Turbulence & Transport in Burning Plasmas

Greg Hammett, Princeton Plasma Physics Lab (PPPL)

http://w3.pppl.gov/~hammett

AAAS Meeting, Seattle, Feb. 2003

http://fire.pppl.gov

Acknowledgments:

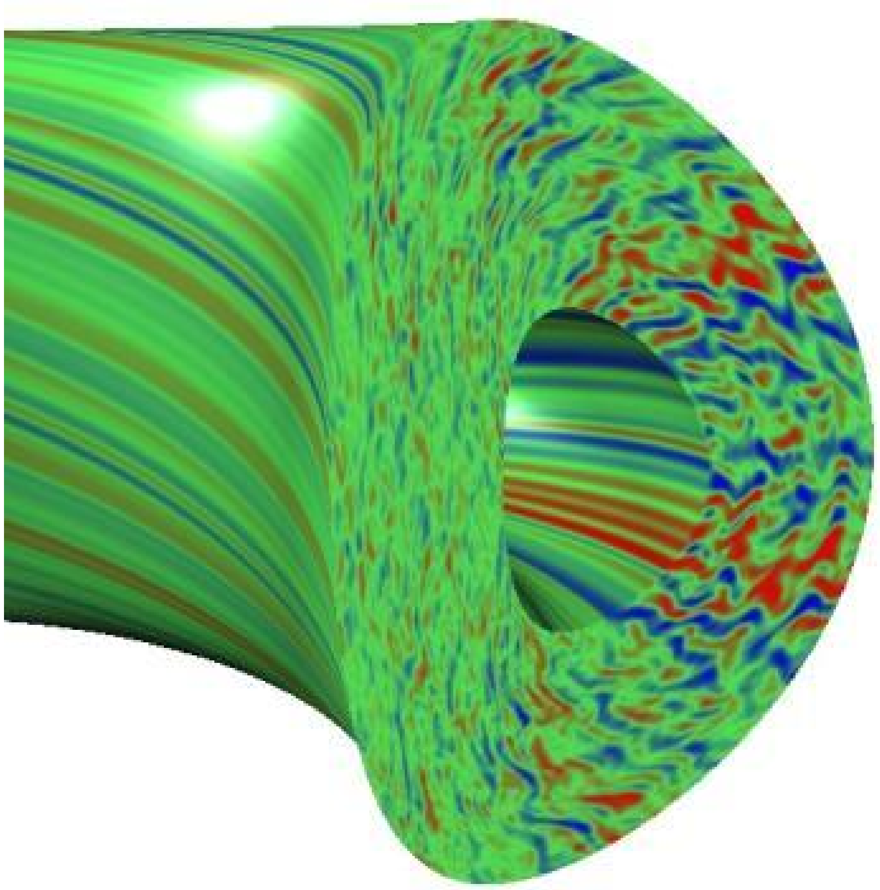
Plasma Microturbulence Project

(LLNL, General Atomics, U. Maryland, 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 …

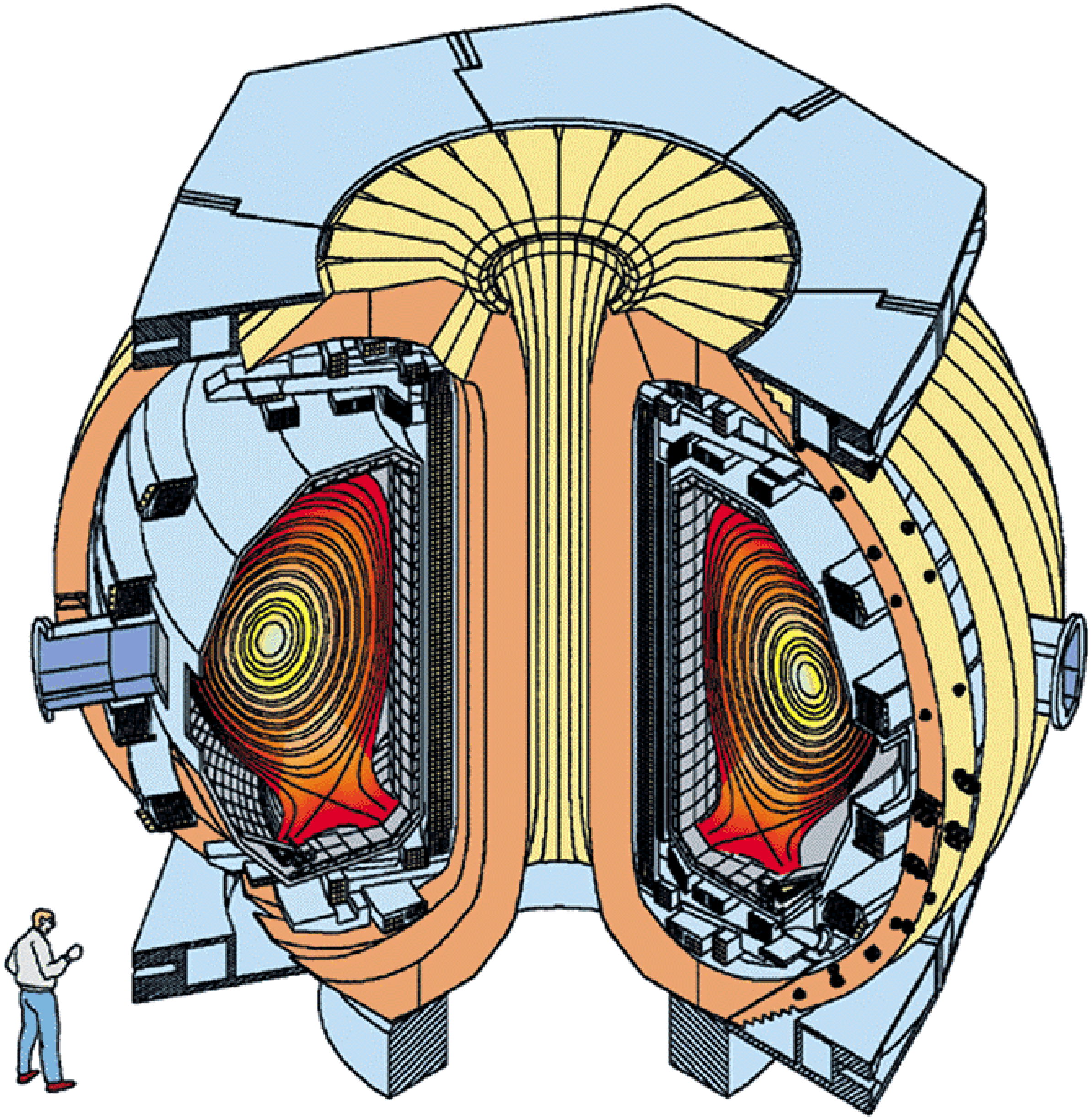
Summary: Turbulence & Transport in Burning Plasmas

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

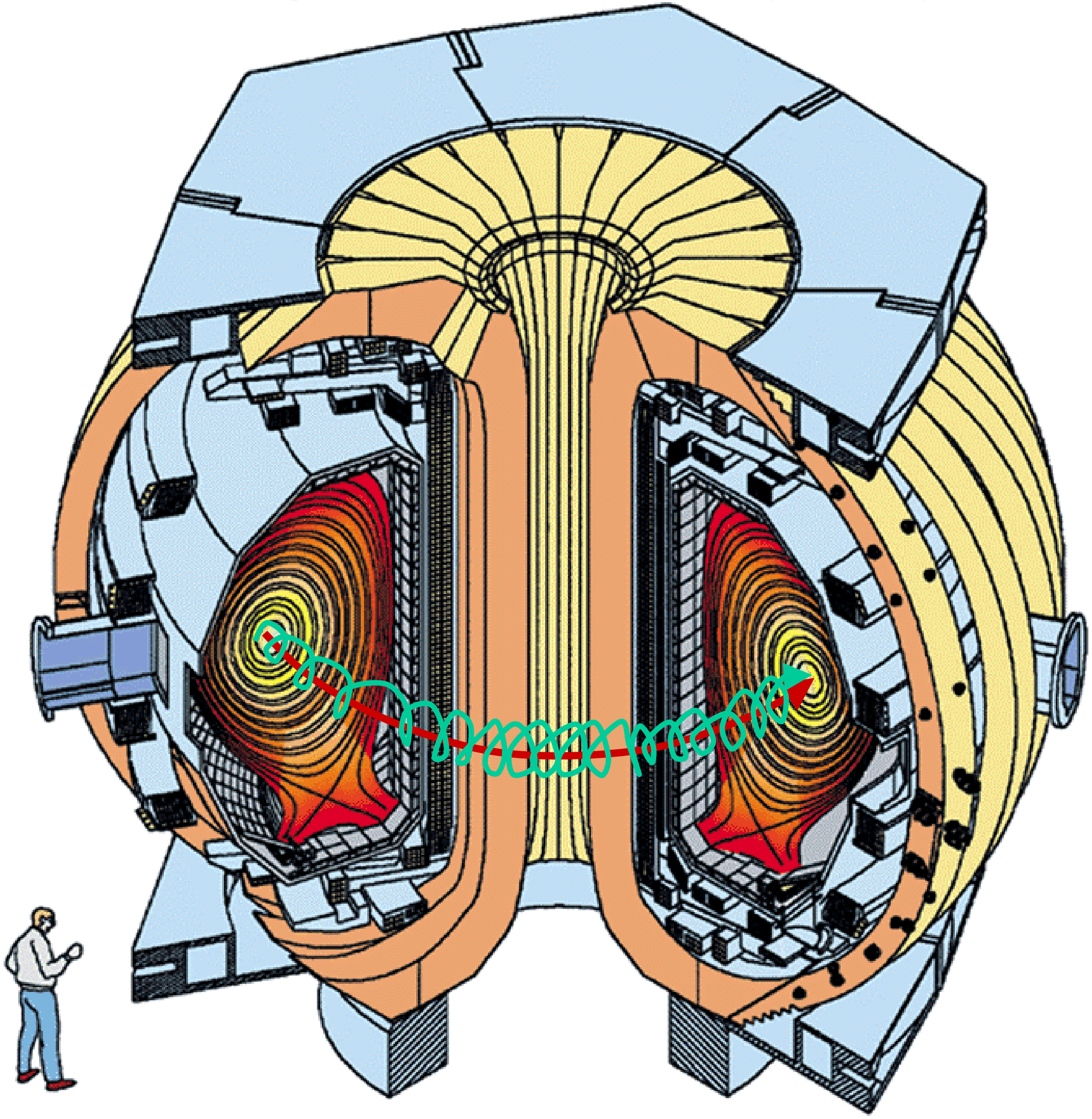
- Several good ideas for improvements in fusion reactor designs

