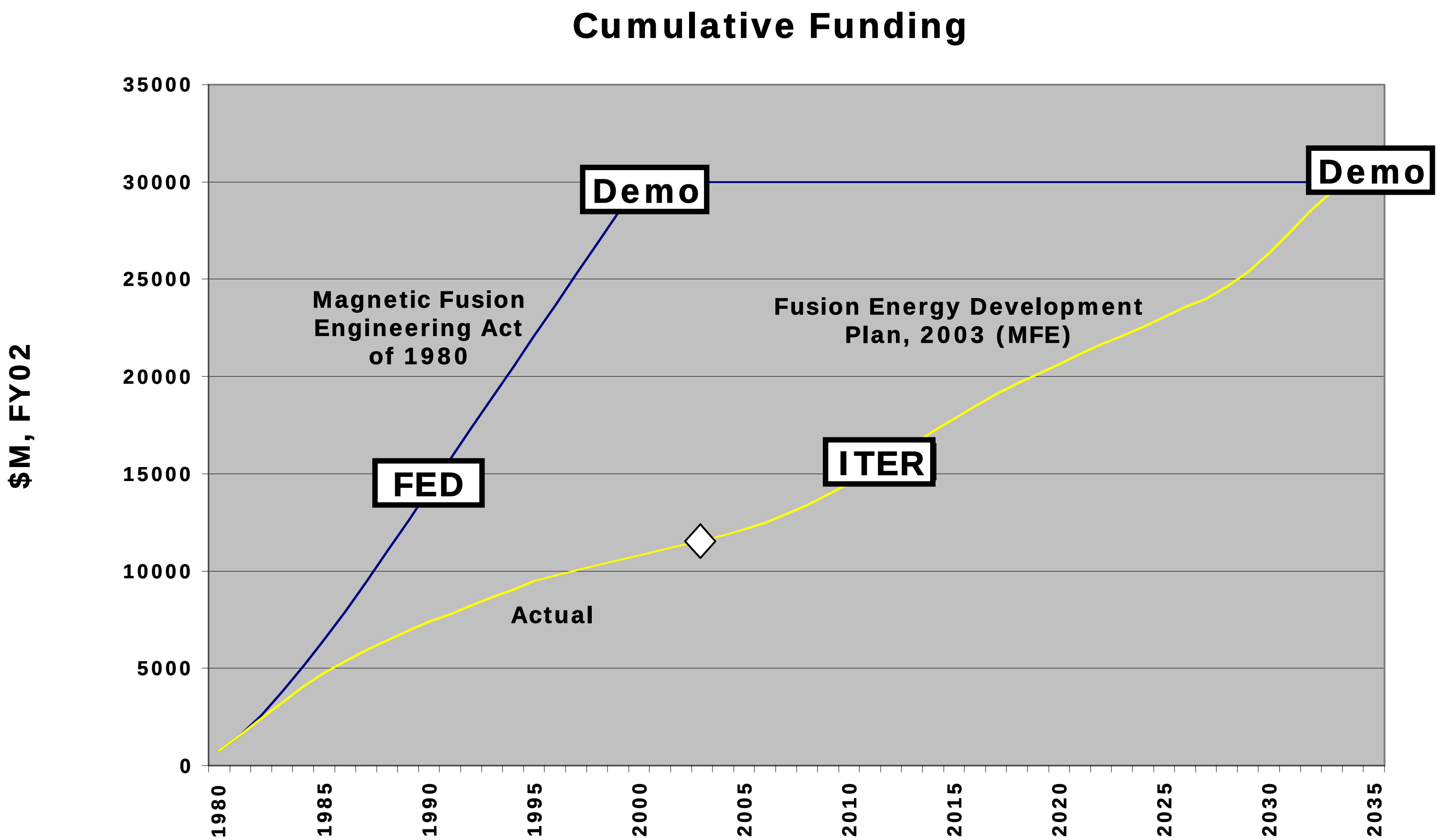
Progress in Fusion Energy has Outpaced Computer Speed



Some of the progress in computer speed can be attributed to plasma science.

The Estimated Development Cost for Fusion Energy is Essentially Unchanged since 1980



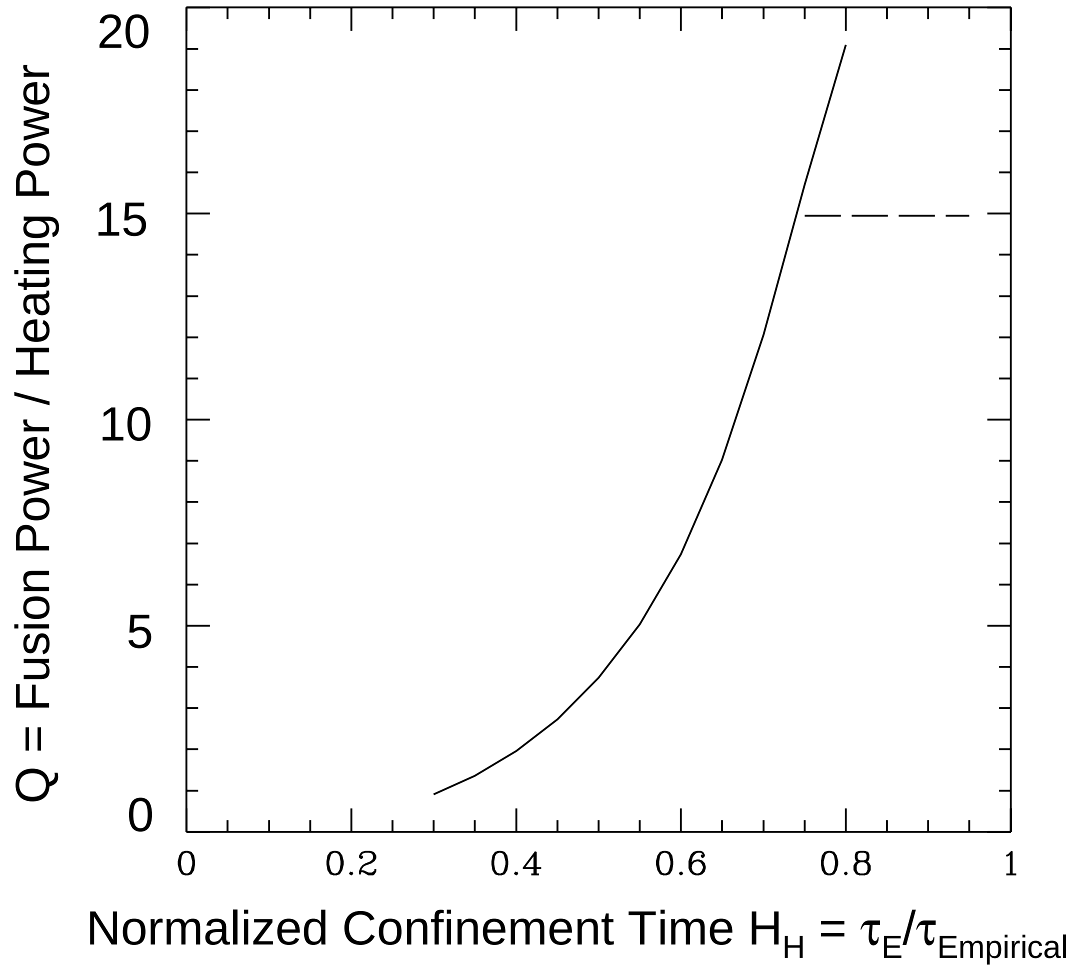
On budget,
if not on time.

$30B development cost tiny compared to >$100 Trillion energy needs of 21st century and potential costs of global warming. Still 40:1 payoff after discounting 50+ years.

Fusion performance depends sensitively on confinement

Sensitive dependence on turbulent confinement causes some uncertainties, but also gives opportunities for significant improvements, if methods of reducing turbulence extrapolate to larger reactor scales.

$$\frac{dE}{dt} = P - \frac{E}{\tau_E}$$



Caveats: best if MHD pressure limits also improve with improved confinement.
Other limits also: power load on divertor & wall, …

↓ turbulence & ↑ β could significantly improve fusion

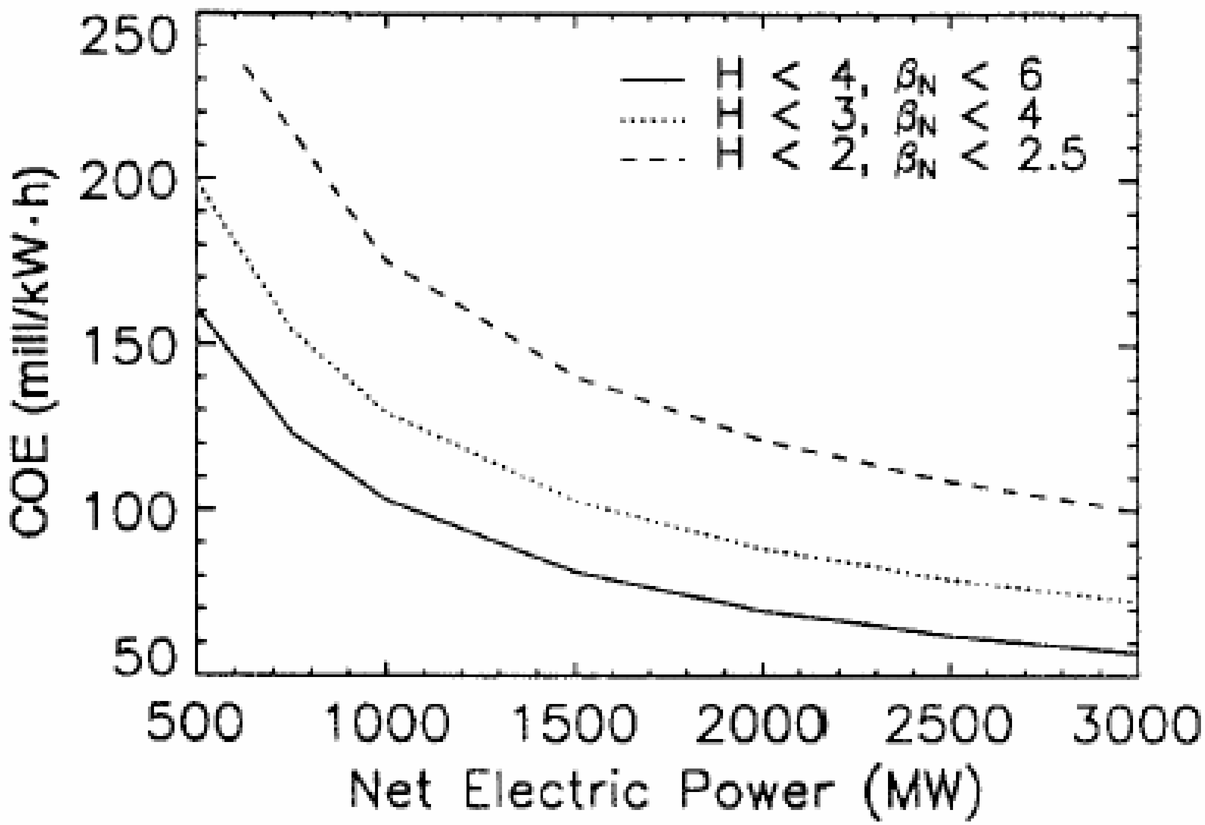


FIG. 4. Minimum COE steady state reactor parameters versus the net electric output. Cases are shown for three physics levels: (a) present day levels that would be sustainable in a non-transient manner in a conservatively designed system ($H \leq 2, \beta_N \leq 2.5$), (b) moderately improved physics ($H \leq 3, \beta_N \leq 4$) and (c) advanced physics ($H \leq 4, \beta_N \leq 6$).

Galambos, Perkins, Haney & Mandrekas
1995 Nucl. Fus. (very good)

Shaping has extremely strong effect on turbulence
Needs theoretical explanation!

Standard IPB98(y,2) empirical scaling (should redo with latest IAEA04 scalings):

$$\tau_E \propto H\, I_p^{0.93} B_T^{0.15} P_{Lth}^{-0.69} \overline{n}_e^{0.41} R^{1.97} \varepsilon^{0.58} \kappa_{area}^{0.78} M^{0.19}$$

Use P = W / $\tau_E \propto$ VnT/τ_E and $q_{95} \propto \dfrac{a^2 B_T}{R I_p} f_s$

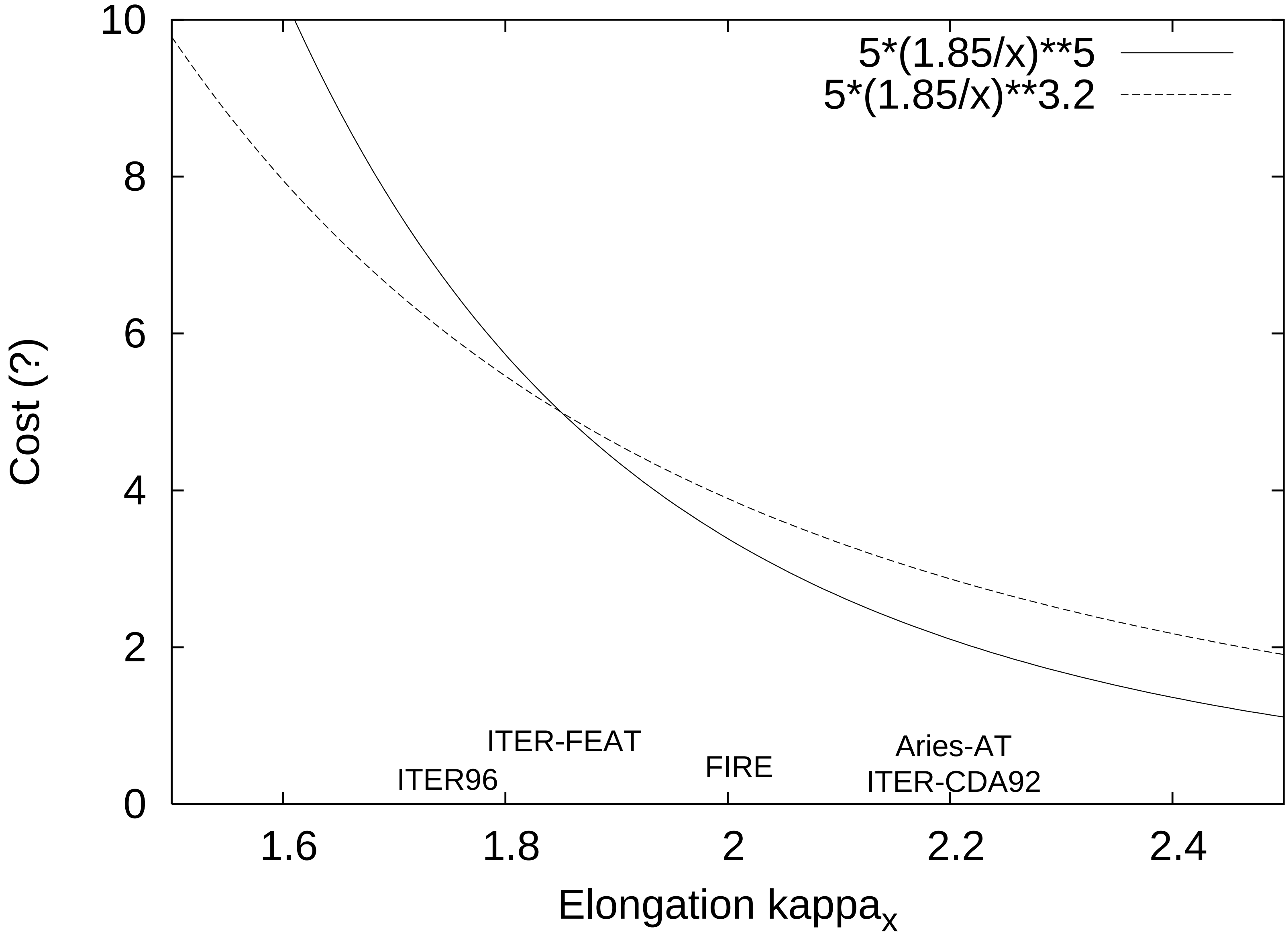
$$D_{avg} \approx \frac{a^2}{\tau_E} \propto \frac{T^{2.2} n^{0.9}}{R^{0.8} \varepsilon^{1.5} B_T^{3.5} f_s^{3.0} \kappa_{area}^{0.3}} \propto \frac{1}{\kappa^{7.8}}$$

Strong shaping effect not understood. Perhaps localized to edge turbulence?

