Advances in Understanding Turbulence & Confinement in Fusion Energy Research

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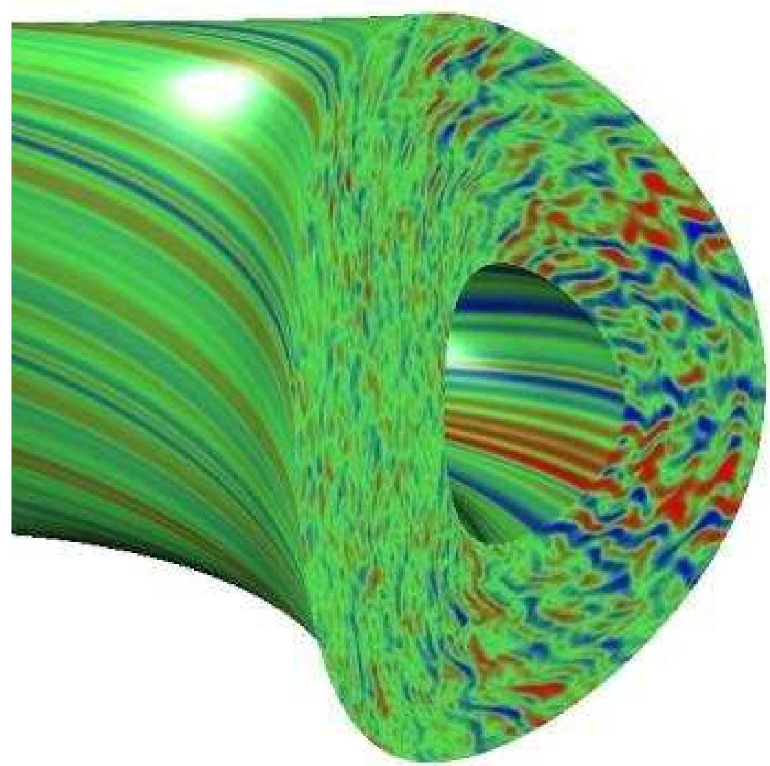
M. Beer, E. Synakowski, J. Ongena, JET

Jeff Candy, Ron Waltz, Bill Nevins
& Plasma Microturbulence Project
http://fusion.gat.com/theory/pmp
a DOE Scientific Discovery Through
Advanced Computing Project
(LLNL, Univ. Maryland, PPPL, General Atomics,
Univ. Colorado, UCLA, U. Texas)



APS April, 2003 Philadelphia

(Sim. by Candy, Waltz, PMP)

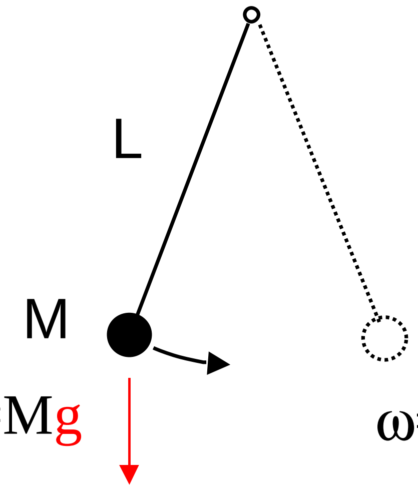
Summary
Advances in Understanding Turbulence & Confinement in Fusion Energy Research