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

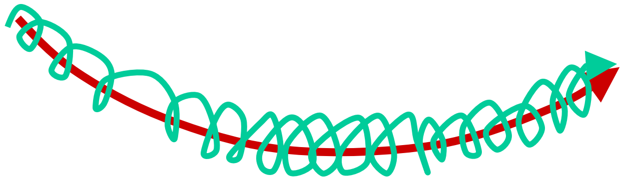
Cut-away view of aTokamak



Helical orbit of particle following magnetic field

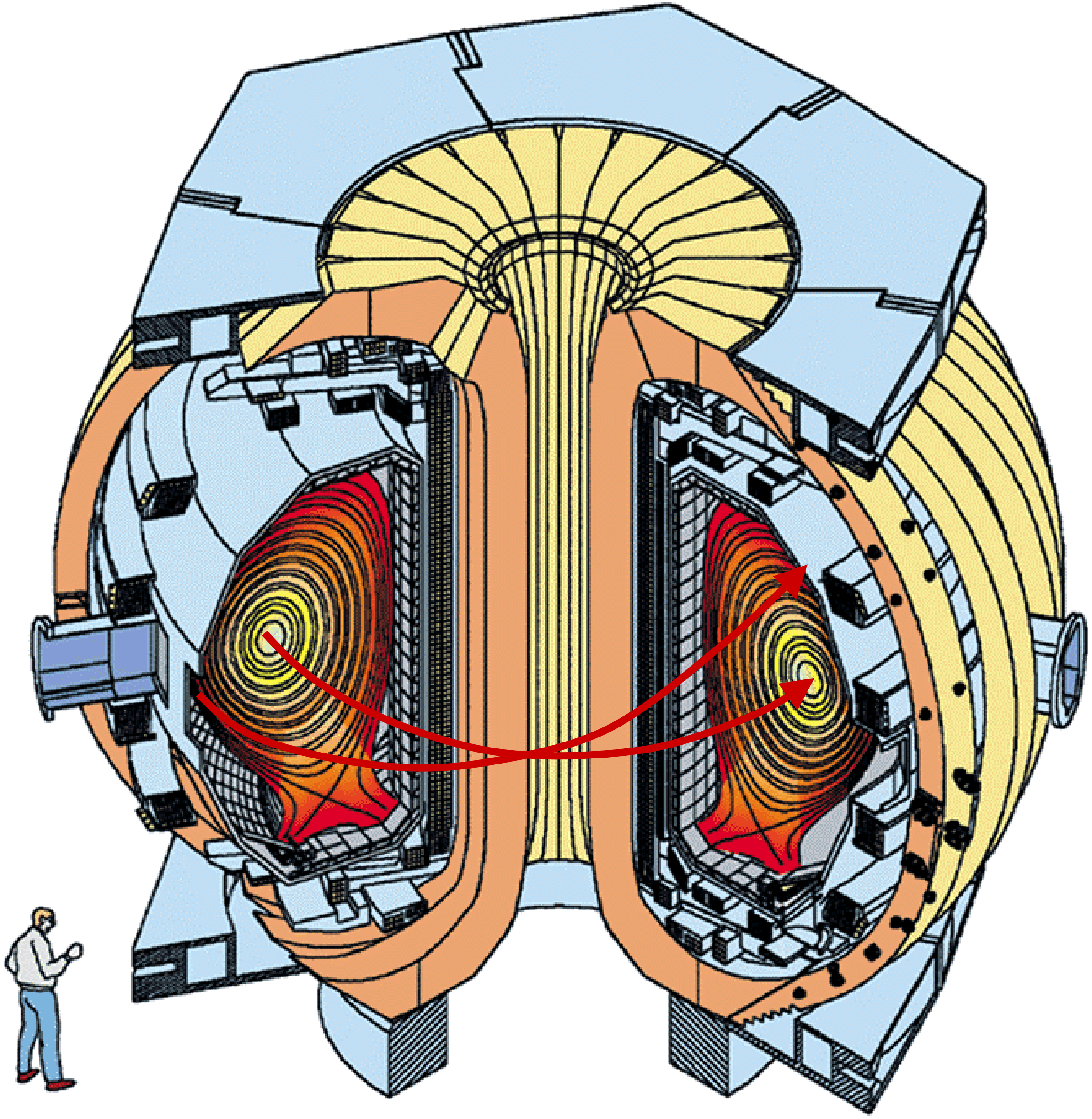


Helical orbit of particle following magnetic field

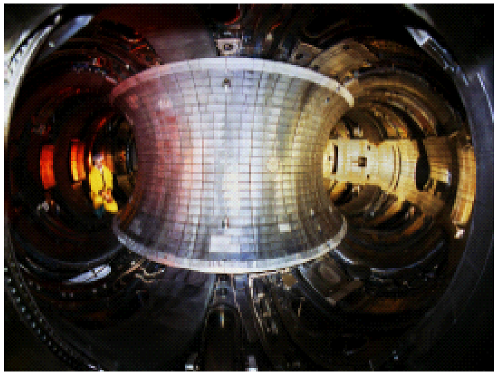


(Size of particle gyro-orbit enlarged for viewing)
(This is just a hand sketch: real orbits have very smooth helical trajectory.)

Magnetic fields twist, form nested tori

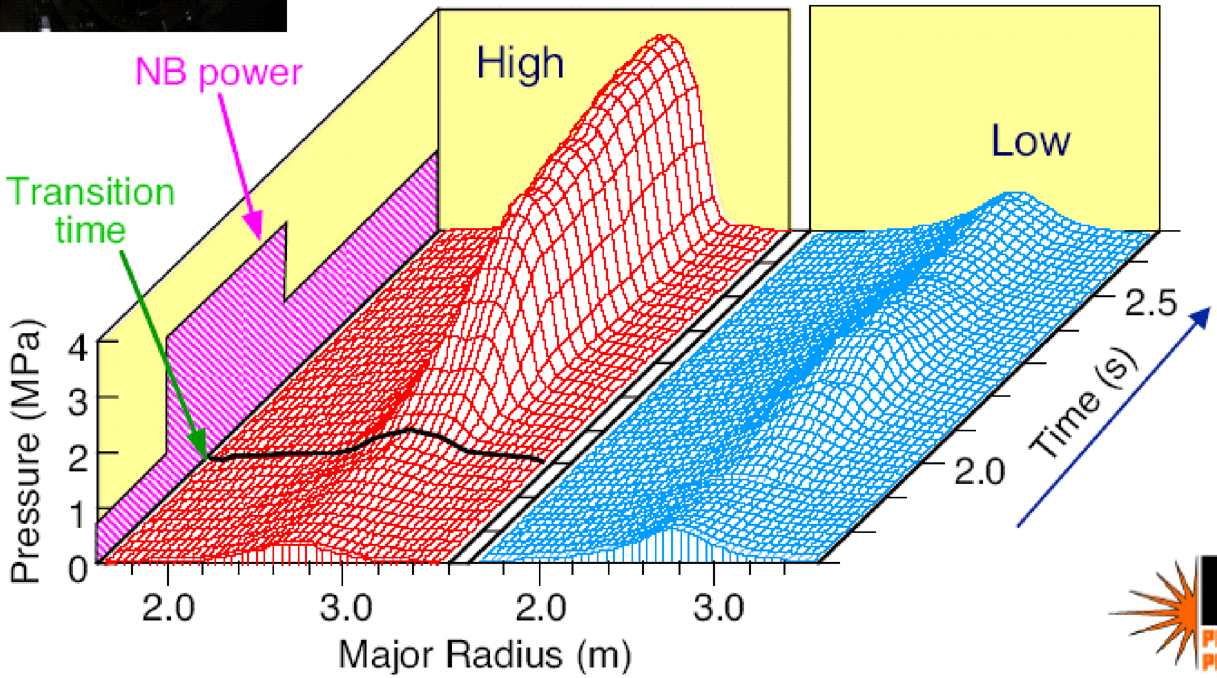


Fascinating Diversity of Regimes in Fusion Plasmas. What Triggers Change? What Regulates Confinement?