Compare with $D_{gyro-Bohm} \approx \dfrac{cT}{eB} \dfrac{\rho}{L} f(\beta, \nu_*, \varepsilon, \kappa, q, \ldots)$

Uckan fit: $f_s \approx \dfrac{1+\kappa_{95}^2 (1+2\delta_{95}^2 - 1.2\delta_{95}^3)\, f_s^{3.0} T^{2.2} n^{0.9}}{2} \dfrac{(1.17 - 0.69 a_{95}/R)}{(1-(a_{95}/R)^2)^2} \sim \kappa_{95}^{2.5}$

Including correlation of δ_{95} with κ_{95} in typical designs

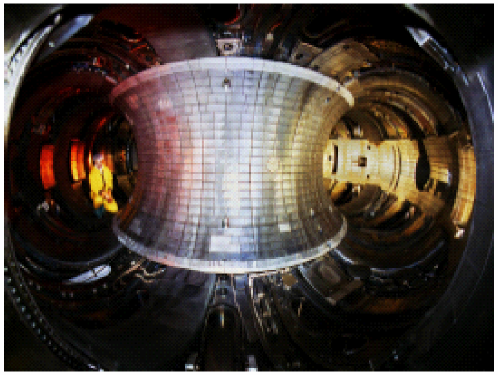


Very rough cost scaling of next step fusion device assuming \$ ~ $R^2\kappa \sim 1/\kappa^5$

Or (fit to Galambos) \$~$P_{fus}^{0.4} \sim R^{1.2}\,\kappa^{0.41} \sim 1/\kappa^{3.2}$

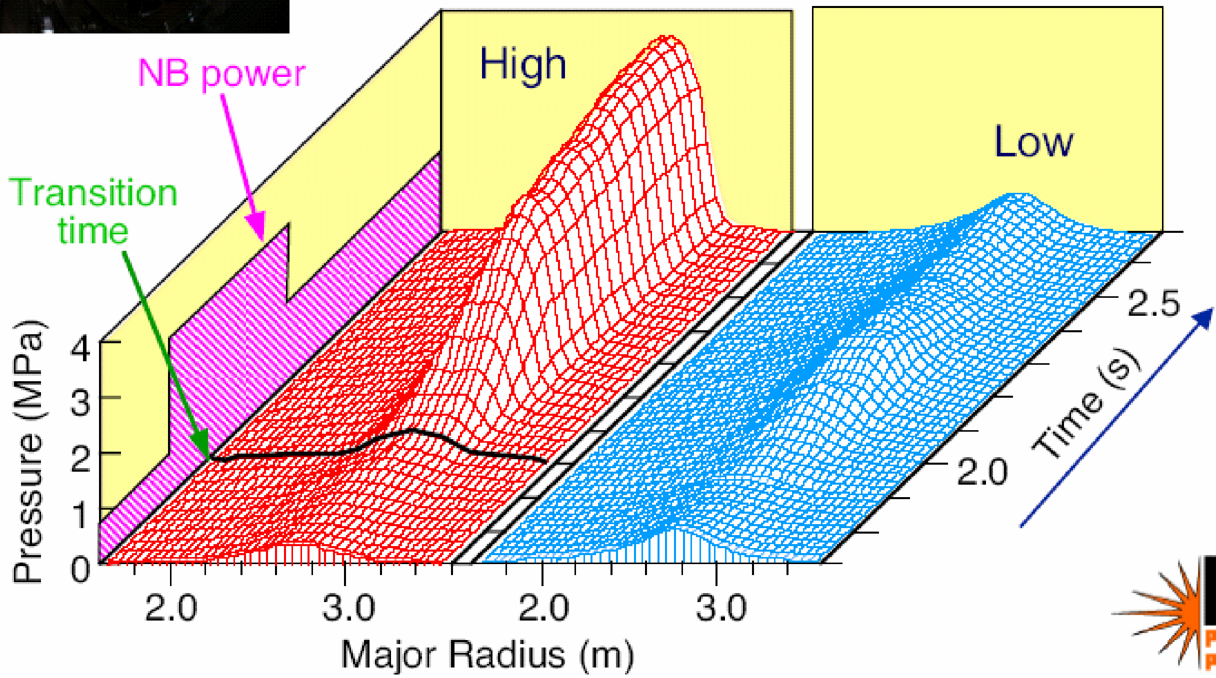
(fixed $nT\tau$, q, assume triangularity also increases with κ, various caveats)

Fascinating Diversity of Regimes in Fusion Plasmas. What Triggers Change? What Regulates Confinement?



TFTR

- Two regimes with very different confinement for similar initial conditions and neutral beam heating
- Access depends on plasma heating and reducing current density on axis
- Can we attribute a difference in turbulence to these two different confinement regimes?



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R. Nazikian et al.

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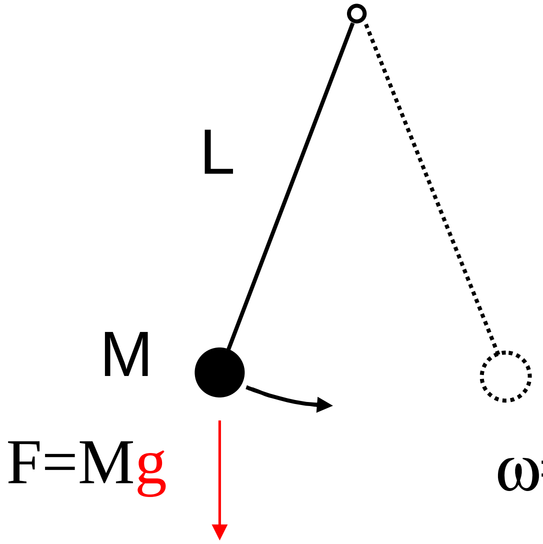
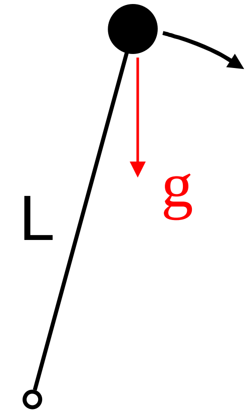
Stable Pendulum



$\omega=(g/L)^{1/2}$

Unstable Inverted Pendulum

(rigid rod)

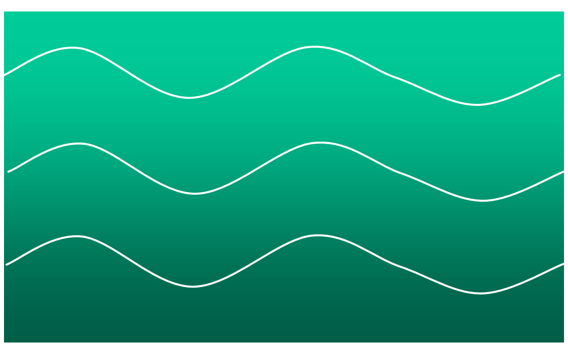


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

└ Instability

Density-stratified Fluid

$\rho=\exp(-y/L)$

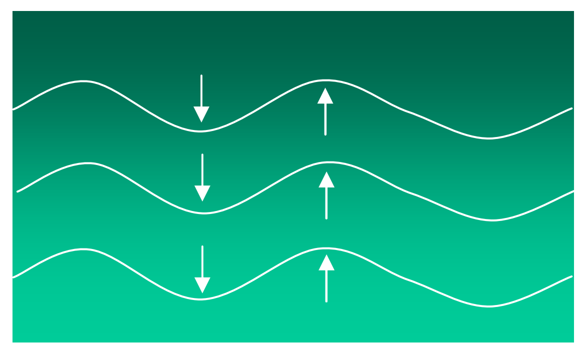


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

$\Rightarrow$Rayleigh-Taylor Instability

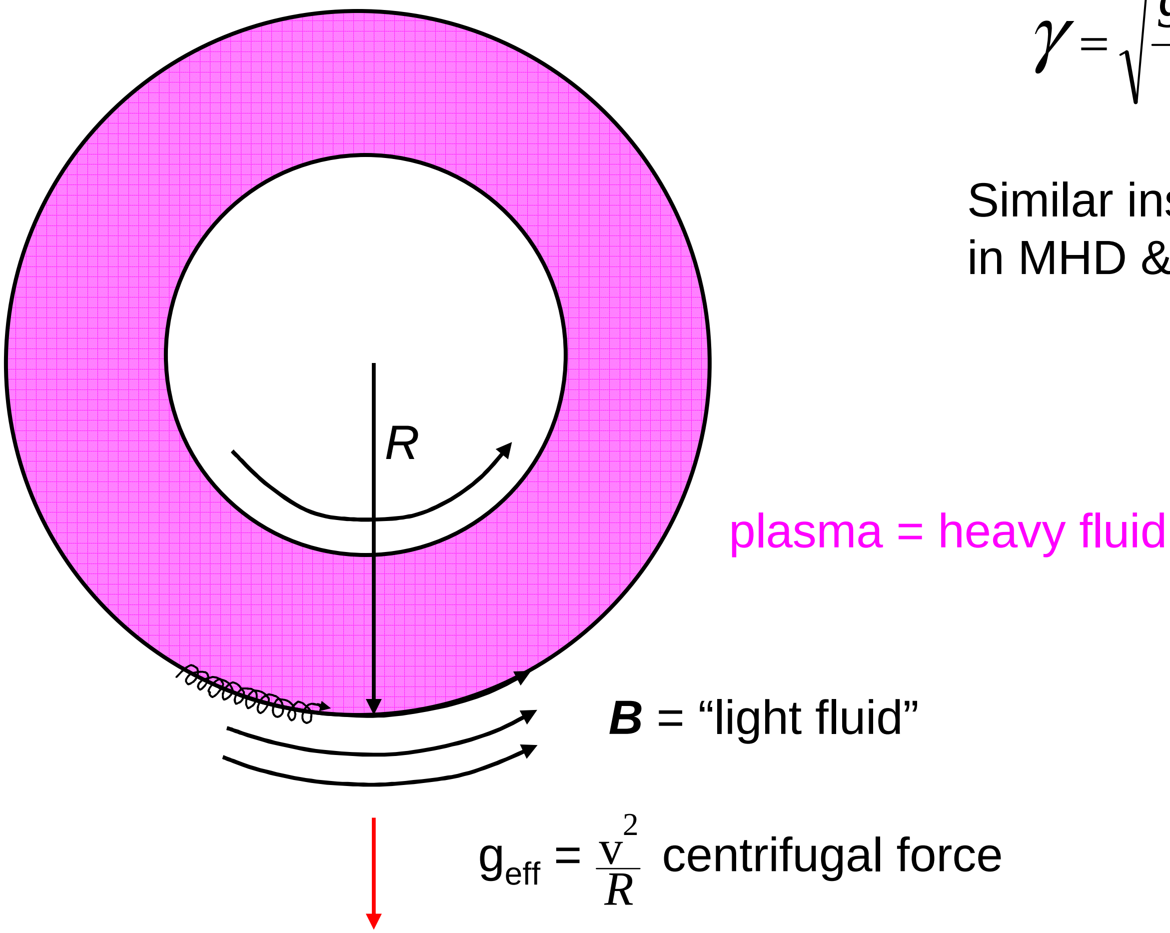
$\rho=\exp(y/L)$



Max growth rate $\gamma=(g/L)^{1/2}$

"Bad Curvature" instability in plasmas ≈ Inverted Pendulum / Rayleigh-Taylor Instability

Top view of toroidal plasma:



Growth rate:

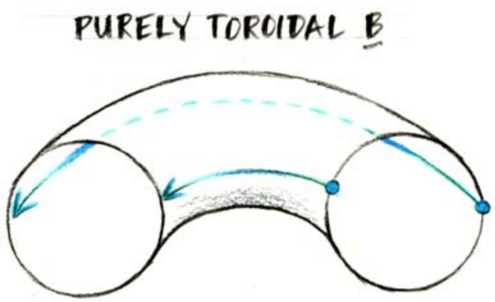
$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{v_t^2}{RL}} = \frac{v_t}{\sqrt{RL}}$$

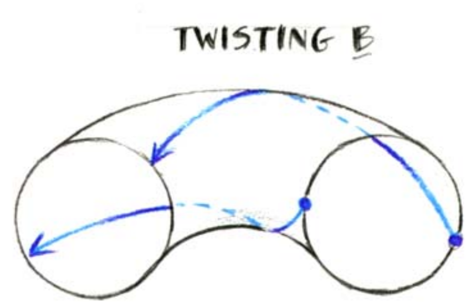
Similar instability mechanism in MHD & drift/microinstabilities

$1/L = \nabla p/p$ in MHD,
$\propto$ combination of ∇n & ∇T in microinstabilities.

The Secret for Stabilizing Bad-Curvature Instabilities

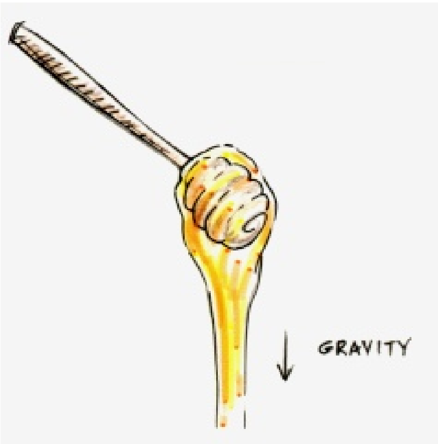
Twist in ***B*** carries plasma from bad curvature region to good curvature region:

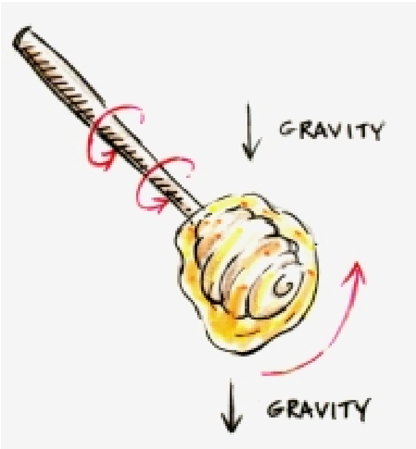




Unstable

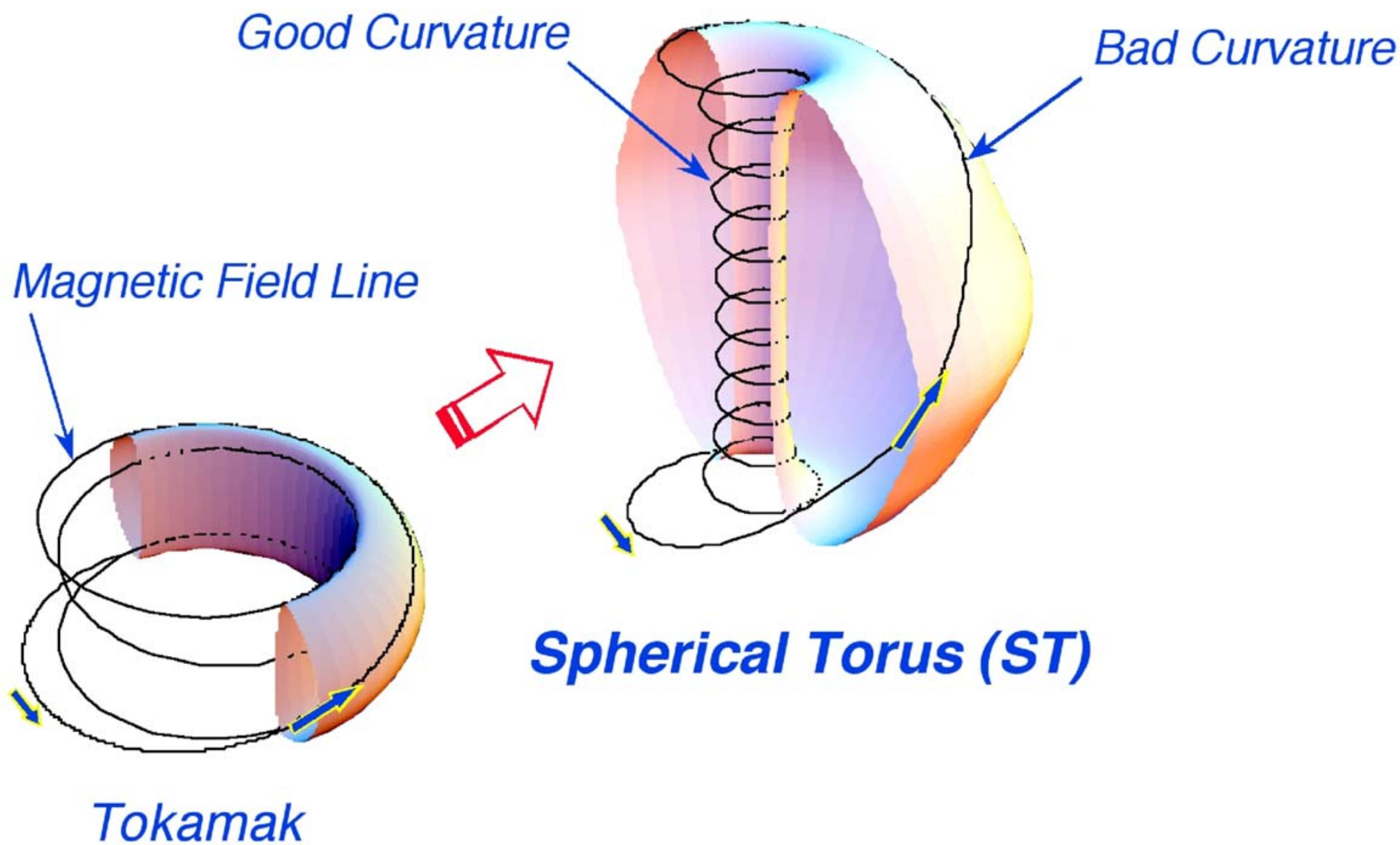
Stable

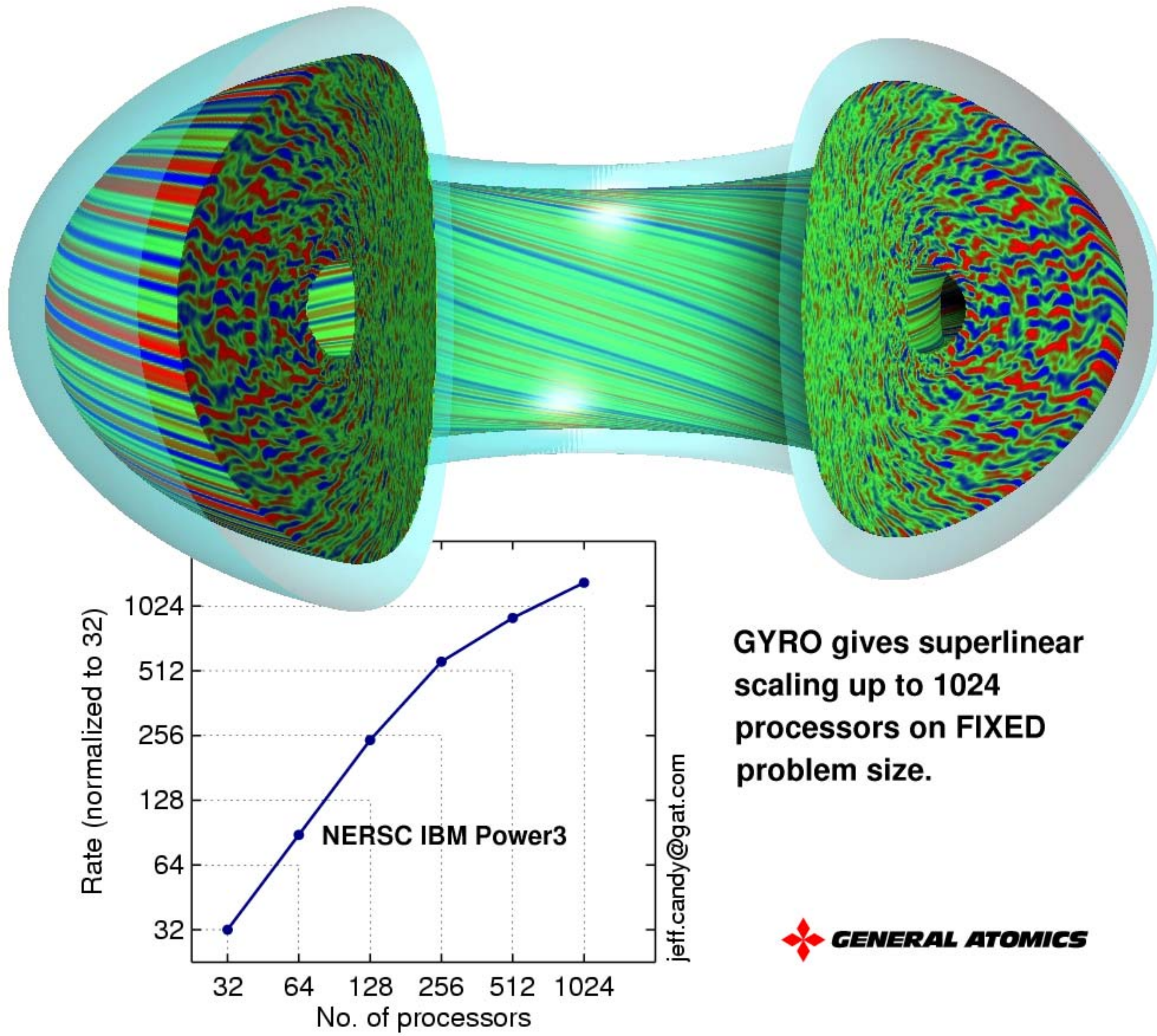




Similar to how twirling a honey dipper can prevent honey from dripping.

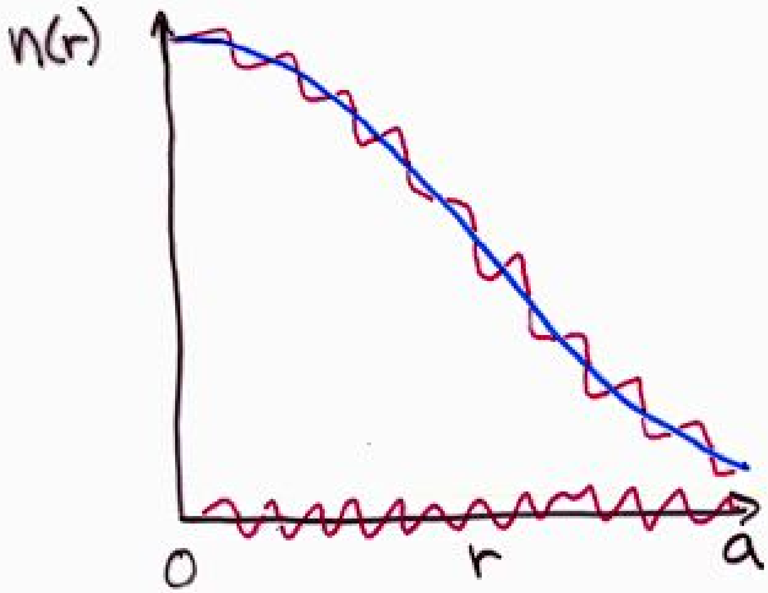
Spherical Torus has improved confinement and pressure limits (but less room in center for coils)





Comprehensive 5-D computer simulations of core plasma turbulence being developed by Plasma Microturbulence Project. Candy & Waltz (GA) movies shown: d3d.n16.2x_0.6_fly.mpg & supercyclone.mpg, from http://fusion.gat.com/comp/parallel/gyro_gallery.html (also at http://w3.pppl.gov/~hammett/refs/2004).

Microinstabilities are small-amplitude but still nonlinear



$$n = n_0(r) + \tilde{n}(\underset{\sim}{x}, t)$$

$$n_0 \gg \tilde{n}$$

$$\text{but} \quad \nabla n_0 \sim \nabla \tilde{n}$$

Can locally flatten or reverse total gradient that was driving instability.

* Turbulence causes loss of plasma to the wall, but confinement still $\times 10^5$ better than without $\underset{\sim}{B}$.

If no $\underset{\sim}{B}$, loss time $\sim \dfrac{a}{V_t} \sim 1\ \mu\text{sec}$

with $\underset{\sim}{B}$, expts. measure $\sim 0.1 - 1.0$ sec.

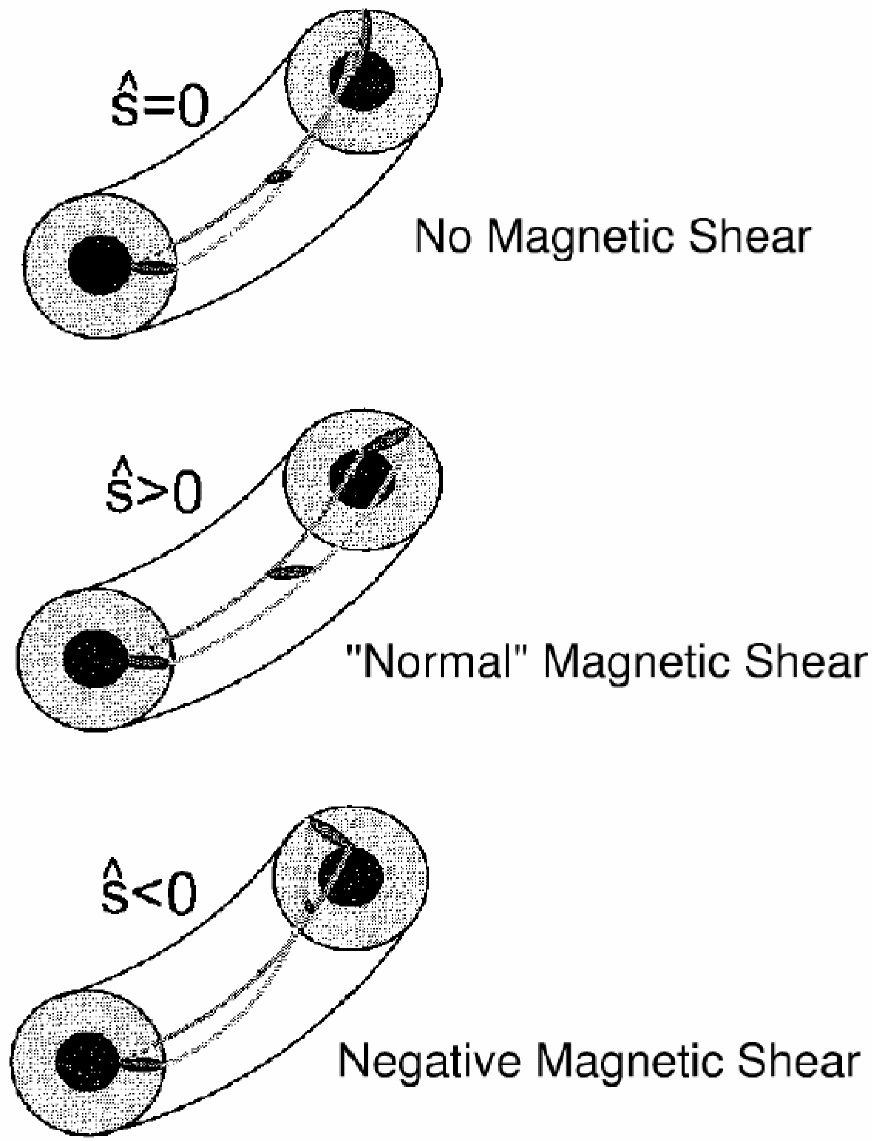
Simple picture of reducing turbulence by negative magnetic shear

Particles that produce an eddy tend to follow field lines.

Reversed magnetic shear twists eddy in a short distance to point in the ``good curvature direction''.

Locally reversed magnetic shear naturally produced by squeezing magnetic fields at high plasma pressure: ``Second stability'' Advanced Tokamak or Spherical Torus.

Shaping the plasma (elongation and triangularity) can also change local shear

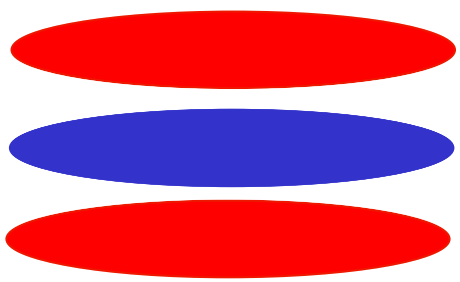


Antonsen, Drake, Guzdar et al. Phys. Plasmas 96

Kessel, Manickam, Rewoldt, Tang Phys. Rev. Lett. 94

Sheared flows can suppress or reduce turbulence

Most Dangerous Eddies:
Transport long distances
In bad curvature direction



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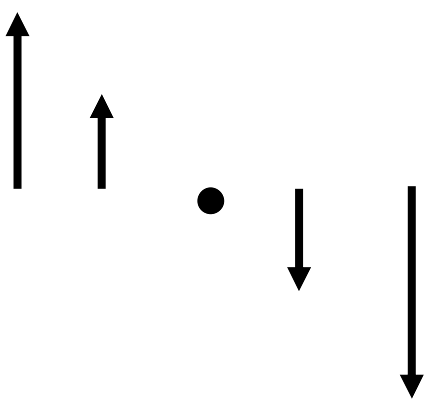
Sheared Flows



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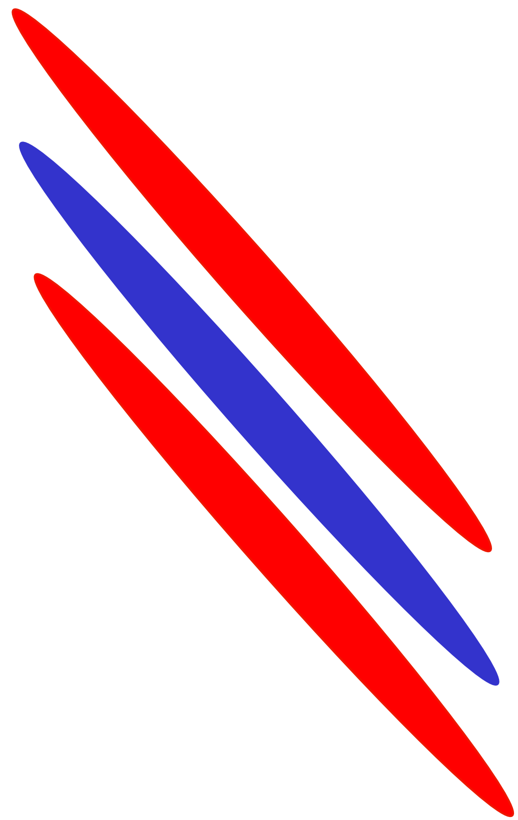
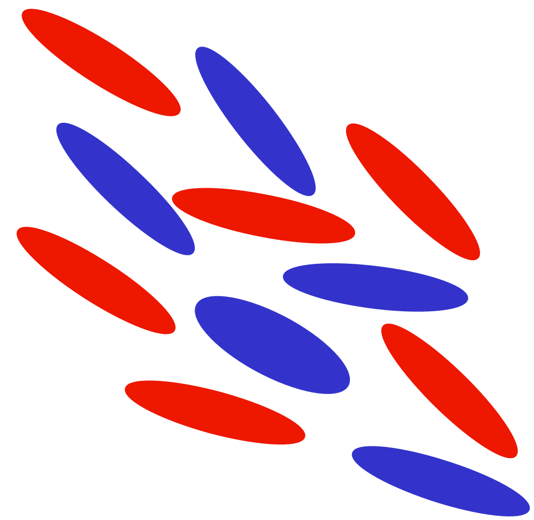
Sheared Eddies
Less effective