I. Simple physical pictures of tokamak plasma turbulence and how to reduce it.

II. Comprehensive computer simulations being developed to understand and optimize performance.

III. Improvements in fusion reactor designs

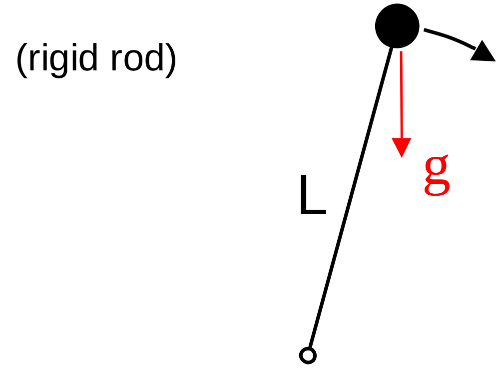
Stable Pendulum



F=Mg

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

Unstable Inverted Pendulum

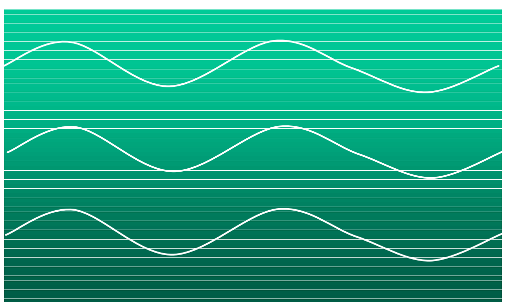


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

Instability

Density-stratified Fluid

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

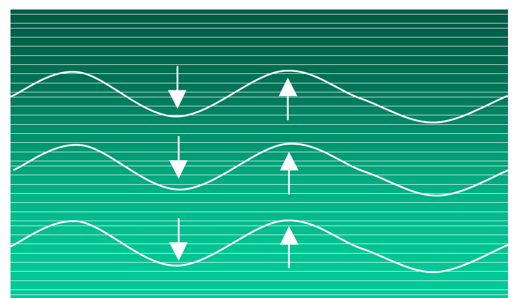


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

⇒Rayleigh-Taylor Instability

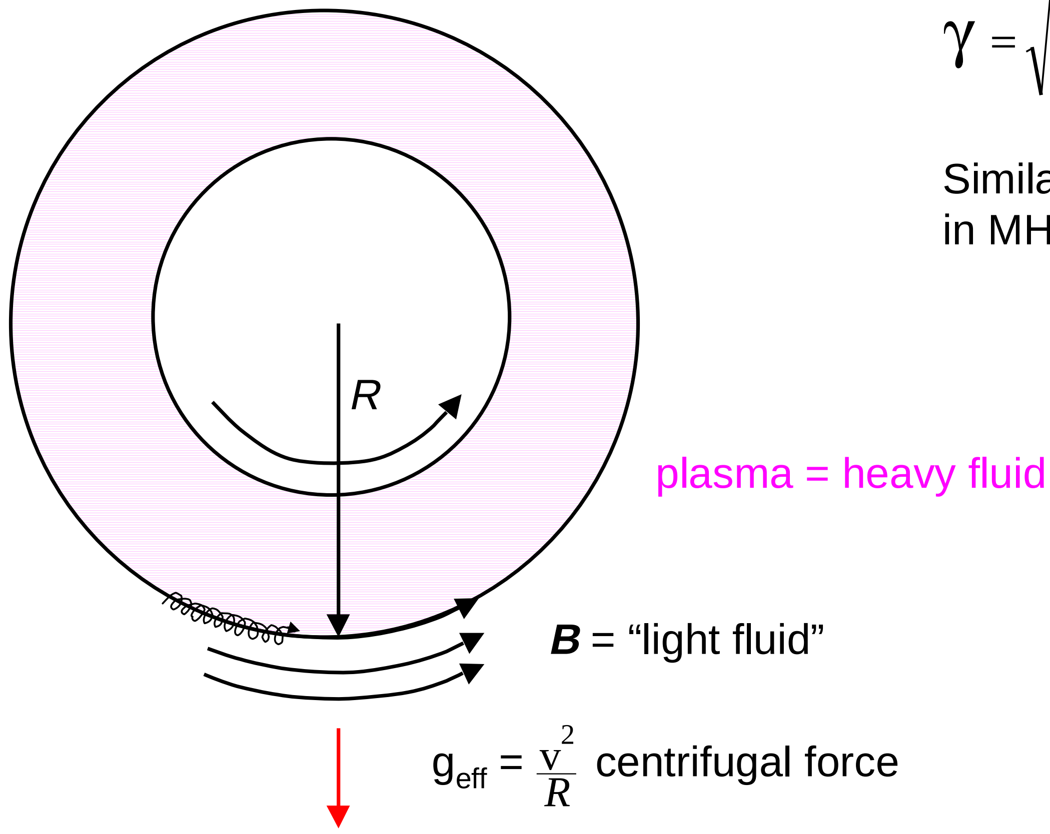
$\rho=\exp(y/L)$



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

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

Top view of toroidal plasma:



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

Growth rate:

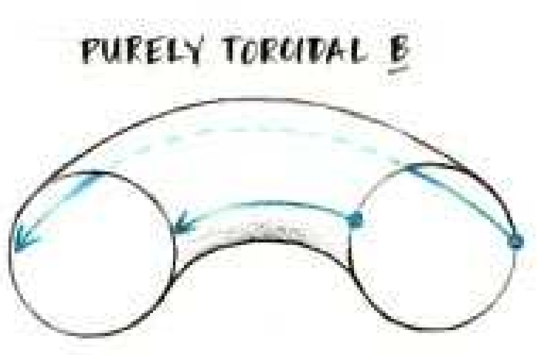
$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{v_t^2}{RL}} = \frac{v_t}{\sqrt{RL}}$$

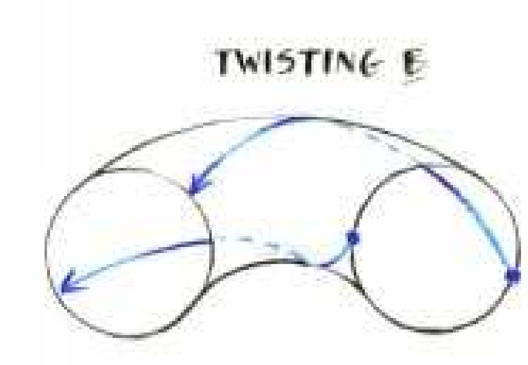
Similar instability mechanism
in MHD & drift/microinstabilities

1/L = ∇p/p in MHD,
∝ combination of ∇n & ∇T
in microinstabilities.

The Secret for Stabilizing Bad-Curvature Instabilities

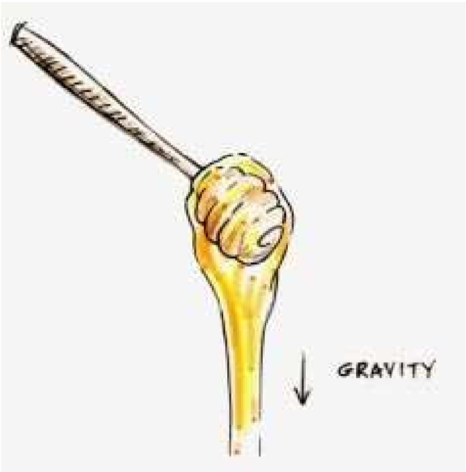
Twist in ***B*** carries plasma from bad curvature region to good curvature region:

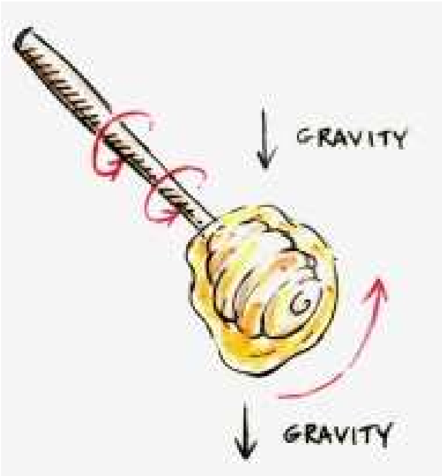




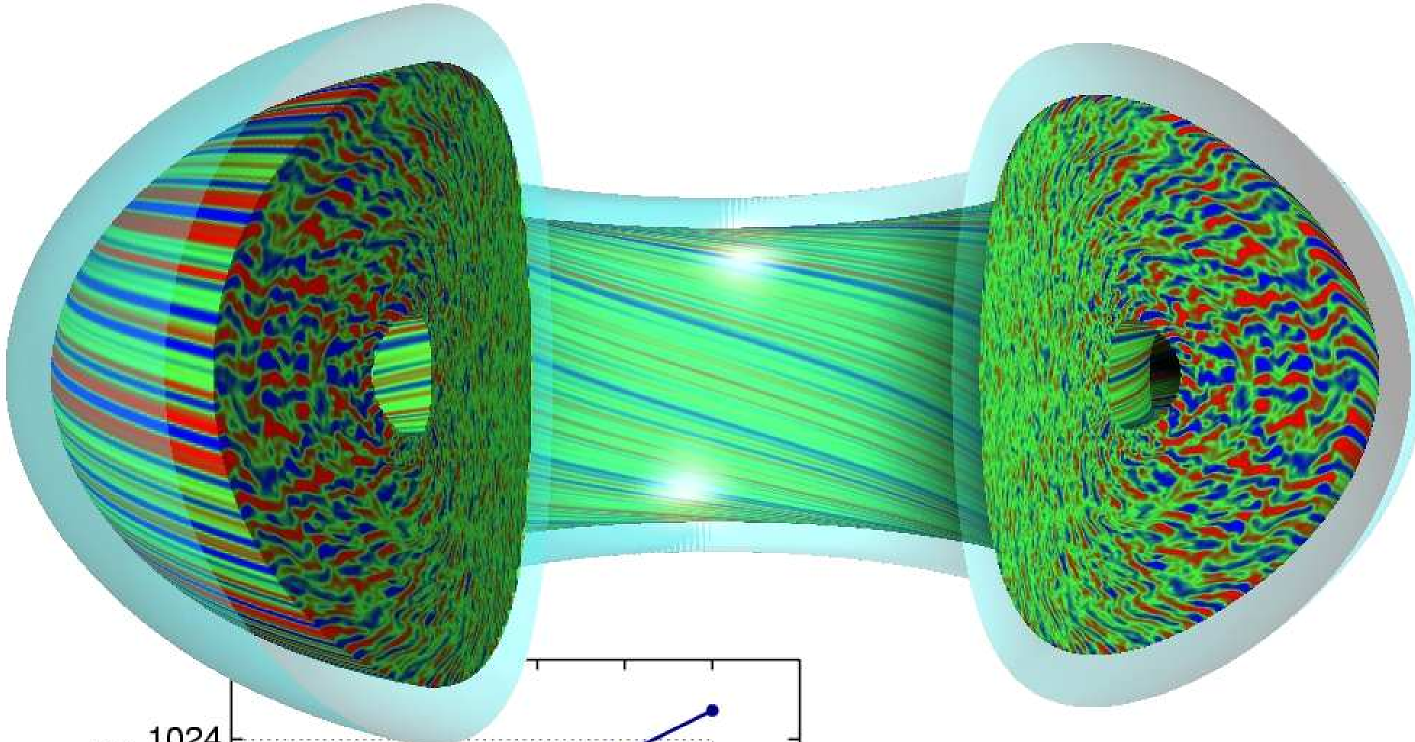
Unstable

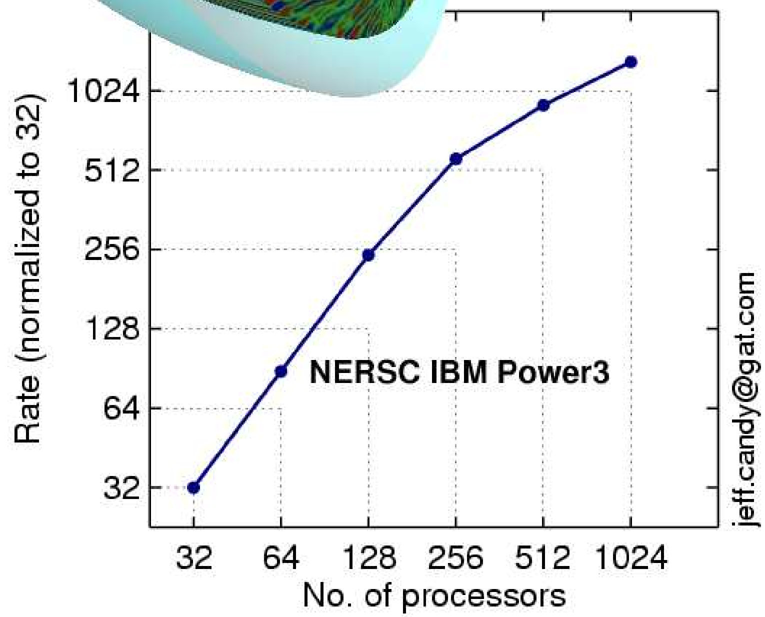
Stable





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





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

GENERAL ATOMICS

Candy and Waltz, JCP 2003, subm. to PRL.

Comprehensive computer simulations being developed.