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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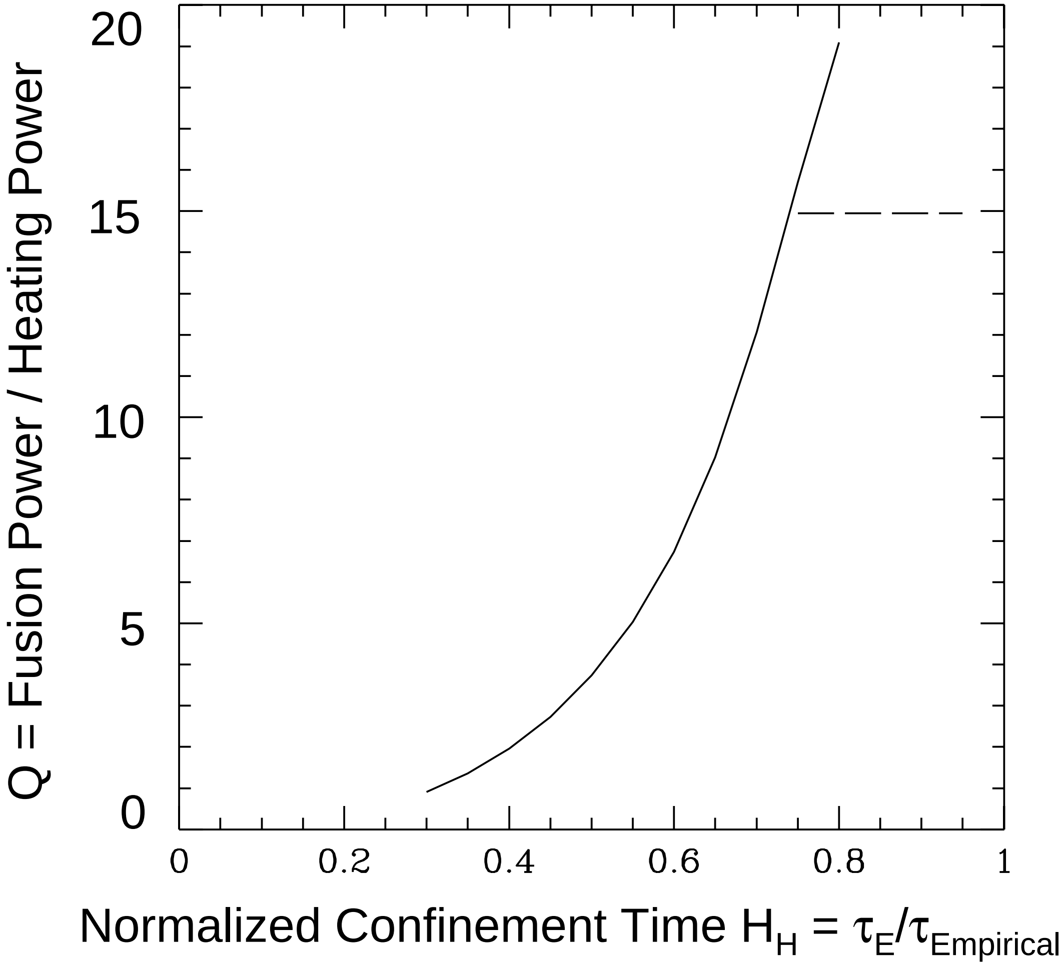
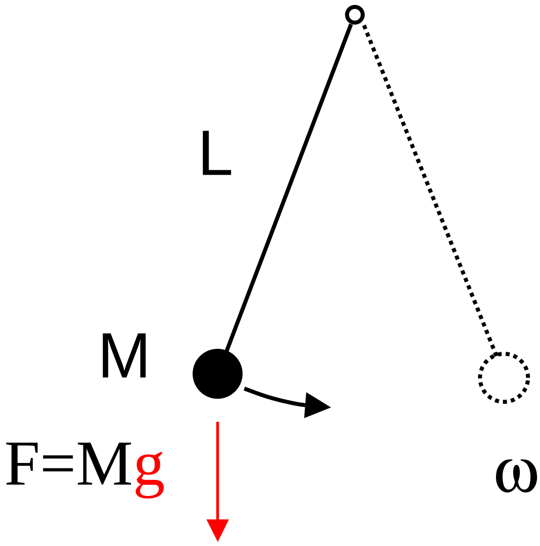
Fusion performance depends sensitively on confinement

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.



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

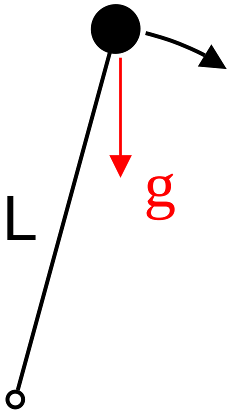
Stable Pendulum



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

Unstable Inverted Pendulum

(rigid rod)

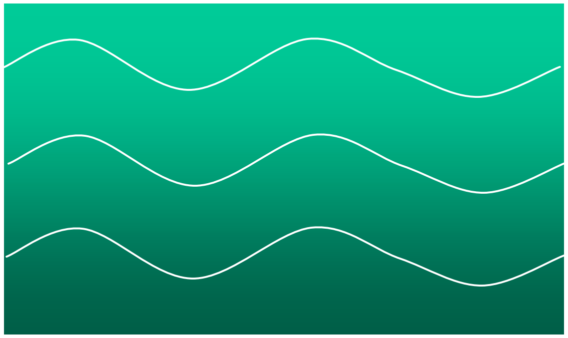


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

Instability

Density-stratified Fluid

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

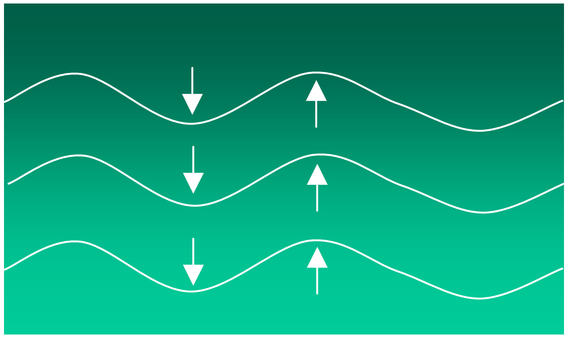


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

$\Rightarrow$Rayleigh-Taylor Instability

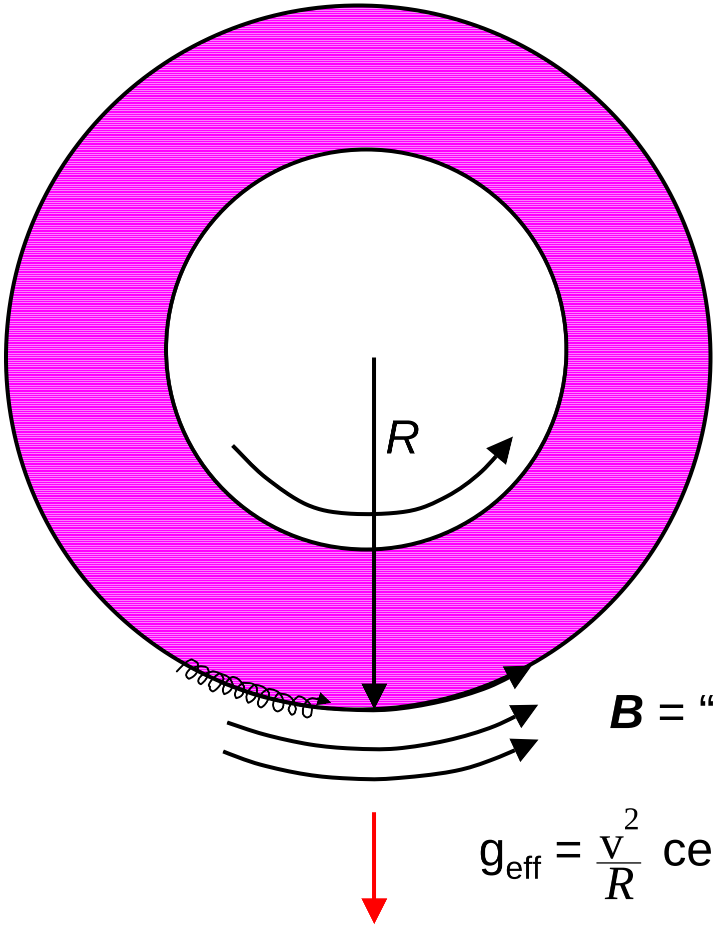
$\rho=\exp(y/L)$



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

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

Top view of toroidal plasma:



plasma = heavy fluid

B = “light fluid”

$g_{eff} = \frac{v^2}{R}$ centrifugal force

Growth rate:

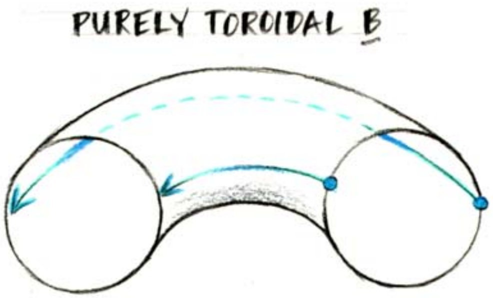
$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{v_t^2}{RL}} = \frac{v_t}{\sqrt{RL}}$$