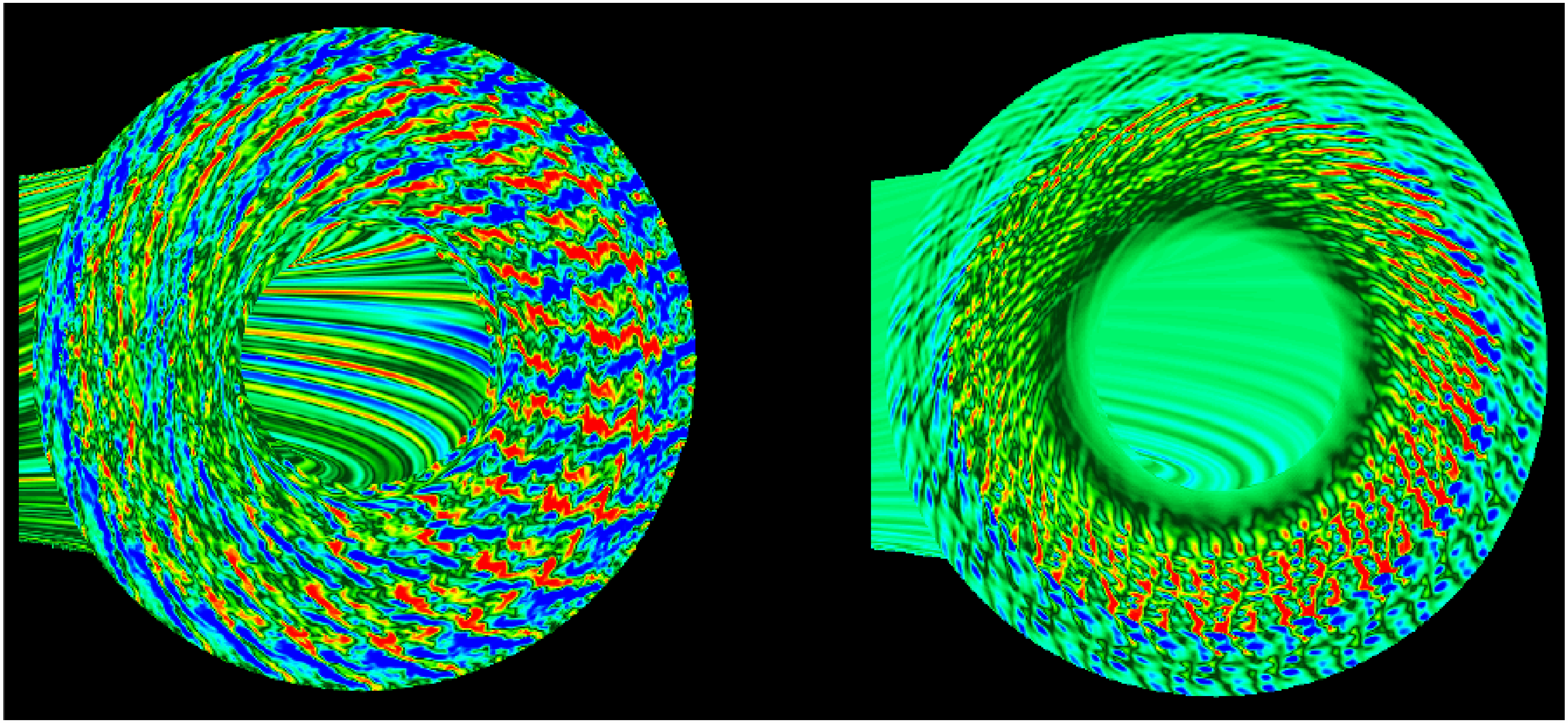


Eventually break up



Biglari, Diamond, Terry (Phys. Fluids1990),
Carreras, Waltz, Hahm, Kolmogorov, et al.

Sheared ExB Flows can regulate or completely suppress turbulence (analogous to twisting honey on a fork)

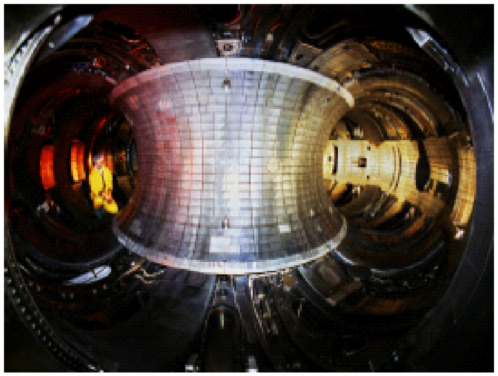


Dominant nonlinear interaction between turbulent eddies and ±θ-directed zonal flows.

Additional large scale sheared zonal flow (driven by beams, neoclassical) can completely suppress turbulence

Waltz, Kerbel, Phys. Plasmas 1994 w/ Hammett, Beer, Dorland, Waltz Gyrofluid Eqs., Numerical Tokamak Project, DoE Computational Grand Challenge

Fascinating Diversity of Regimes in Fusion Plasmas. What Triggers Change? What Regulates Confinement?



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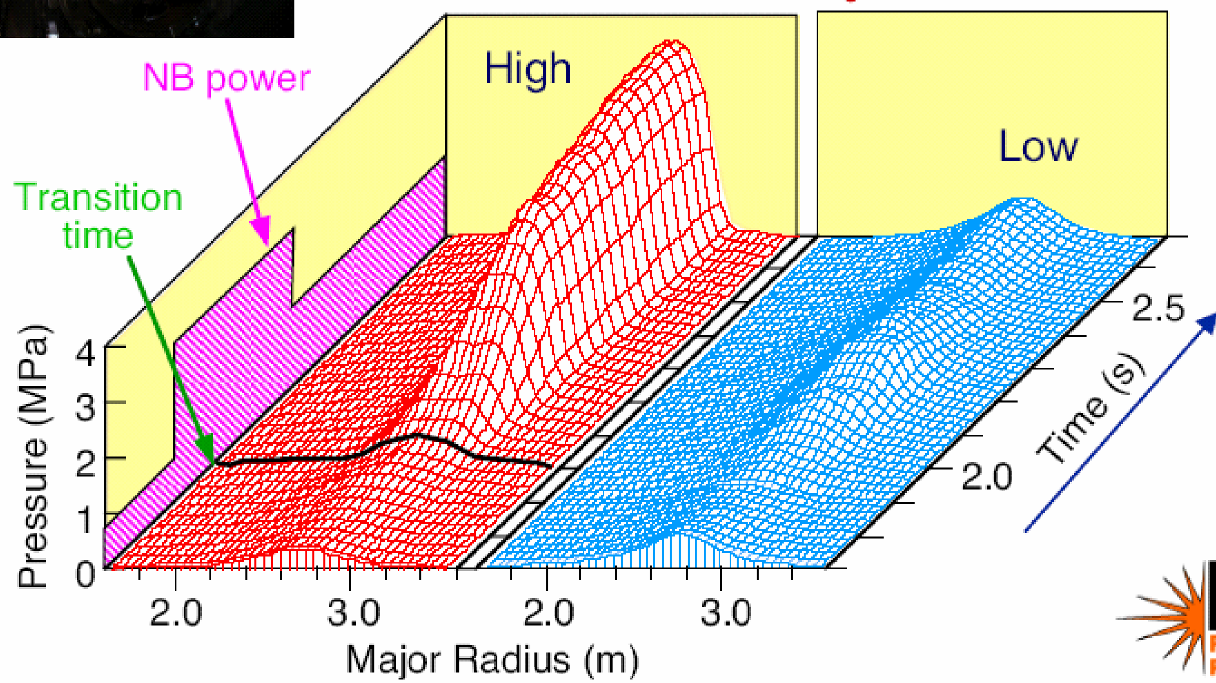

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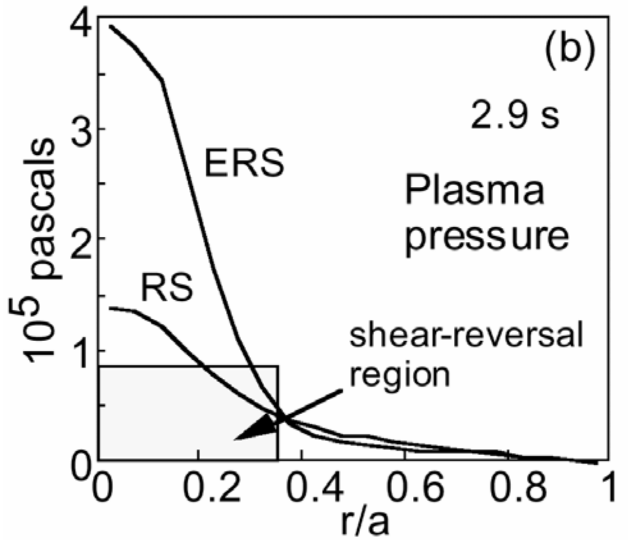
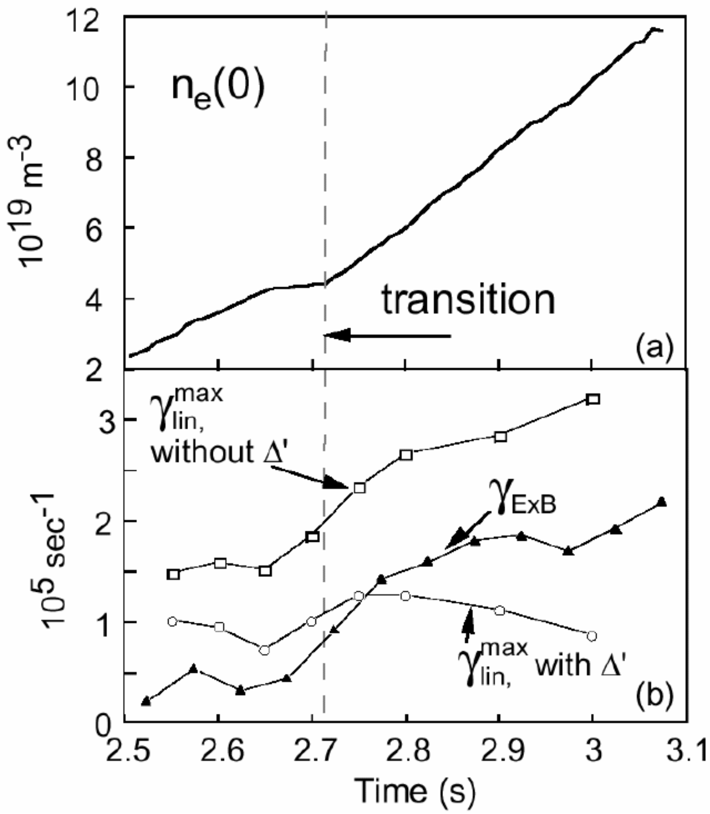
All major tokamaks show turbulence can be suppressed w/ sheared flows & negative magnetic shear / Shafranov shift





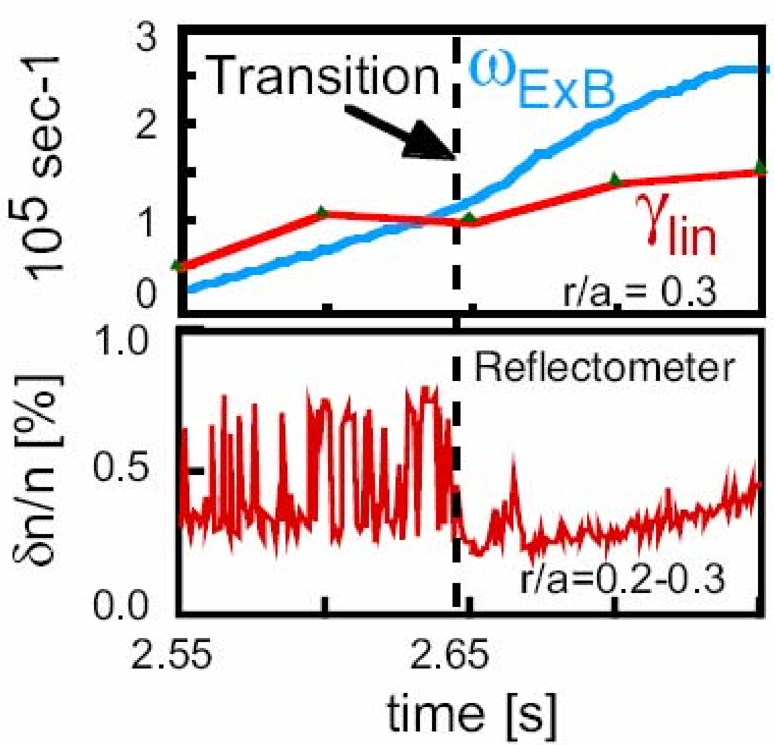
Synakowski, Batha, Beer, et.al. Phys. Plasmas 1997

Internal transport barrier forms when the flow shearing rate $dv_\theta/dr >\sim$ the max linear growth rate γ_{lin}^{max} of the instabilities that usually drive the turbulence.

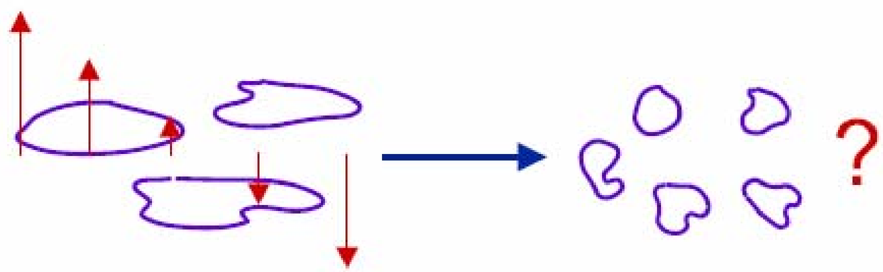
Shafranov shift Δ' effects (self-induced negative magnetic shear at high plasma pressure) also help reduce the linear growth rate.

Advanced Tokamak goal: Plasma pressure ~ x 2, $P_{fusion} \propto \text{pressure}^2$ ~ x 4

Transition to Enhanced Confinement Regime is Correlated with Suppression of Core Fluctuations in TFTR



- Theory predicts fluctuation suppression when rate of shearing (ω_{ExB}) exceeds rate of growth (γ_{lin})
- Outstanding issue:
  Is suppression accompanied by radial decorrelation?



- Similar suppression observed on JET (X-mode reflectometer) and DIII-D (FIR Scattering)

Hahm, Burrell, Phys. Plas. 1995, E. Mazzucato et al., PRL 1996.