Plasma Microturbulence Project movies & viz. at http://fusion.gat.com/theory/pmp

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

Challenges:

(1) Finish using to understand core turbulence, detailed experimental comparisons and benchmarking

(2) 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).

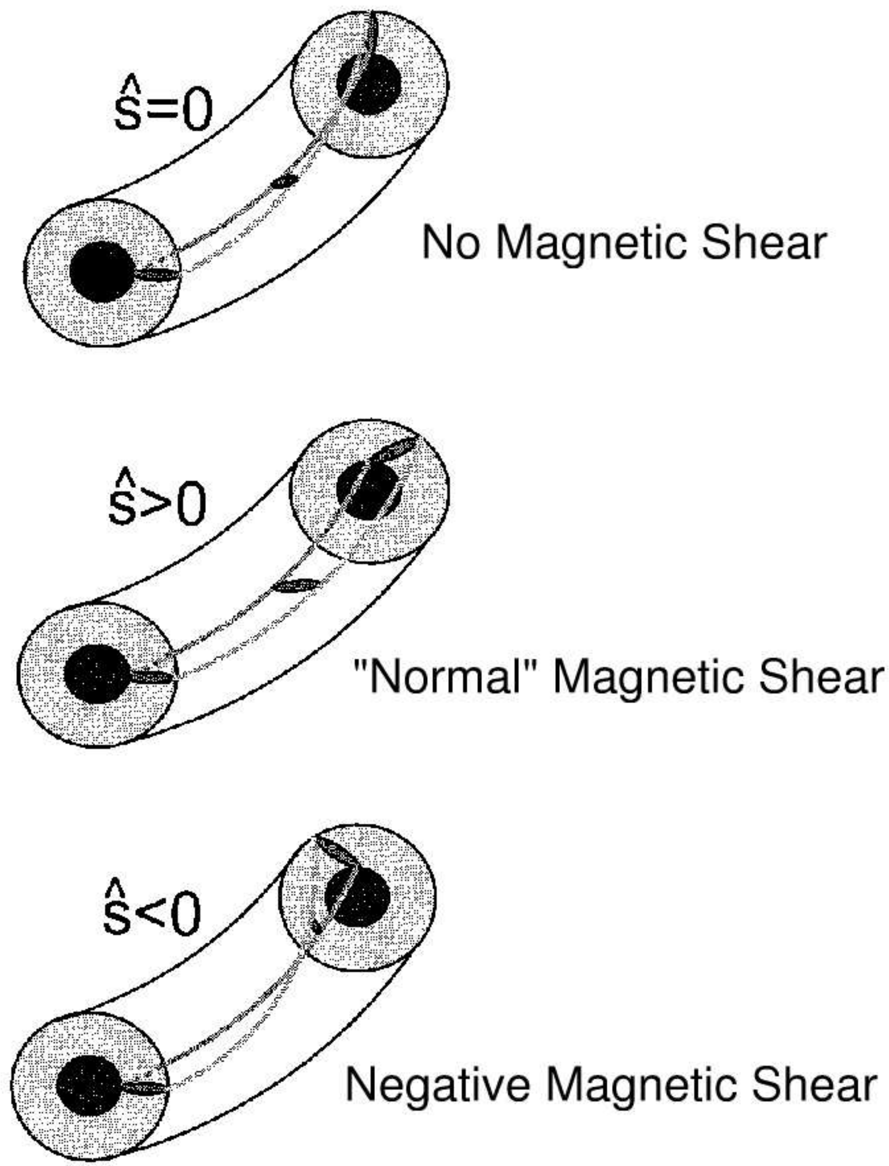
(3) Use to optimize fusion reactor designs.