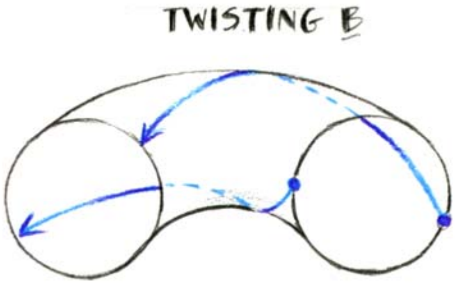
Similar instability mechanism
in MHD & drift/microinstabilities

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

The Secret for Stabilizing Bad-Curvature Instabilities

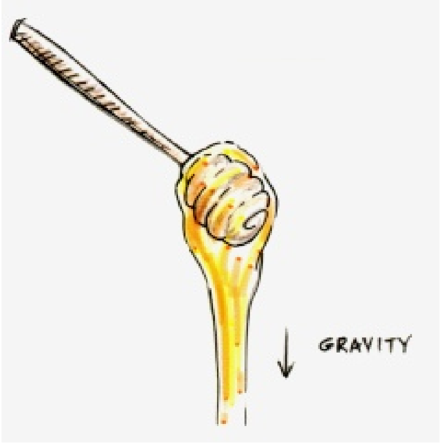
Twist in ***B*** carries plasma from bad curvature region to good curvature region:

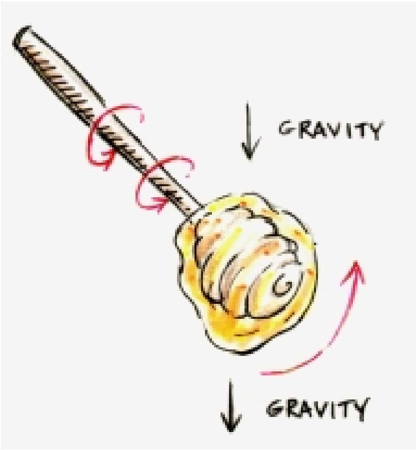




Unstable

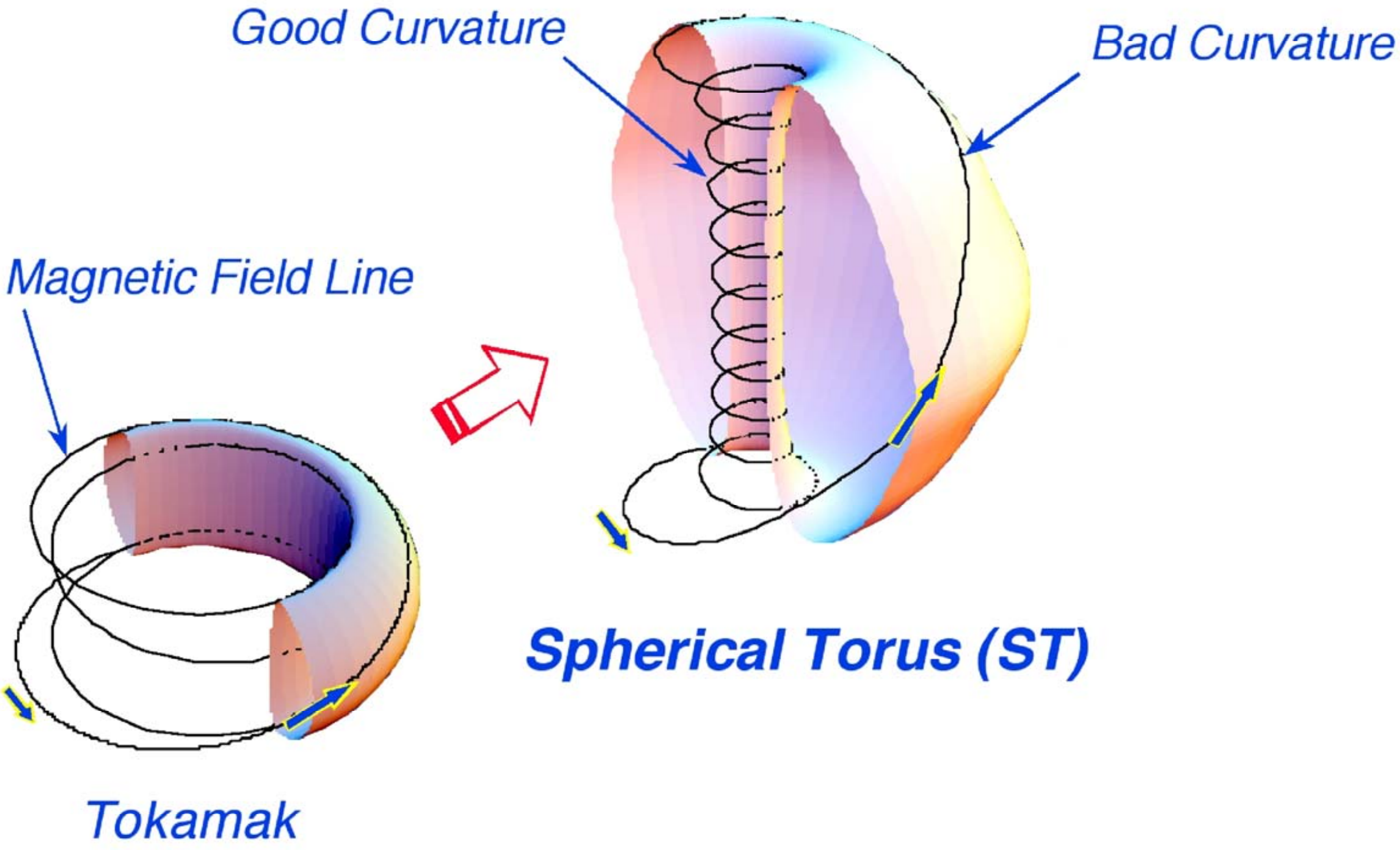
Stable

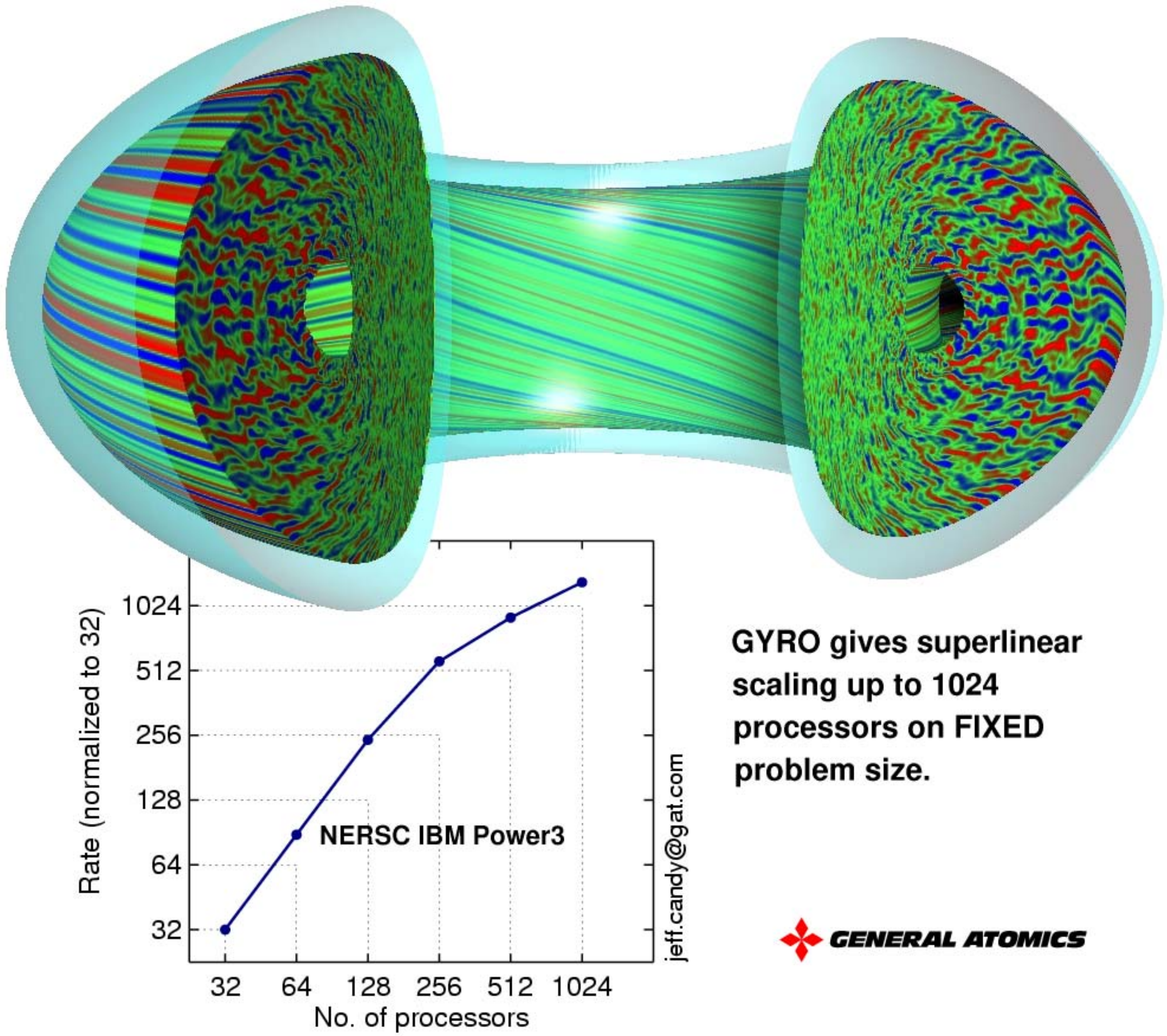




Similar to how twirling a honey dipper can prevent honey from dripping.