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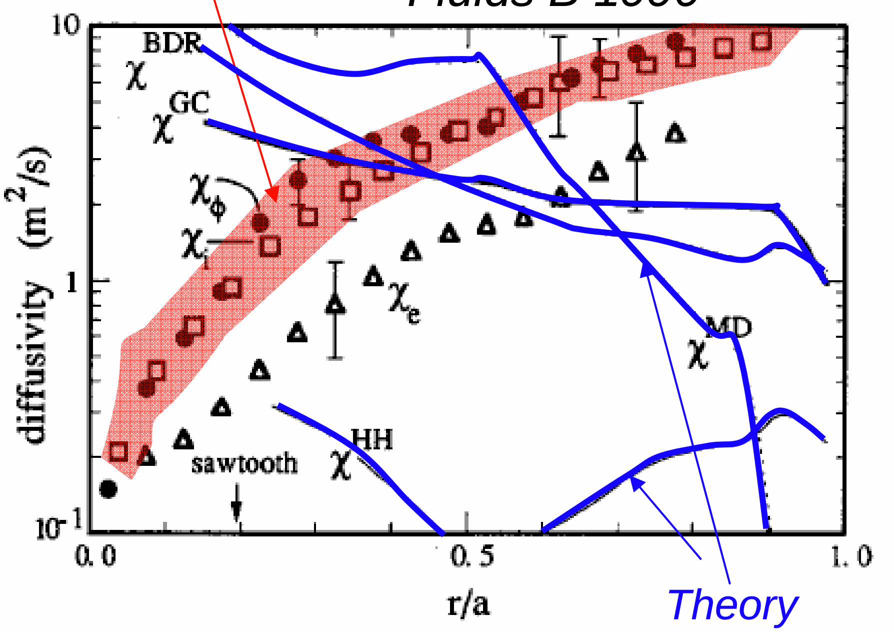
…but 1980's analytic theories did not capture radial dependence of the experimental χ

- $\chi_e << \chi_i \sim \chi_\phi$ consistent with electrostatically-driven transport, but ITG predictions of χ_i profiles are far off from experiment in L mode

- Much discussion about marginal stability in LM & SS, but pellet experiments drive $\eta_i > \eta_i^{crit}$ (slab theory) without changing transport.
  – Proposed at the time: may not have been beyond marginal stability for toroidal modes (Rewoldt & Tang, 1990)

S.D. Scott et al., Phys. Fluids B 1990

Experimental χ_i, χ_ϕ



TFTR L mode

Ion channel dominant. $\eta_i > \eta_i^{crit}$

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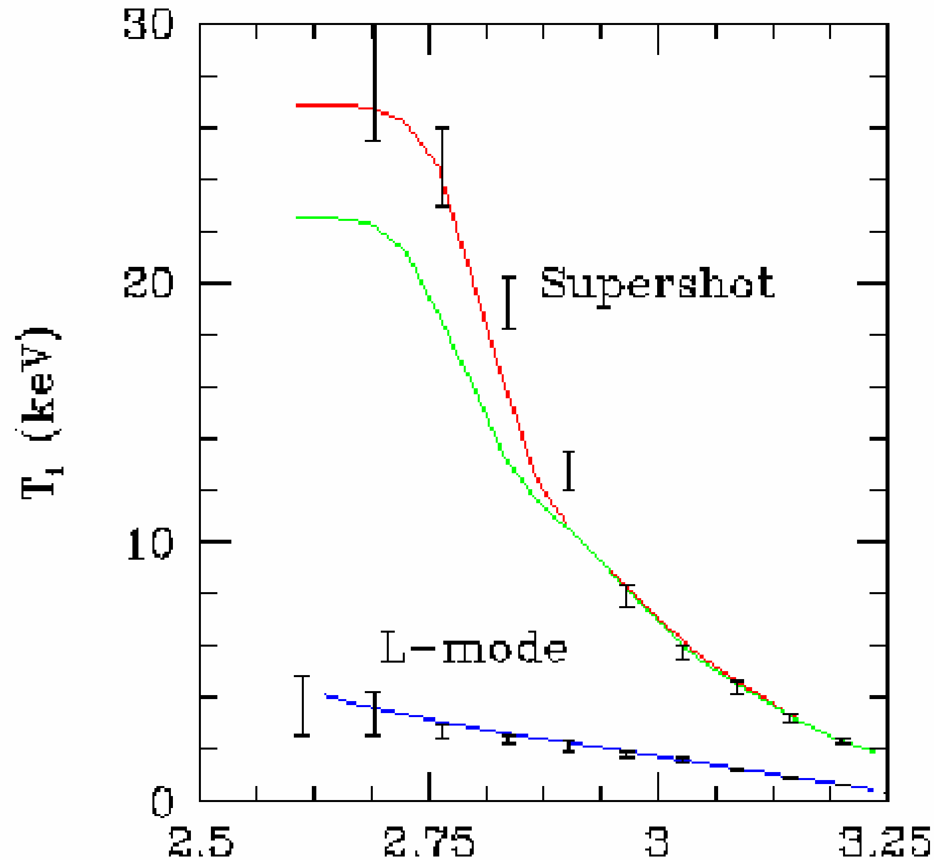
(slide from E. Synakowski 1/29/2004)

A big shift: turbulence theory-based ion transport model *challenges experiment*

- IFS-PPPL gets the changes between different confinement regimes about right
  - Linear gyrokinetics identify critical gradients.
  - Nonlinear gyrofluids map out parametric shape of χ_i.
- Spectroscopy hears for the first time from theorists: "We think your measurements of T_i are incorrect in some cases - can you reanalyze these shots?"
  - Theorists are *right*: the analysis was *wrong*
- An indicator of a profound shift in the dialogue between experiment & theory.



Kotschenreuther, Dorland, Hammett, Phys. Plasmas 2 (1995)

(slide from E. Synakowski 1/29/2004)

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IFS-PPPL Transport Model

Kotschenreuther, Dorland, Beer, Hammett 94

- Based on nonlinear gyrofluid simulations of ITG turbulence for scaling of ion thermal conductivity χ_i & linear gyrokinetic calc for accurate critical gradients

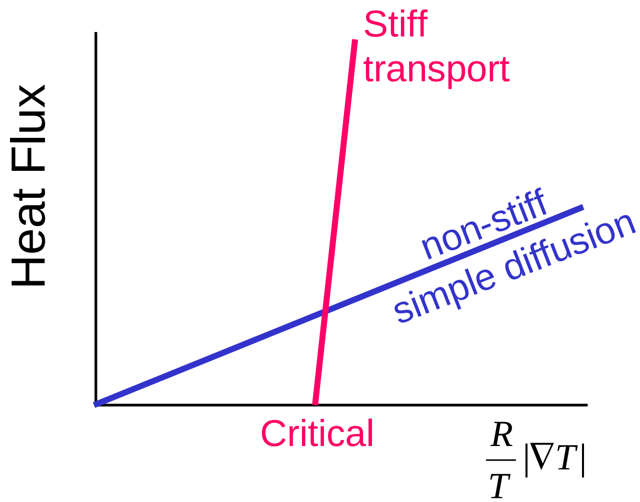
$$\chi_i = \rho_i^2 \frac{v_{ti}}{R} \left(\frac{R}{L_T} - \frac{R}{L_{T,crit}(p_j)} \right) F(p_j) \left(1 - \frac{\gamma_{shear}}{\gamma_{lin}} \right)$$

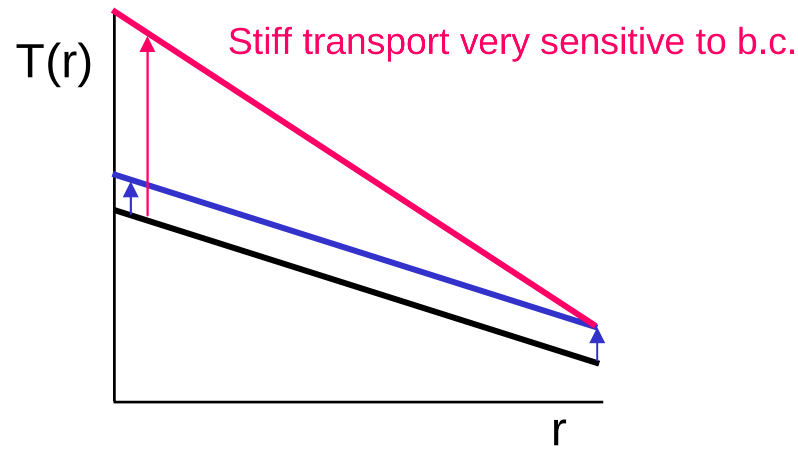
$$\frac{1}{L_T} = -\frac{1}{T} \frac{dT}{dr} \qquad p_j = \left(\frac{R}{L_T}, \frac{R}{L_T}, \frac{T_i}{T_e}, q, \hat{s}, Z_{eff}, nu, \frac{r}{R}, \ldots \right)$$

- Brought together scalings from selected analytic theories into a single formulas. Comprehensive enough to explain many observed trends in standard tokamak operating regimes, including some improved confinement regimes (given edge B.C.'s and sheared flows).
- Very successful in demonstrating that detailed transport model based on microturbulence simulations was possible. Raised legitimate concerns about ITER-96 design. But needed improvement for more accuracy, wider range of parameters, missing some key physics…

Large diffusion predicted by many 1980's analytic ITG theories lead to proposal that temperature gradients would be forced to near marginal stability

For example: Biglari, Diamond, Rosenbluth, Phys. Fluids B1, 109 (1989), Horton et al. Phys. Fluids B4, 953 (1992), Bateman PB B4, 634 (1992) and refs therein, Kotschenreuther, Dorland, Beer, Hammett (1994).





- Resulting temperature profiles is more sensitive to critical gradient than to magnitude of χ_i. Core temperature becomes very sensitive to boundary condition, if there is perfect marginal stability:

$$T(r) = T_0 e^{-r/L_{Tcrit}}$$

- Helps explain experimental sensitivity to edge boundary conditions (neutral recycling, wall conditions, supershots, edge transport barriers). Similar to the largest fusion reactor in the solar system…

Solar Convection Zone Near Marginal Stability

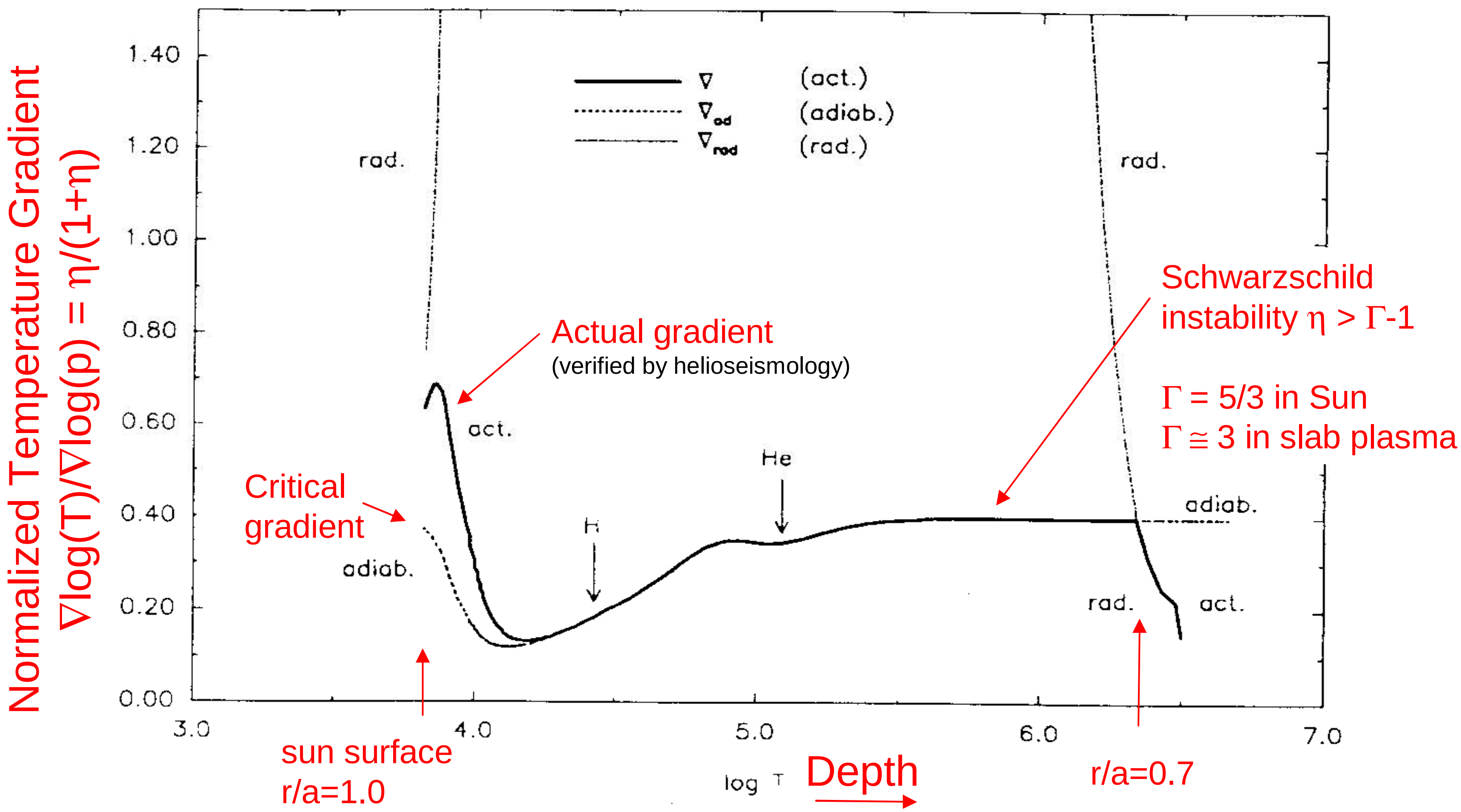


Figure 2: Temperature gradients $\nabla_{rad}, \nabla_{ad}$, and ∇ as functions of $\log T$ for a mixing length model of the solar convection zone (Spruit 1977). At the bottom of the convection zone ($\log T \approx 6.3$, depth $\approx 2 \cdot 10^5$ km) the actual temperature gradient changes from $\nabla \approx \nabla_{rad}$ to $\nabla \approx \nabla_{ad}$. The superadiabaticity becomes significant only in the surface layers ($\log T < 4.$) where the whole flow is driven. The ionization regions of hydrogen and helium are indicated; the adiabatic temperature gradient decreases there due to the effect of latent heat. (from Spruit, 1977 Ph.D., in Schüssler '92)

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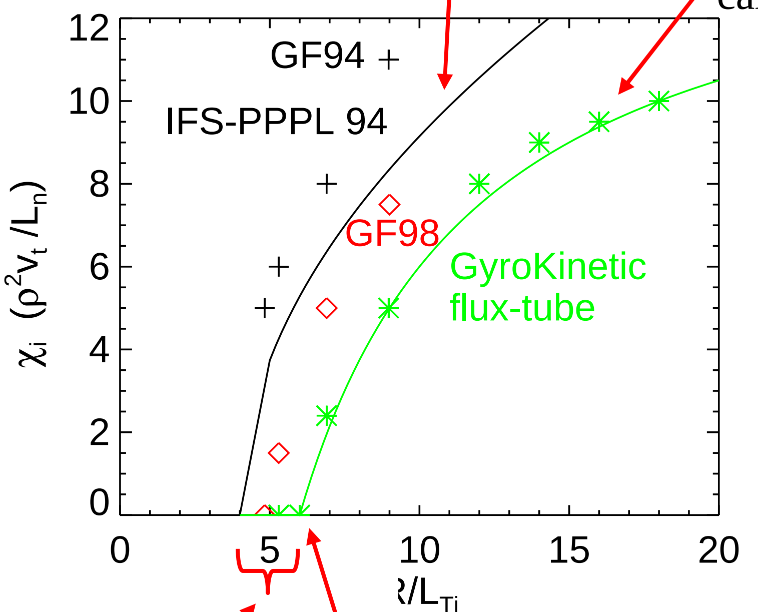
Part of the confusion some people have about gyrofluid/gyrokinetic comparisons comes from focusing on heat conductivity χ vs. temperature gradient. But reversing this plot shows errors in predicted temperature gradient are smaller.

IFS-PPPL model

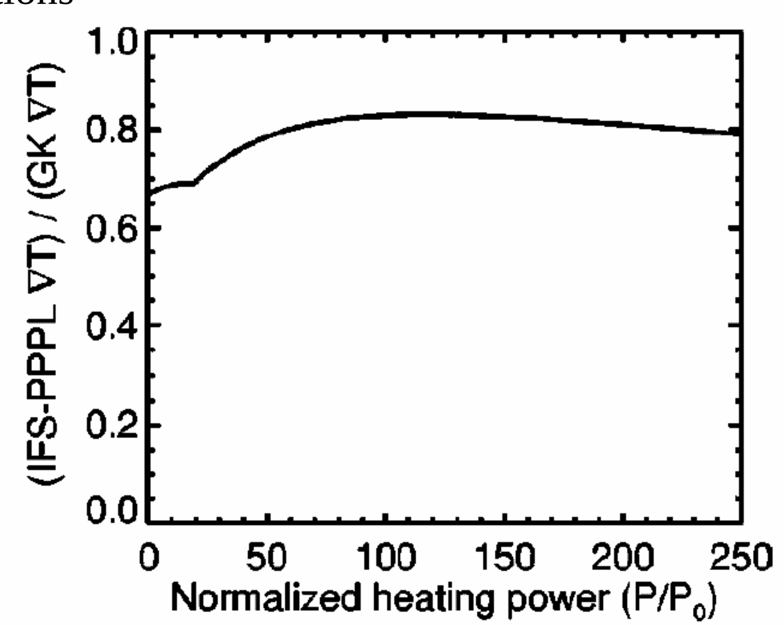
Gyrokinetic calculations



Dimits shift

Relative error $\chi_{IFS\text{-}PPPL}/\chi_{GK}$ becomes infinite right at marginal stability, but that isn't very relevant.

Fig. 3 & 7, Dimits, et.al. Phys. Plasmas 2000.