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





GYRO gives superlinear scaling up to 1024 processors on FIXED problem size.

GENERAL ATOMICS

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).

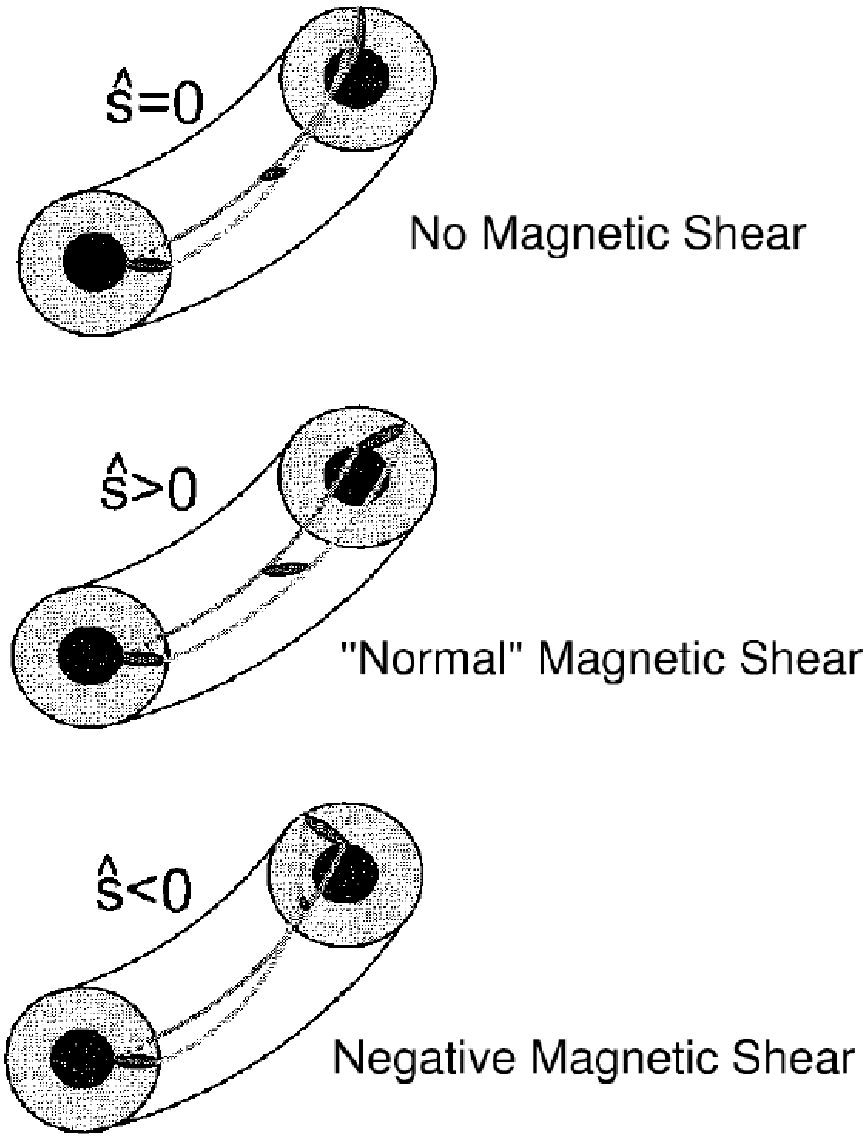
Simple picture of reducing turbulence by negative magnetic shear

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.

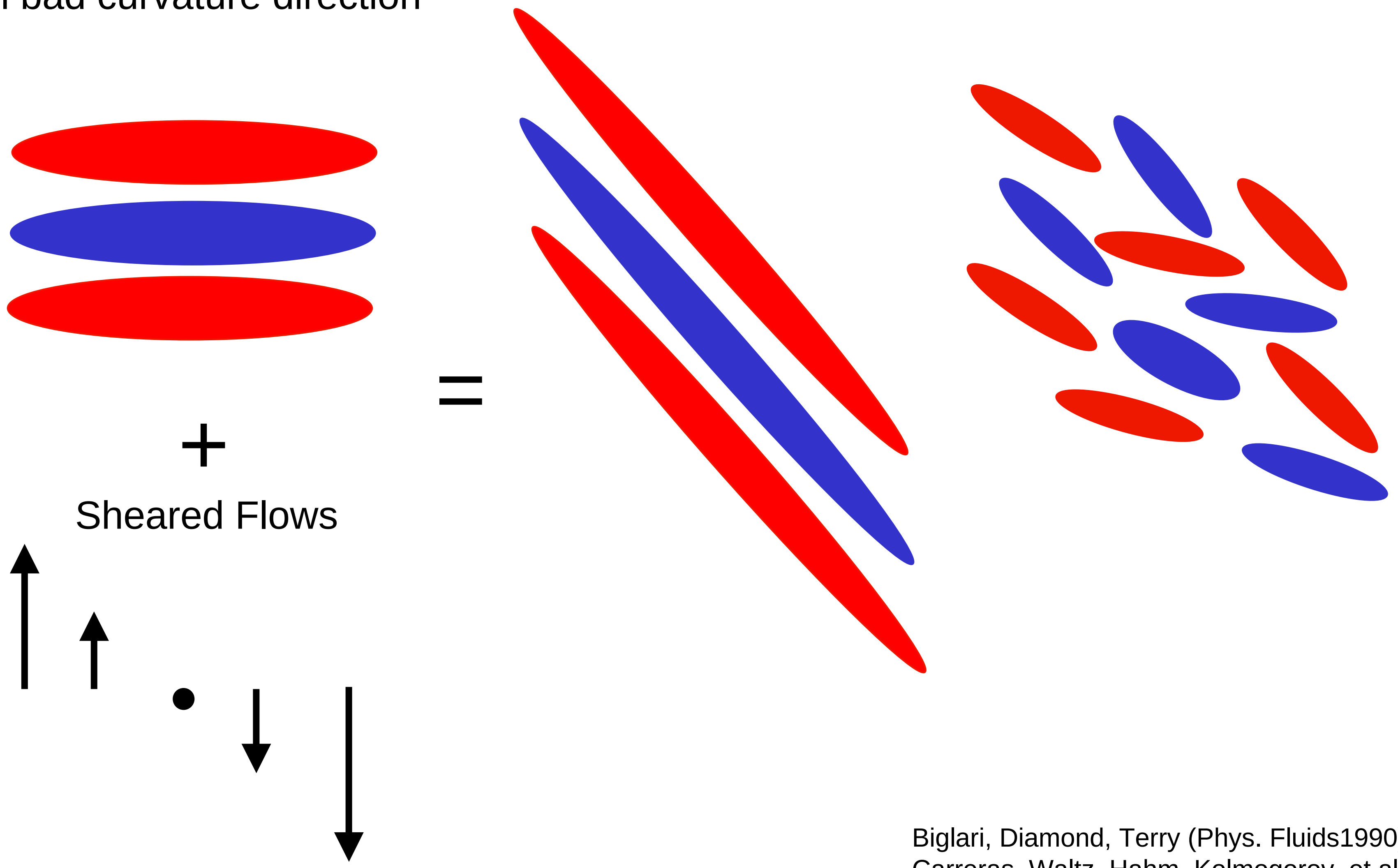
Shaping the plasma (elongation and triangularity) can also change local shear



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

+

Sheared Flows

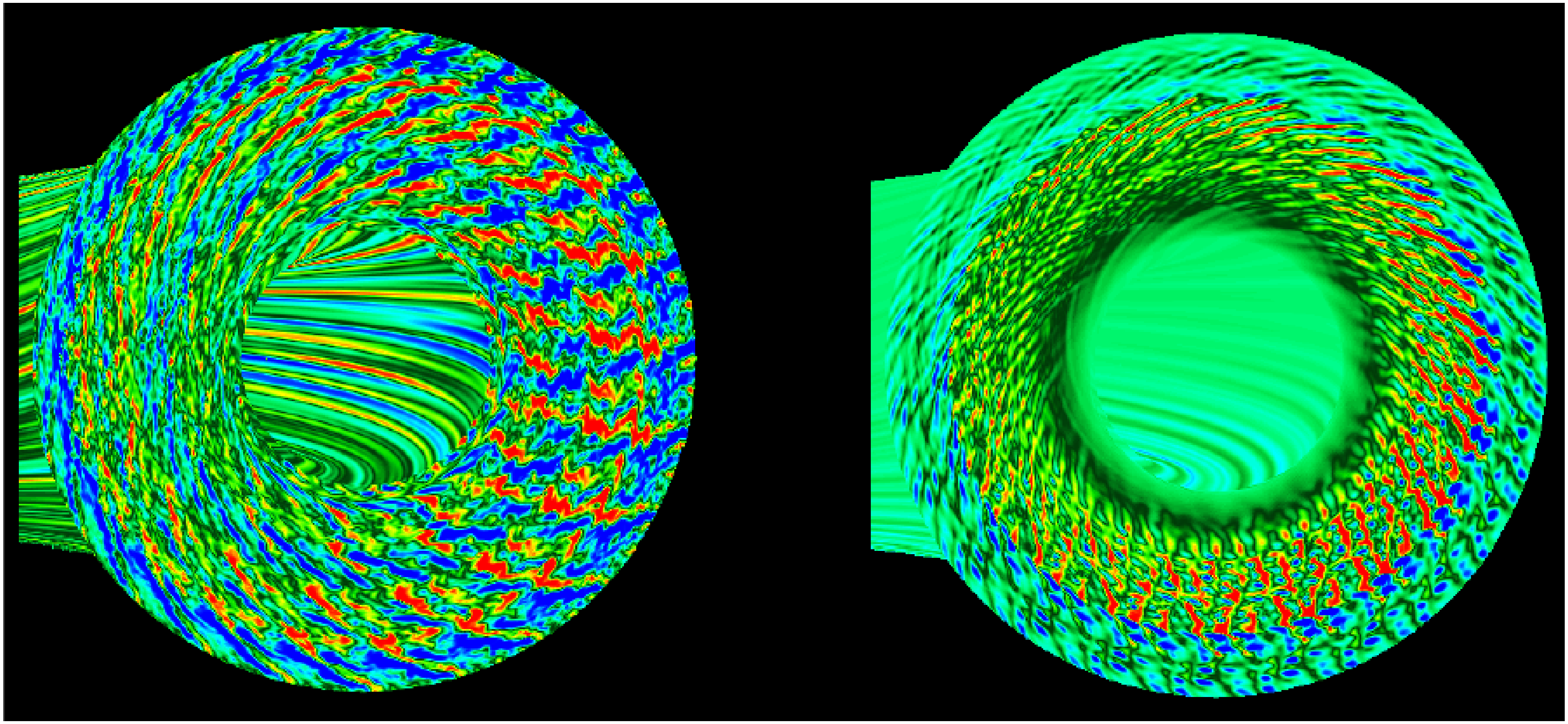
=

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)

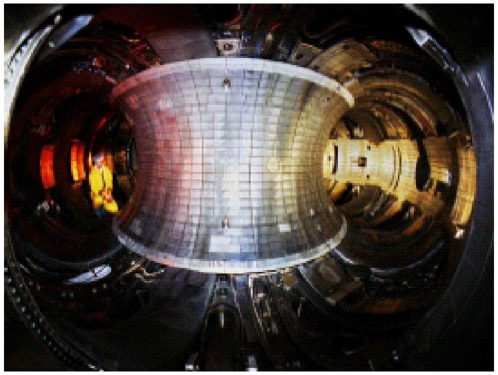


Dominant nonlinear interaction between turbulent eddies and θ-directed zonal flows.

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/HPCC Computational Grand Challenge

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



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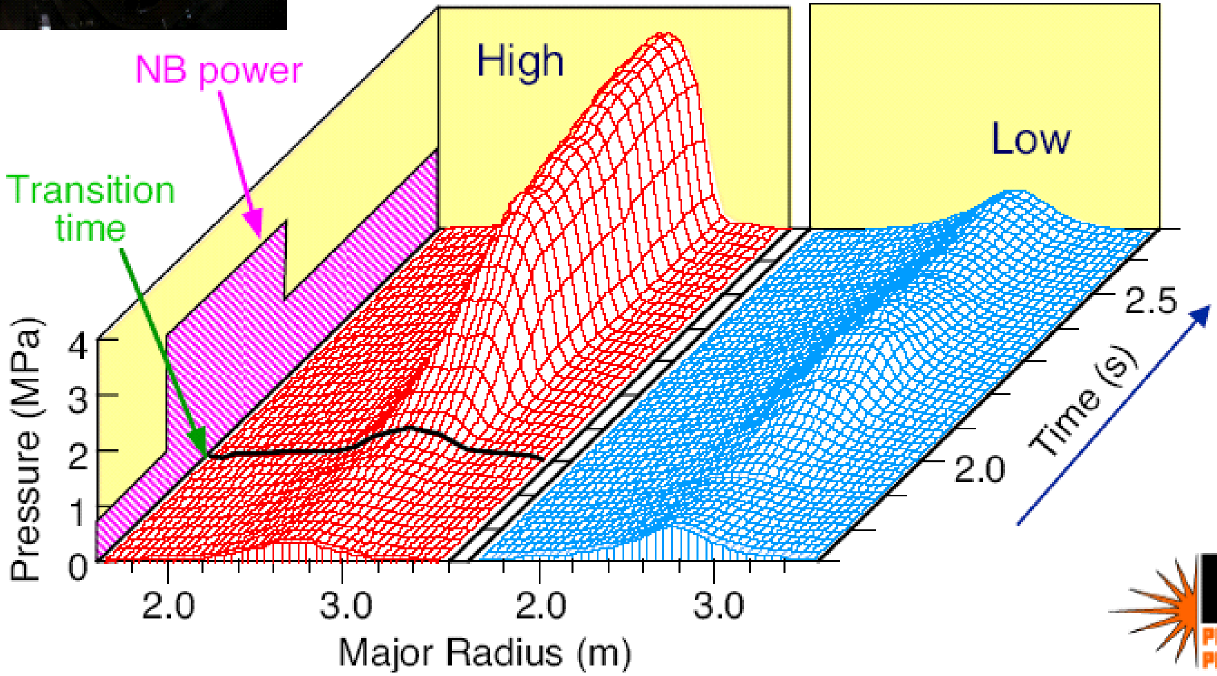

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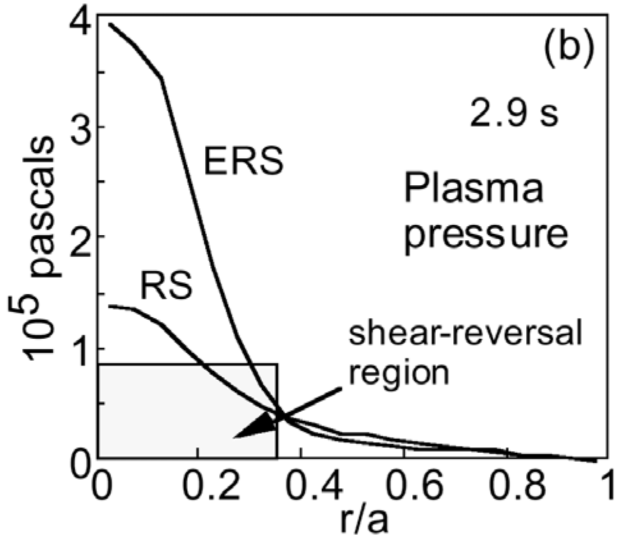
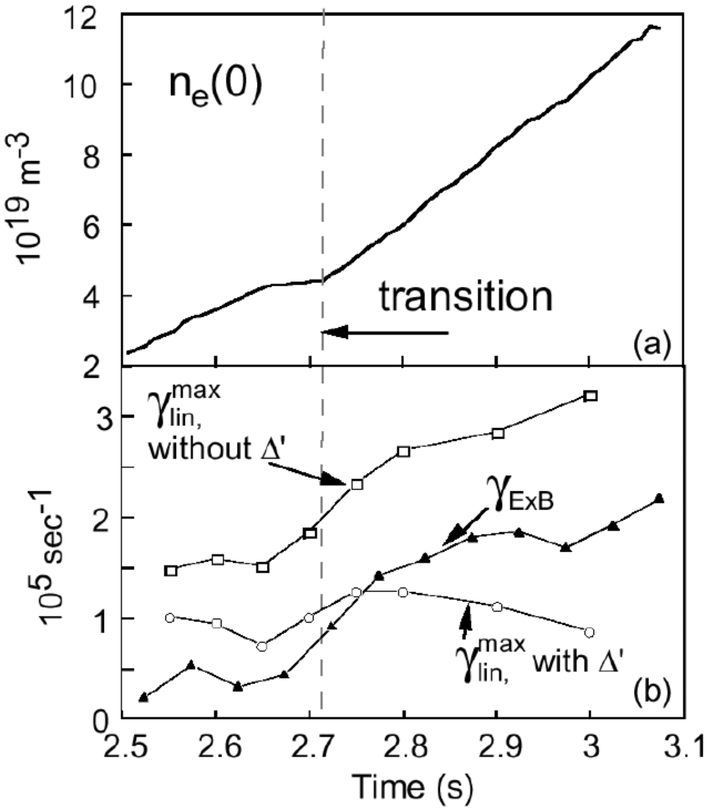
All major tokamaks show turbulence can be suppressed w/ sheared flows & negative magnetic shear / Shafranov shift





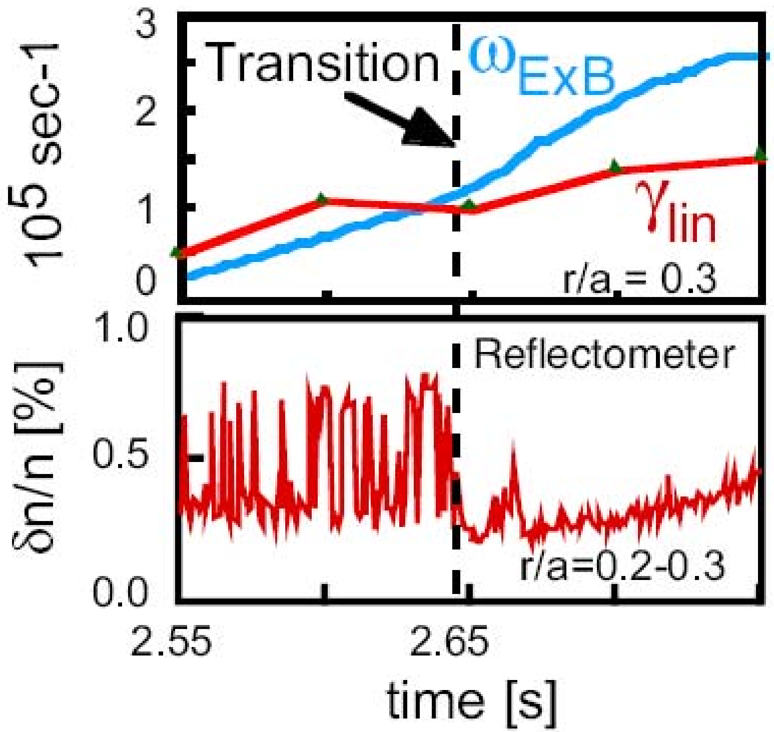
Synakowski, Batha, Beer, et.al. Phys. Plasmas 1997

Internal transport barrier forms when the flow shearing rate dv_θ/dr > ~ 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.