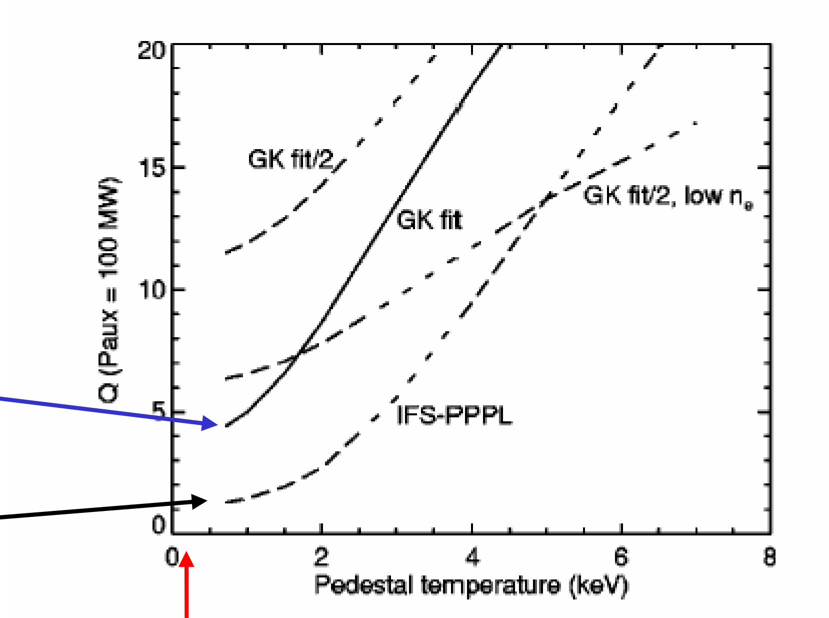
Turn previous plot around: calculate temperature gradient for a given heat flux ($\sim \chi$ R/L_{Ti}). Find that IFS-PPPL prediction is only 20-33% low. [Nevertheless, $P_{fusion} \sim T^2$, we ultimately want more accurate theory.]

Dimits shift, by itself, was not enough to insure ITER-96 success (which required Q=15, P_{fusion}=1500 MW for nuclear testing)

From Dimits, et.al. Phys. Plasmas 2000
Predictions for 1996 ITER.

Modified transport model to approximate reduced transport due to Dimits shift seen in electrostatic adiabatic-electron gyrokinetic simulations

original 1995 IFS-PPPL model



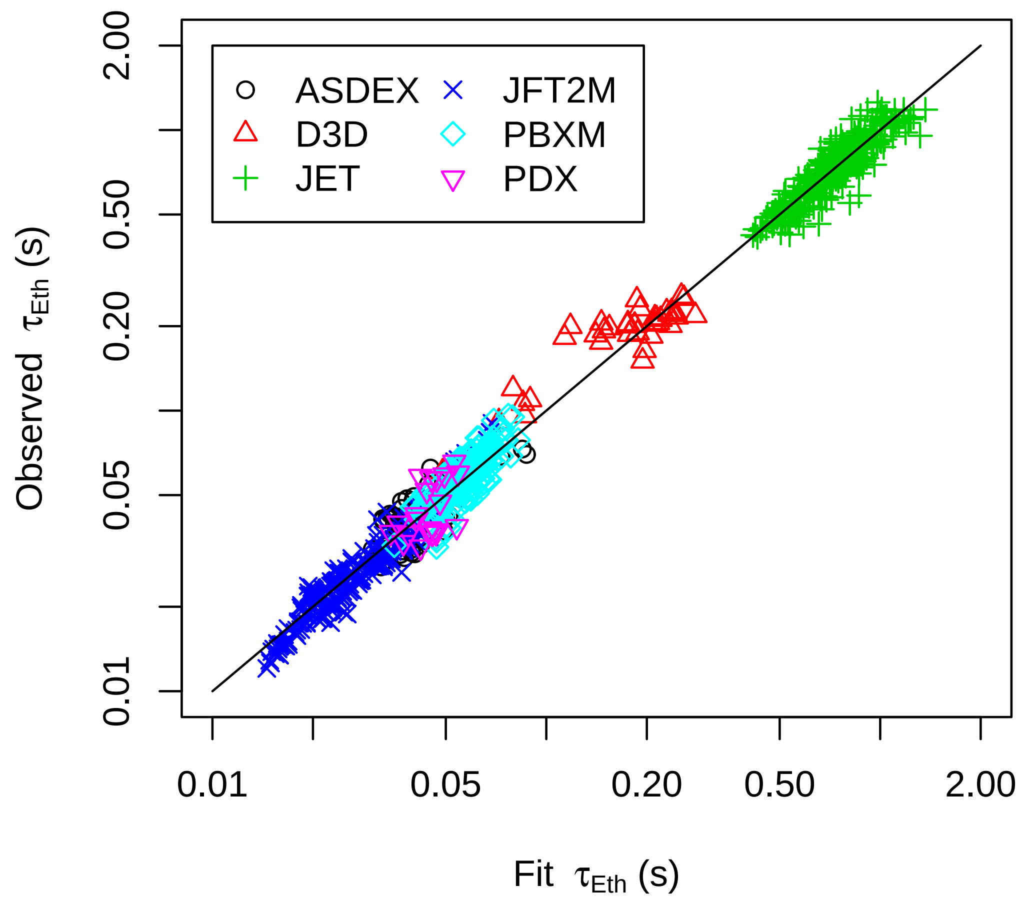
JET 1998 IAEA and ITER 1996 IAEA papers predicted Tped ~ 0.14 keV! for ITER-96

Caveats: Dimits shift may be less important at low collisionality with trapped electrons (Dorland IAEA 2000, Mikkelsen IAEA 2002), or offset by including ETG.

Empirical Confinement Time Scaling Looks Good at First

If all measurements are independent (i.e. random uncorrelated errors), (and if model has correct functional form)

then error in fit ~ 1/sqrt(N) and error very small…

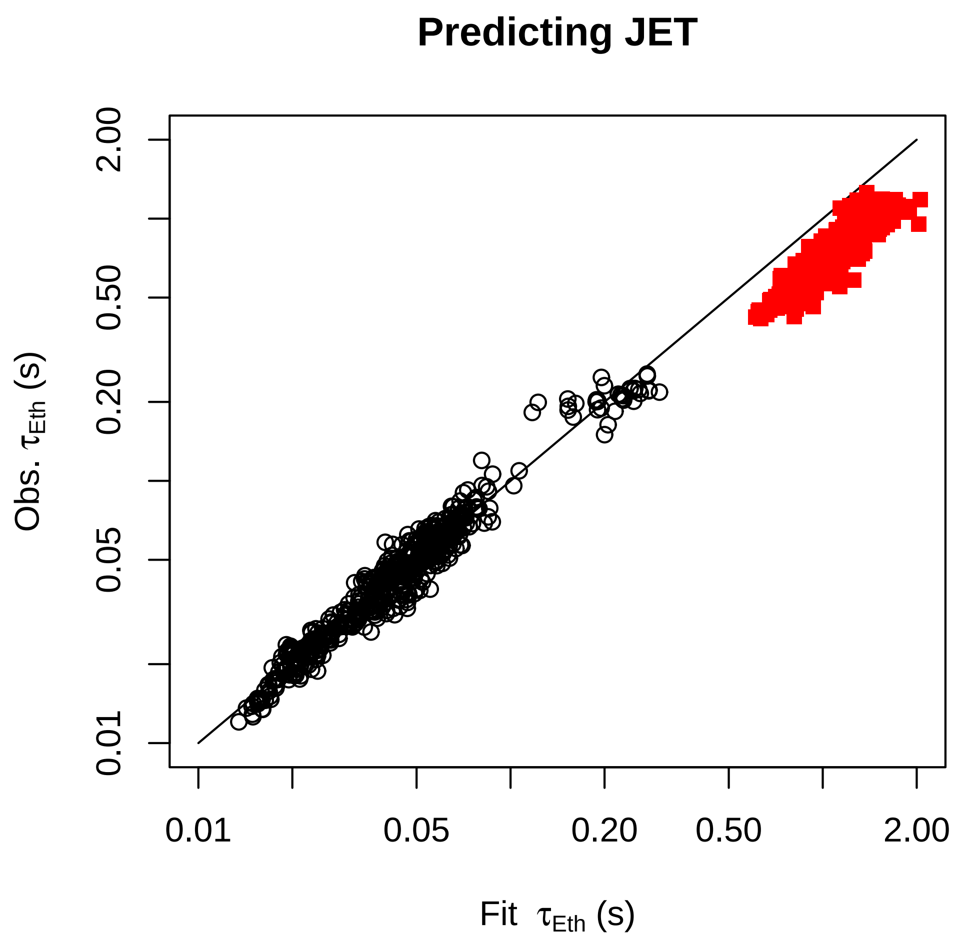


$$\tau_{E,93H} = e^{-3.35\pm0.071}\, I_p^{1.06\pm0.028}\, B_T^{0.33\pm0.038}\, P_{Lth}^{-0.68\pm0.014}$$

$$n_e^{0.17\pm0.022}\, R^{\pm1.80\pm0.062}\, (a/R)^{-0.11\pm0.041}\, \kappa^{0.65\pm0.051}\, M^{0.40\pm0.027}$$

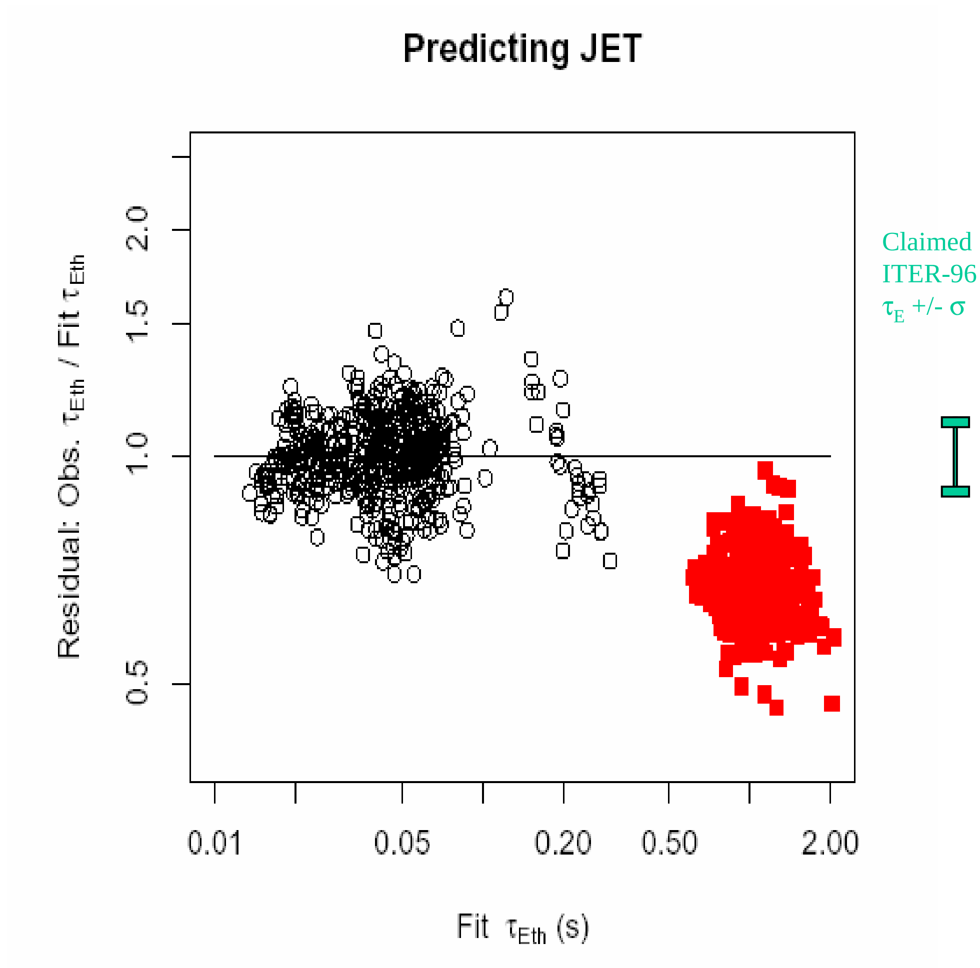
Cross-validation (fit to a subset of data, test by predicting rest of data) shows significant uncertainties

- Prediction of JET data (red) using fit to other 5 tokamaks excluding JET. RMS error of fit to data excluding JET is 0.125. RMSE of predicting JET is 0.408, significantly larger than expected error 0.138 if all errors statistically independent.
- JET data systematically low, mean prediction error -0.393, significantly larger than expected ideal error in the mean of ±0.060.
- Repeat for all other tokamaks.
- Conclusion: significant correlations among errors (i.e., systematic errors between different tokamaks, or between different regimes). Uncertainties in predicting ITER much larger than previously acknowledged.



Predicting JET from other tokamaks gave huge error

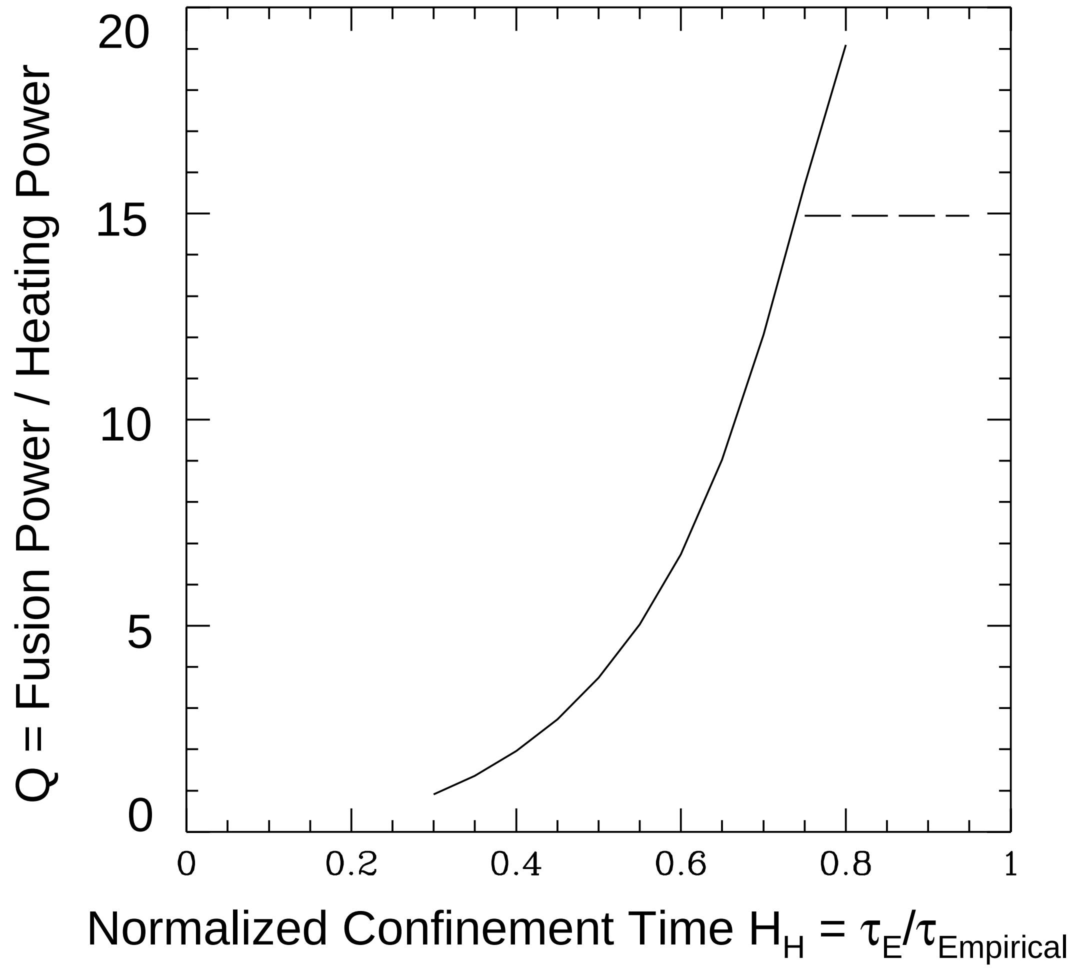
- Main critique of ITER had nothing to do with complex turbulence theories, but with experimental global confinement scalings.
- Clear evidence of significant systematic tokamak-to-tokamak variations show that the simple error formulas originally used by some to predict ITER were inappropriate.
- New data since 1996 reduces uncertainties, but also confirms that original scalings were too optimistic.
- Predictions of new ITER-FEAT design more realistic, particularly since it would operate below the Greenwald density limit (original ITER-96 was to operate at 1.5 x Greenwald density limit, much larger extrapolation.)