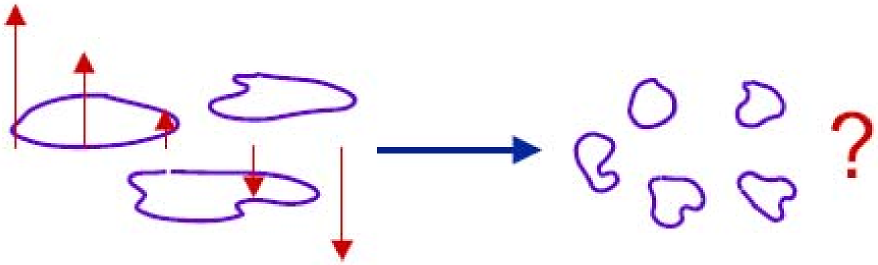
Advanced Tokamak goal: Plasma pressure ~ x 2, $P_{fusion} \propto \text{pressure}^2 \sim \times 4$

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})

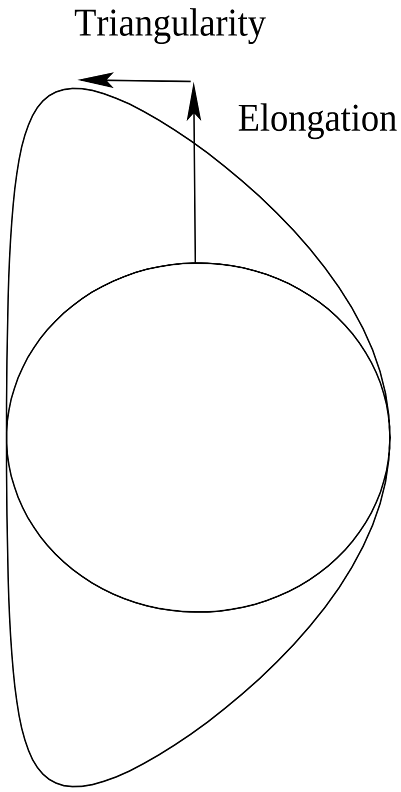
- Outstanding issue:
  Is suppression accompanied by radial decorrelation?

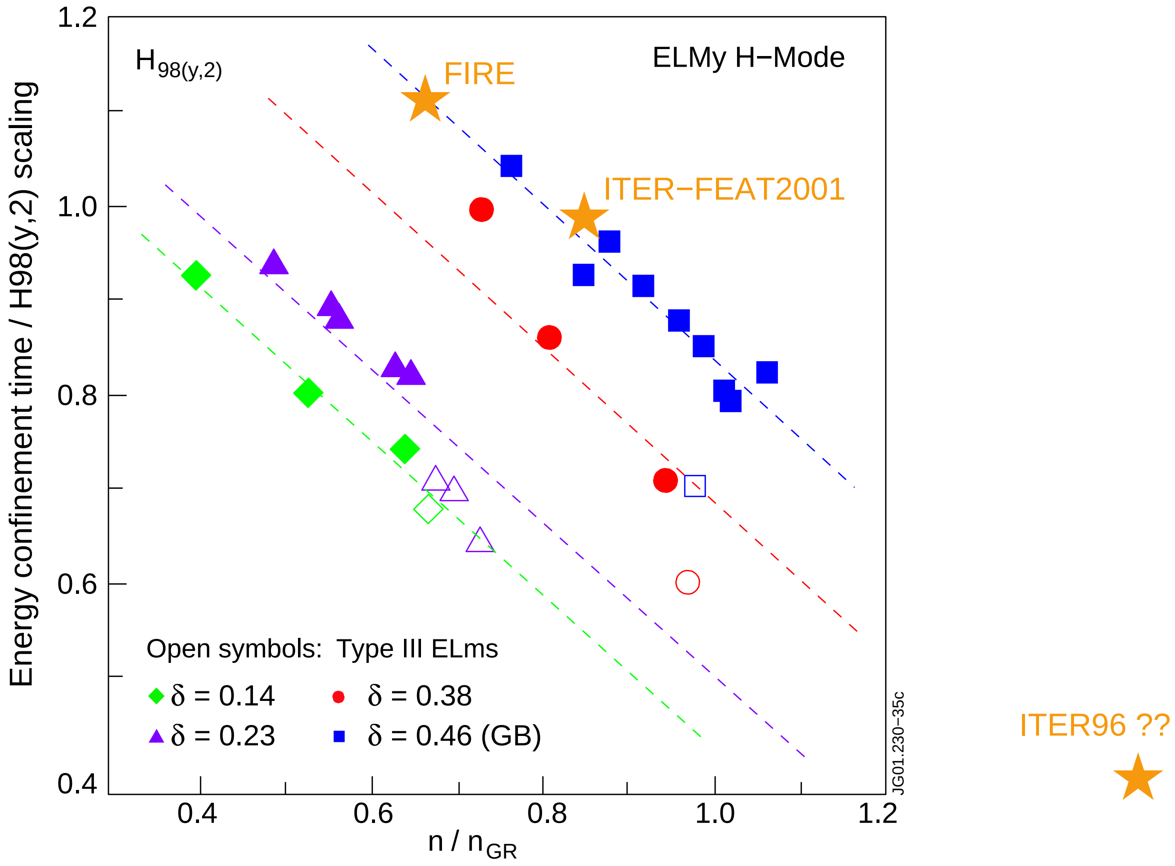


- Similar suppression observed on JET (X-mode reflectometer) and DIII-D (FIR Scattering)

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

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.

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. (Integral equations) 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):

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

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.

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

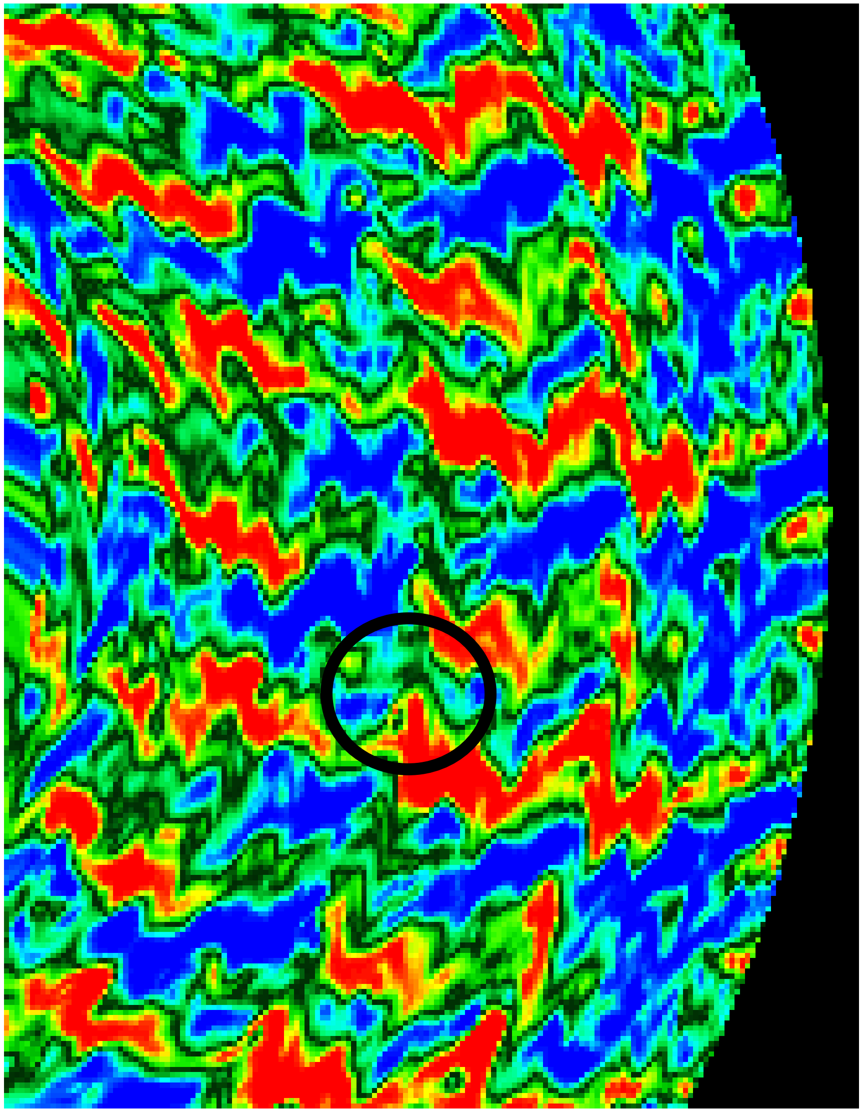
Bessel Functions represent averaging around particle gyro-orbit

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.