Fusion performance depends sensitively on confinement

Sensitive dependence on turbulent confinement causes some uncertainties, but also gives opportunities for significant improvements, if methods of reducing turbulence extrapolate to larger reactor scales.

$$\frac{dE}{dt} = P - \frac{E}{\tau_E}$$



Caveats: best if MHD pressure limits also improve with improved confinement.
Other limits also: power load on divertor & wall, …

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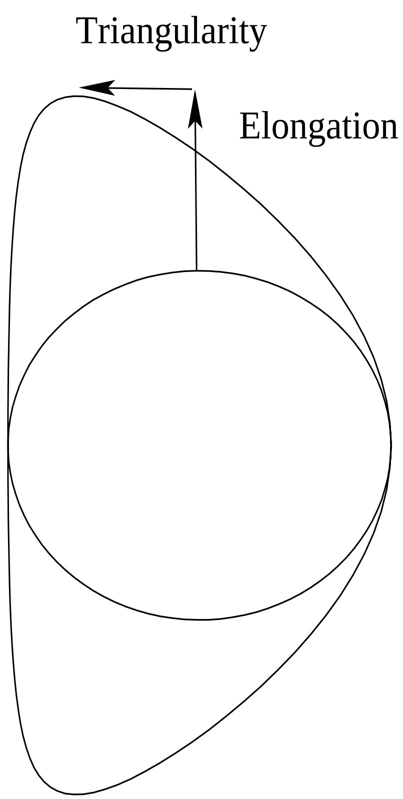
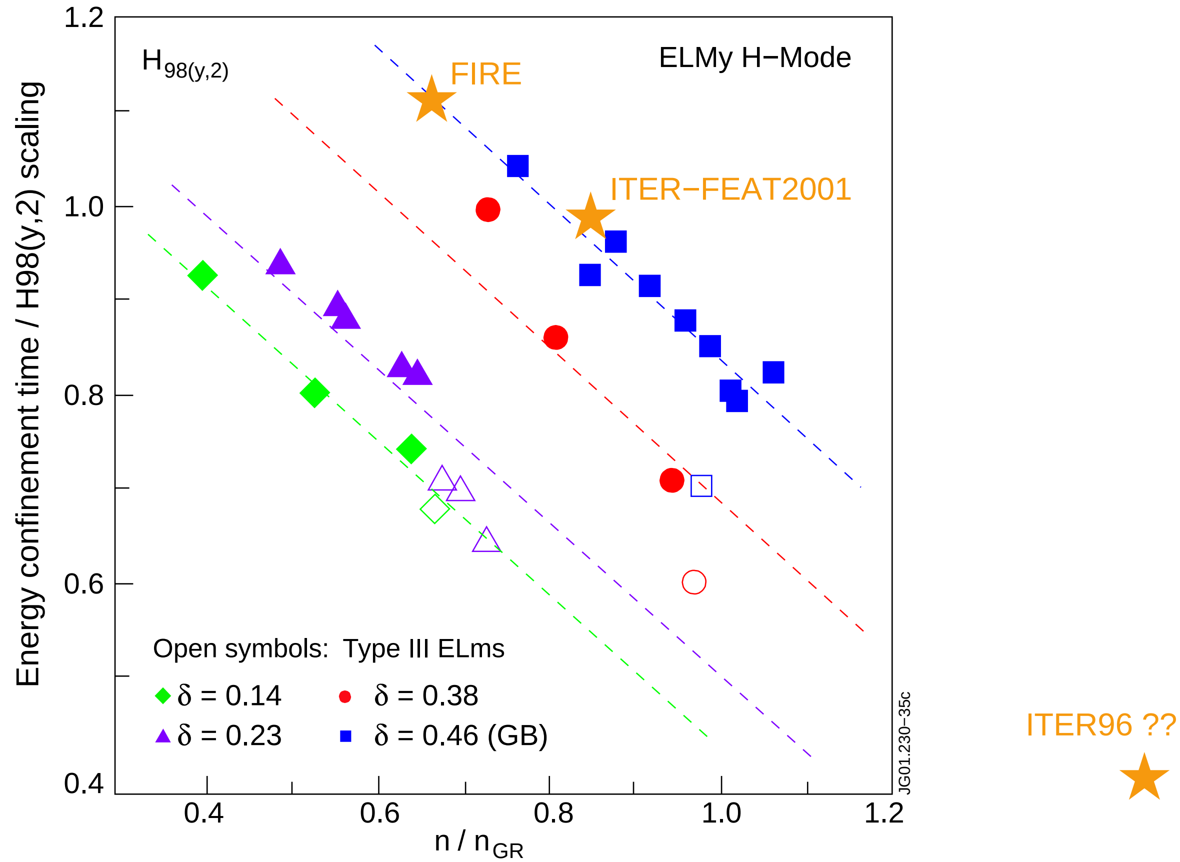
Stronger plasma shaping improves performance





Confinement degrades if density too large relative to empirical Greenwald density limit $n_{Gr} = I_p /(\pi a^2)$, but improves with higher triangularity.

Compared to original 1996 ITER design, new ITER-FEAT 2001 and FIRE designs can operate at significantly lower density relative to Greenwald limit, in part because of higher triangularity and elongation.

JET data from G. Saibene, EPS 2001, J. Ongena, PPCF 2001. Seen in other tokamaks also.

Improved new fusion designs ↓ uncertainties

Density and pressure limits improve with elongation κ & triangularity δ:

Empirical Greenwald density limit
$$n_{Gr} = \frac{I_p}{\pi a^2} \propto \frac{B_T}{R q_{95}} \left[1+\kappa^2\left(1+2\delta^2\right)\right]$$

Pressure limit
$$\beta = \frac{p}{B^2/8\pi} \propto \frac{I_p}{a B_T} \propto \frac{a}{R q_{95}} \left[1+\kappa^2\left(1+2\delta^2\right)\right]$$

New ITER-FEAT design uses segmented central solenoid to increase shaping.

FIRE pushes to even stronger shaping (feedback coils closer) & reduced size with high field cryogenic CuBe (achievable someday with high-Tc superconductors?)

	R (m)	a (m)	B (T)	I_p (MA)	n_{Gr} $10^{20}/m^3$	$\langle n_e \rangle / n_{Gr}$	κ_x	δ_x	P_{fusion} MW	$P_\alpha / 2\pi R$
ITER-96	8.14	2.80	5.68	21.0	0.85	1.50	1.75	0.35	1500	5.9
ITER-FEAT	6.20	2.00	5.30	15.1	1.19	0.85	1.85	0.48	400	2.0
FIRE	2.14	0.60	10.0	7.7	6.92	0.66	2.00	0.70	150	2.2
Aries-AT ~goal	5.20	1.30	5.86	12.8	2.41	1.00	2.18	0.84	1760	9.0

Caveats: remaining uncertainties regarding confinement, edge pedestal scaling, ELMs, disruptions & heat loads, tritium retention, neoclassical beta limits, but also good ideas for fixing potential problems or further improving performance.

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

Scale from JET to some proposed reactor designs, using this Tped formula (with a D ~ rho_theta assumption), and other pedestal scalings also.

	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-FEAT	6.20	2.00	5.30	15.1	0.58	0.48	.65	1.70	.33	2.9	2.1	7.4
FIRE	2.0	0.53	10.0	6.44	3.6	0.48	.65	1.77	.40	4.8	3.0	6.7

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

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))

Impact of design changes in new ITER-FEAT.

- ITER-FEAT uses a segmented central solenoid which provides more shape control than the fixed central solenoid in the original 1996 ITER (some U.S. physicists/engineers had been pushing for this design change before the U.S. pulled out).
- Increased elongation κ_x from 1.75 to 1.85, triangularity δ_x from 0.34 to 0.48, reduced size from R=8.14 to 6.2 m. (FIRE pushes each of these even further)

$$n_{Greenwald} = \frac{I_p}{\pi a^2} \propto \frac{B_t}{qR}\left[1+\kappa^2(1+2\delta^2)\right]$$

- At fixed B_t & q, can increase Greenwald density limit (and current) by increasing κ & δ.
- Net effect: $n_{Greenwald}$ increased by 40% and $n_e/n_{Greenwald}$ dropped from 1.5 in ITER-96 to only 0.85 in ITER-FEAT (now accepted as a design rule maximum value for ITER-FEAT).

- When we started looking at these issues in 1995, some members of ITER central team said ITER had to work at this high density in order to not melt (or erode too quickly) the divertor.
- Rough measure of the divertor power load is P/R: 3 times lower in ITER-FEAT than ITER-96. Divertor plates have been inclined further. Now easier to handle lower density.
- By dropping nuclear testing requirement of P=1500 MW, Q can be increased by lowering power (until hitting H-mode power threshold), since if $\tau_E \sim P^{-2/3}$, then $n\, T\, \tau_E \sim P\, \tau_E^2 \sim P^{-1/3}$

More experience with advanced tokamak regimes.

- Advanced tokamak regimes with internal transport barriers (ITBs) might help to significantly improve tokamak confinement, beta limits, and power plant design (with higher self-driven bootstrap current).

- 1996/97 consensus expressed in 1997 FESAC review: advanced tokamak studies were very important, but were too new and uncertain for ITER to depend on.

- Further experience since then has been encouraging: internal transport barriers of various kinds achieved in largest tokamaks (incl. JET and JT-60U). These include electron transport barriers that apparently depend on high beta Shafranov shift effects and not on rotation (which might be harder to obtain at large reactor scales). Also have more experience sustaining them for longer times (DIII-D feedback expts.).

- Main mechanisms of ITBs qualitatively understood theoretically, but there are significant quantitative uncertainties in accessibility requirements. Nevertheless, experimental experience is encouraging that it may be possible.

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Complex 5-dimensional Computer Simulations being developed

- Solving gyro-averaged kinetic equation to find time-evolution of particle distribution function

  $$f(\vec{\mathbf{x}}, E, v_{||}/v, t)$$

- Gyro-averaged Maxwell's Eqs. determine Electric and Magnetic fields
- "typical" grid 96x32x32 spatial, 10x20 velocity, x 3 species for 10^4 time steps.
- Various advanced numerical methods: implicit, semi-implicit, pseudo-spectral, high-order finite-differencing and integration, efficient field-aligned coordinates, Eulerian (continuum) & Lagrangian (particle-in-cell).

Gyrokinetic Eq. Summary

Gyro-averaged, non-adiabatic part of 5-D particle distribution function: $f_s = f_s(\,\mathbf{x}, \varepsilon, \mu, t)$ determined by gyrokinetic Eq. (in deceptively compact form):

$$\frac{\partial f}{\partial t} + \left(v_{\|}\hat{\mathbf{b}} + \mathbf{v}_d\right)\cdot \nabla f + \underbrace{\hat{\mathbf{b}} \times \nabla \chi \cdot \nabla\left(f + F_0\right)} + q\,\frac{\partial F_0}{\partial \varepsilon}\frac{\partial \Phi}{\partial t} = C(f)$$

Generalized Nonlinear ExB Drift
Incl. Magnetic fluctuations

$\chi(\mathbf{x},t)$ is gyro-averaged, generalized potential. Electric and magnetic fields from gyro-averaged Maxwell's Eqs.

$$\chi = J_0\left(\tfrac{k_\perp v_\perp}{\Omega}\right)\left(\phi - \frac{v_\|}{c}A_\|\right) + \frac{J_1\left(\frac{k_\perp v_\perp}{\Omega}\right)}{\frac{k_\perp v_\perp}{\Omega}}\frac{m v_\perp^2}{q}\frac{\delta B_\|}{B}$$

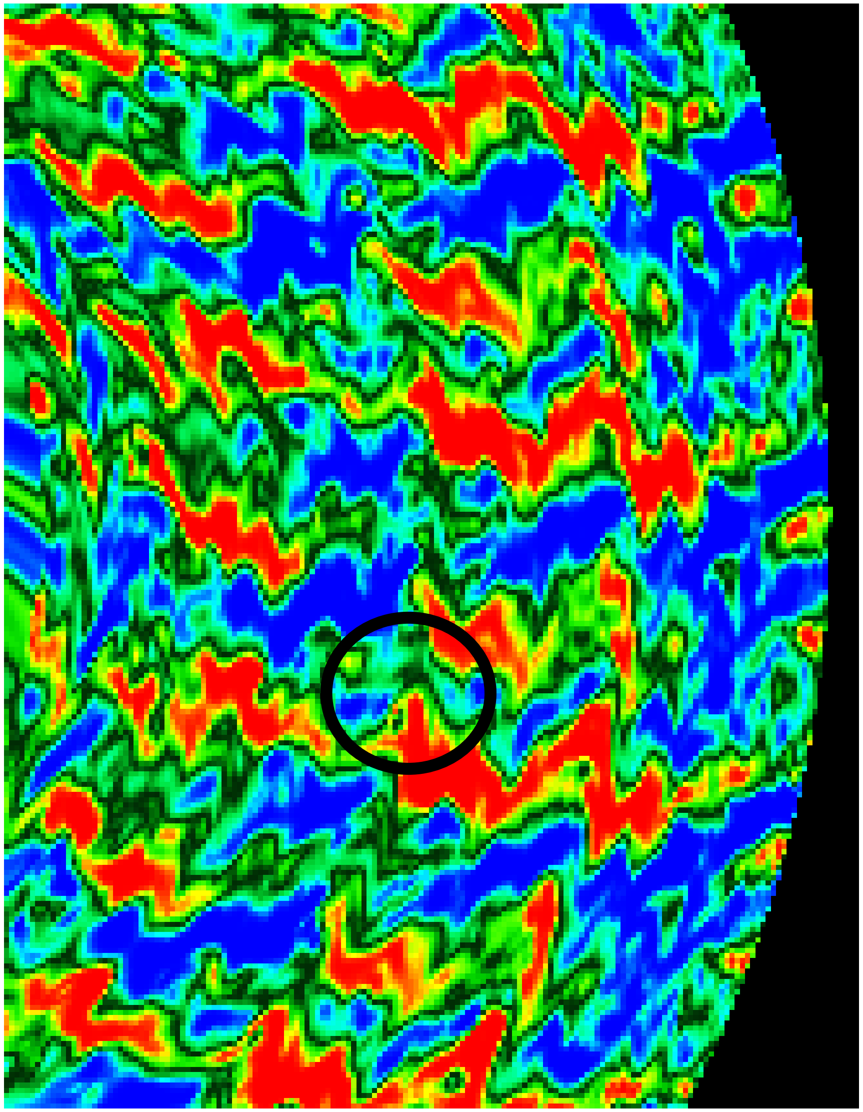
Bessel Functions represent averaging around particle gyro-orbit

Gyroaveraging eliminates fast time scales of particle gyration (10 MHz- 10 GHz)

Easy to evaluate in pseudo-spectral codes. Fast multipoint Padé approx. in other codes.

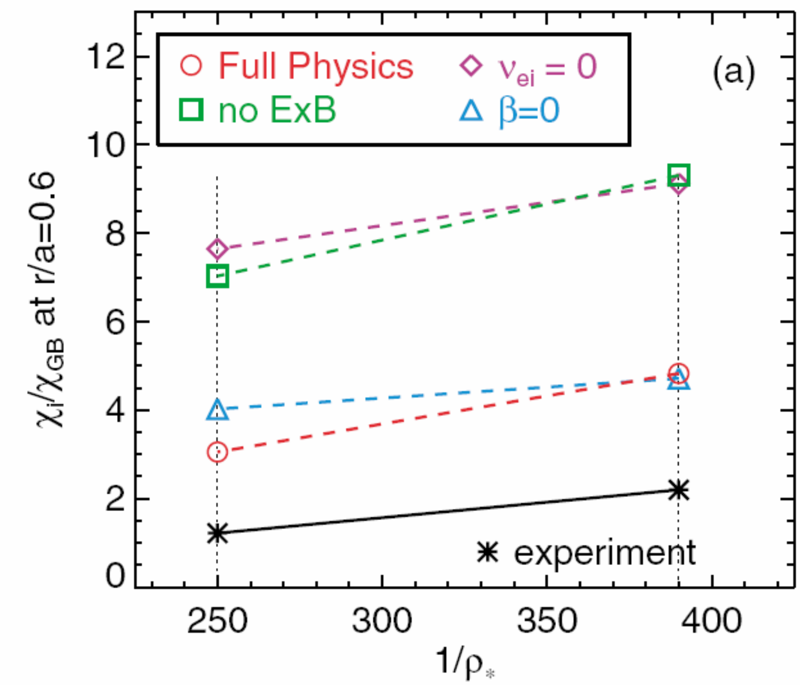
$$\chi = J_0(k_\perp \rho)\,\Phi$$

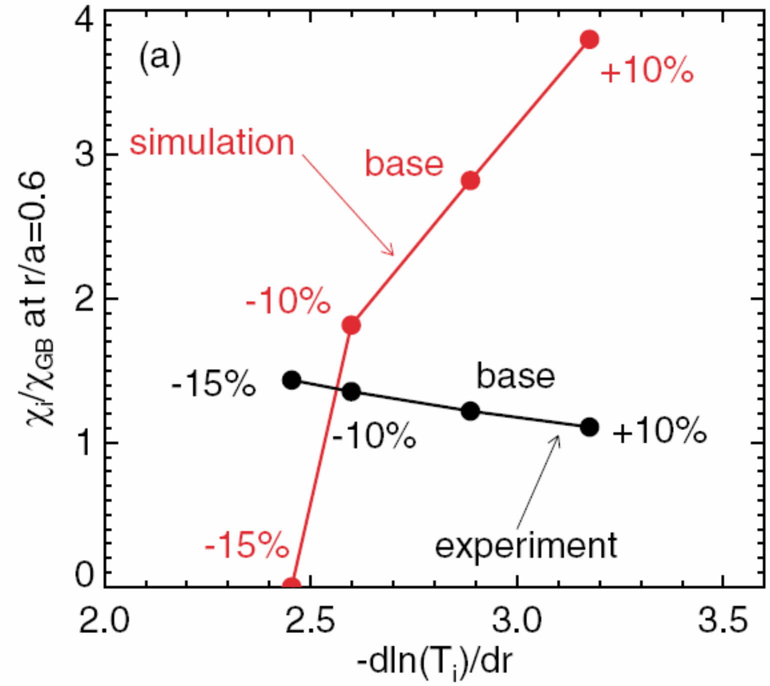
$$\chi(\vec{\mathbf{x}}) = \oint d\theta\ \Phi(\vec{\mathbf{x}} + \vec{\boldsymbol{\rho}}(\theta))$$



Comparison of GYRO Code & Experiment

Candy & Waltz, Phys. Rev. Lett. 2003





Gyrokinetic turbulence codes now including enough physics (realistic geometry, sheared flows, magnetic fluctuations, trapped electrons, fully electromagnetic fluctuations) to explain observed trends in thermal conductivity, in many regimes.

Big improvement over 15 years ago, when there were x10 – x100 disagreements between various analytic estimates of turbulence & expts.

Now within experimental error on temperature gradient. Importance of critical gradient effects emphasized in 1995 gyrofluid-based IFS-PPPL transport model.

Caveats: Remaining challenges: quantitative predictions of internal transport barriers, test wider range of parameters, & more complicated edge turbulence.

Turbulence & Transport Issues Particularly Important in Burning plasmas

- Performance of burning plasma & fusion power plant very sensitive to confinement: potential significant improvements
- Uncertainties: Maintain good H-mode pedestal in larger machine at high density? ELM bursts not too big to avoid melting wall? Can internal transport barriers be achieved in large machine, for long times self-consistently with beta limits on pressure profiles and desired bootstrap current?
- In present experiments, pressure profile can be controlled by external heating, currents primarily generated inductively. In a reactor, pressure and current profiles determined self-consistently from fusion heating and bootstrap currents. (Fortuitously, bootrap currents give naturally hollow profiles, which gives favorable reversed magnetic shear.)
- Proposed Burning Plasma devices will pin down uncertainties in extrapolations: help design final power plant.
- Comprehensive computer simulations being developed to understand & optimize performance

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Selected Further References

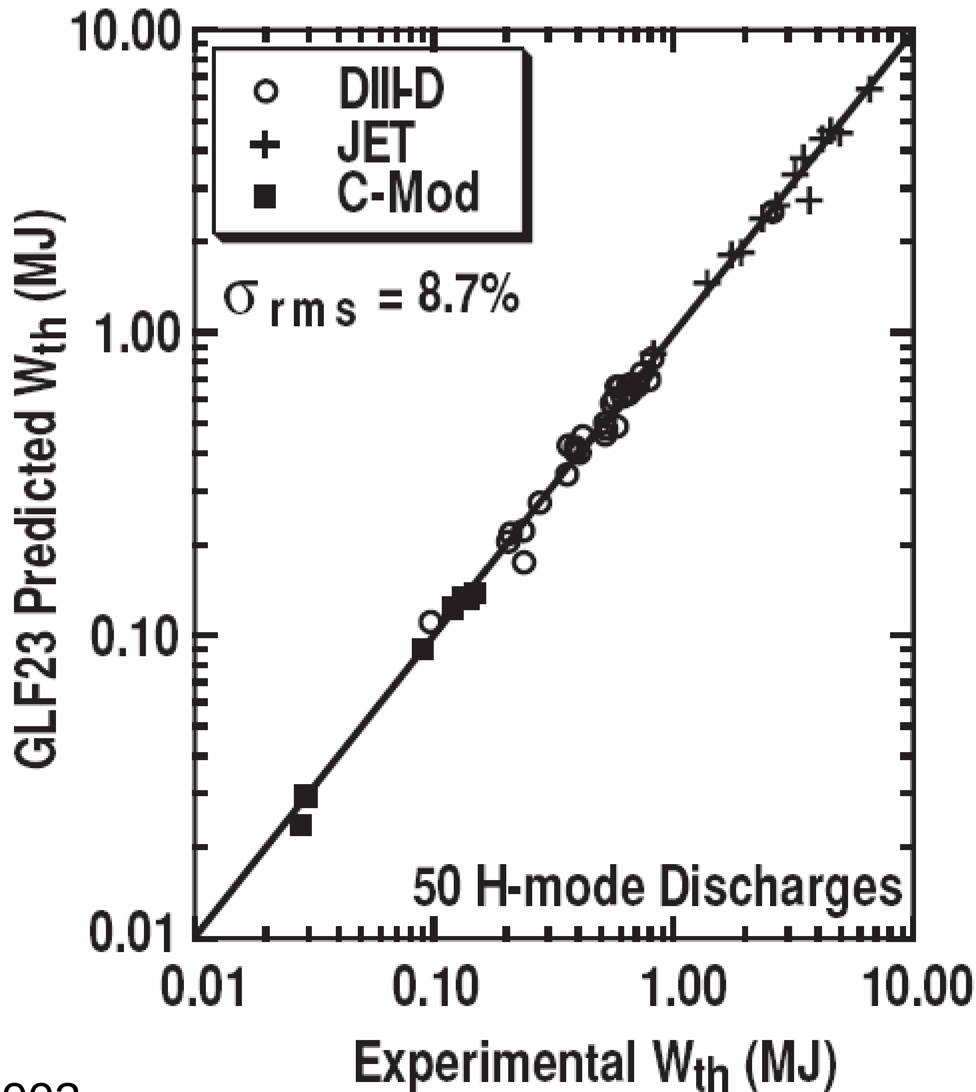
- This talk: http://fire.pppl.gov & http://w3.pppl.gov/~hammett
- Plasma Microturbulence Project http://fusion.gat.com/theory/pmp
- GYRO code and movies http://fusion.gat.com/comp/parallel/gyro.html
- GS2 gyrokinetic code http://gs2.sourceforge.net
- My gyrofluid & gyrokinetic plasma turbulence references: http://w3.pppl.gov/~hammett/papers/

- “Anomalous Transport Scaling in the DIII-D Tokamak Matched by Supercomputer Simulation”, Candy & Waltz, Phys. Rev. Lett. 2003
- “Burning plasma projections using drift-wave transport models and scalings for the H-mode pedestal”, Kinsey et al., Nucl. Fusion 2003
- “Electron Temperature Gradient Turbulence”, Dorland, Jenko et al. Phys. Rev. Lett. 2000
- “Generation & Stability of Zonal Flows in Ion-Temperature-Gradient Mode Turbulence”, Rogers, Dorland, Kotschenreuther, Phys. Rev. Lett. 2000
- "Comparisons and Physics Basis of Tokamak Transport Models and Turbulence Simulations", Dimits et al., Phys. Plasmas 2000.

Backup Slides

Comparison of experiments with 1-D transport model GLF23 based on gyrofluid & gyrokinetic simulations

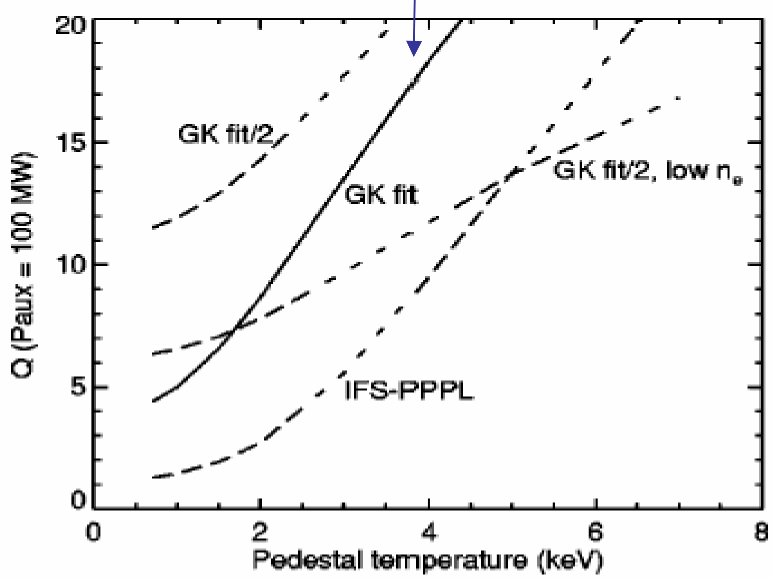
Caveats: core turbulence simulations use observed or empirical boundary conditions near edge. Need more complicated edge turbulence code to make fully predictive & sufficiently accurate. Edge very challenging: wider range of time and space scales, atomic physics, plasma-wall interactions…



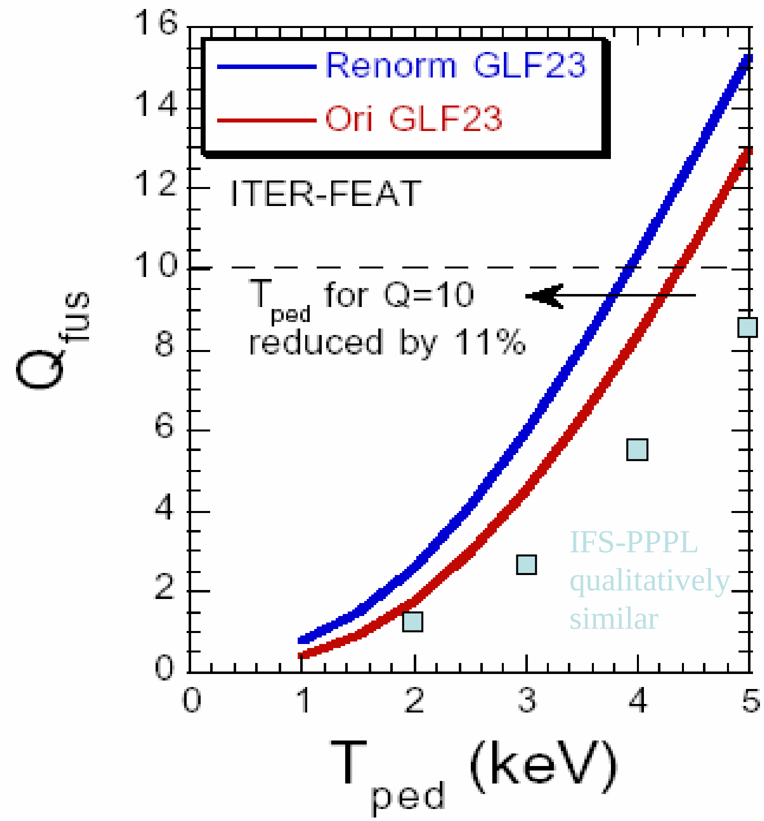
Kinsey, Bateman, et al., Nucl. Fus. 2003

Latest renormed GLF23 (used at Snowmass) shows only small difference from original GLF23 (which is similar to original IFS-PPPL) because reduction in ITG due to Dimits shift offset by increase in ETG

I.e., this curve may be too optimistic because it neglects ETG and trapped electron effects.



From Dimits, et.al. Phys. Plasmas 2000
Predictions for 1996 ITER.



From Kinsey, Staebler, Waltz, Sherwood 2002.
Predictions for 2001 ITER-FEAT.

A Grand Challenge for Fusion Science is to Understand, Predict and Control Turbulent Transport

Understand:

- structure and dynamics of turbulence and induced transport

↓

Predict:

- scaling of different confinement regimes

↓

Control:

- plasma equilibrium and confinement, local turbulence control

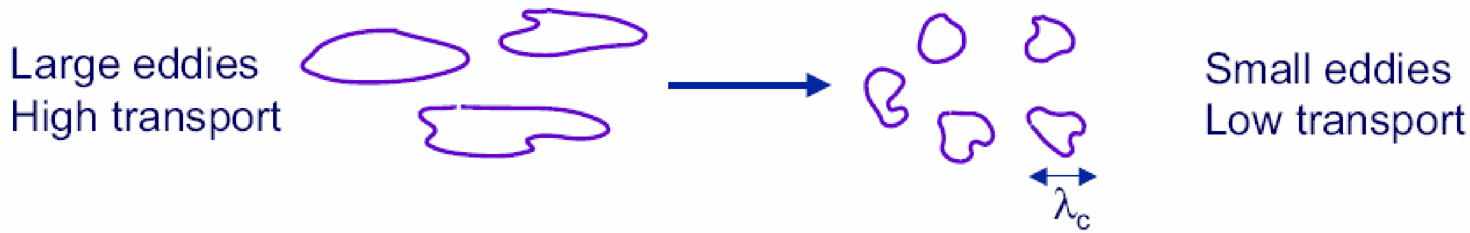
Continued improvement in measurement capability is essential to advance predictive understanding and develop methods for turbulence control

R. Nazikian et al.

A Major Challenge in Fusion Science is to Measure Turbulent Fluctuations with Good Spatial and Temporal Resolution

- Important turbulence parameters for measurement
  - correlation length λ_c
  - correlation time τ_c
  - density, potential, temperature fluctuation levels
  - velocity fluctuations (self regulation)

- Simple Random Walk Estimate: Diffusivity $D \propto \lambda_c^2 / \tau_c$



Outstanding questions in fusion science

- Is there a correlation between eddy size, fluctuation level and confinement?
- What controls the turbulent scale length in fusion plasmas?

R. Nazikian et al.

Recent advances in computer simulations

- Computer simulations recently enhanced to include all key effects believed important in core plasma turbulence (solving for particle distribution functions $f(x, v_{||}, v_{\perp},t)$ w/ full electron dynamics, electromagnetic fluctuations, sheared profiles).

- Challenges:
  - Finish using to understand core turbulence, detailed experimental comparisons and benchmarking
  - Extend to edge turbulence

- Edge region very complicated (incl. sources & sinks, atomic physics, plasma-wall interactions)

- Edge region very important (boundary conditions for near-marginal stability core, somewhat like the sun's convection zone).

- (3) Use to optimize fusion reactor designs. Large sensitivity → both uncertainty and opportunity for signficant improvement