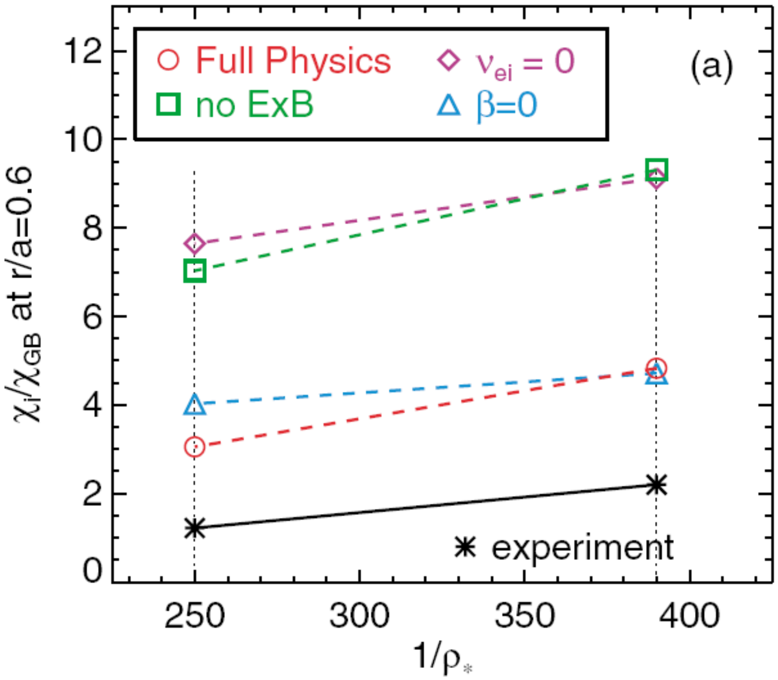
$$\chi = J_0(k_\perp \rho)\Phi$$

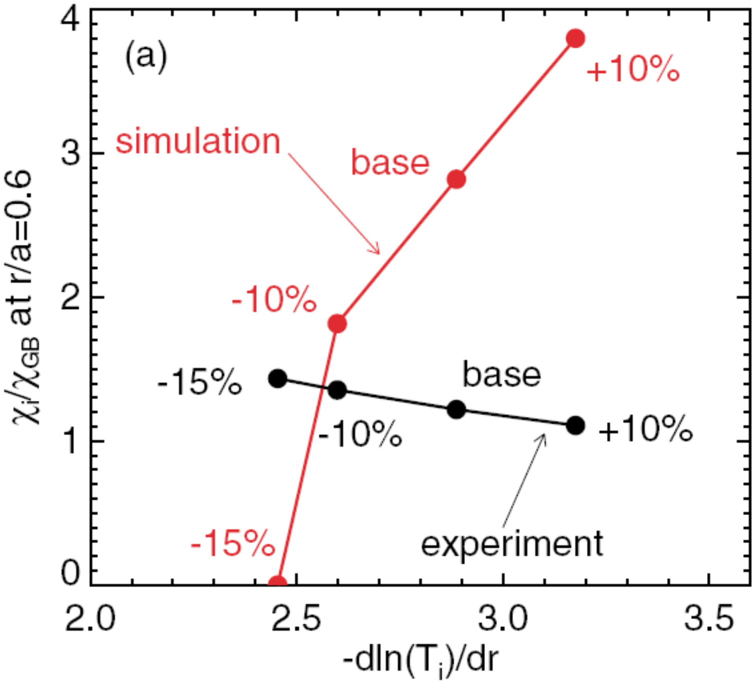
$$\chi(\vec{\mathbf{x}}) = \oint d\theta\ \Phi(\vec{\mathbf{x}} + \vec{\boldsymbol{\rho}}(\theta))$$



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

Summary: Turbulence & Transport in Burning Plasmas

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

- Several good ideas for improvements in fusion reactor designs

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

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

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

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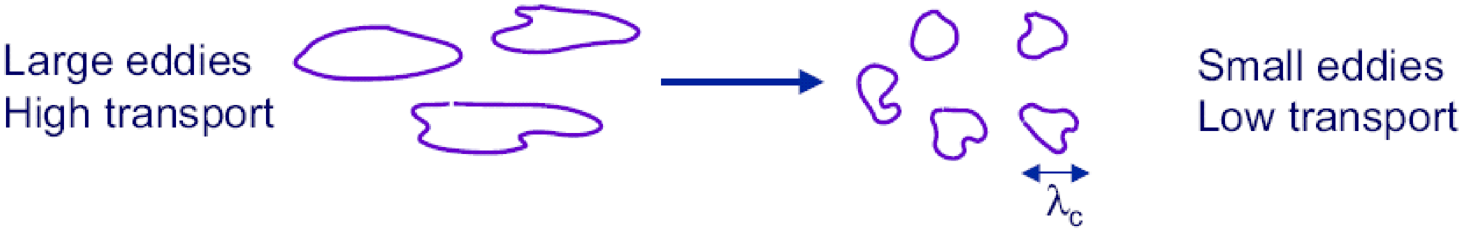
A Major Challenge in Fusion Science is to Measure Turbulent Fluctuations with Good Spatial and Temporal Resolution

- 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?

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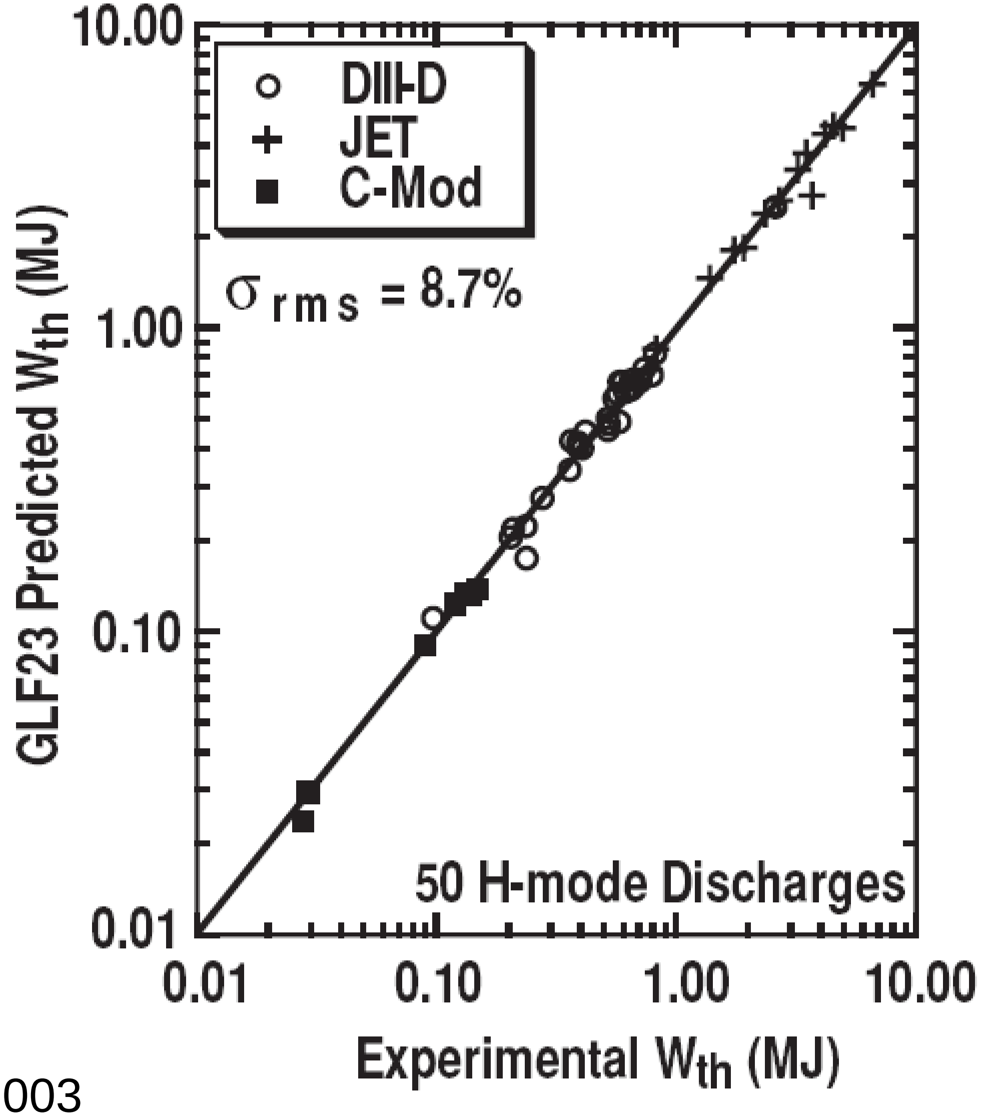
Recent advances in computer simulations

- 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

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