Simple picture of reducing turbulence by negative magnetic shear

Particles that produce an eddy tend to follow field lines.

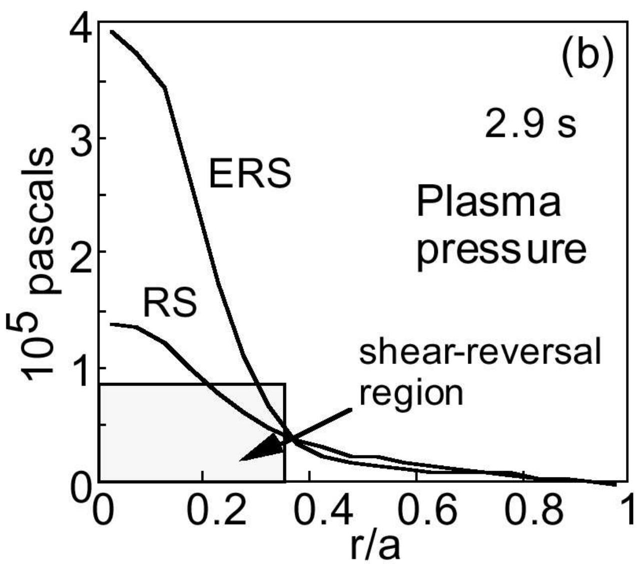
Reversed magnetic shear twists eddy in a short distance to point in the "good curvature direction".

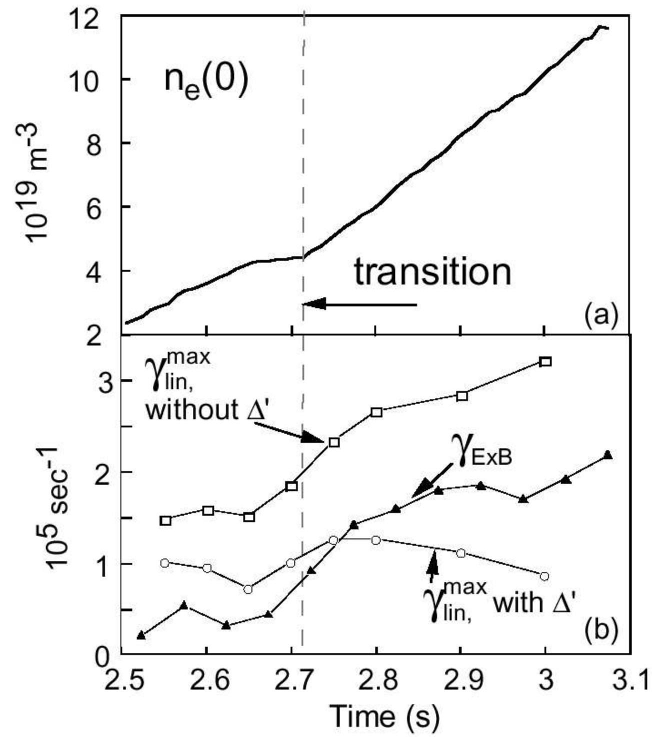
Locally reversed magnetic shear naturally produced by shaping the plasma (elongation and triangularity) and squeezing magnetic fields at high plasma pressure: "Second stability" Advanced Tokamak or Spherical Torus.



Antonsen, Drake, et al. Phys. Plasmas 96

All major tokamaks have shown turbulence can be suppressed with sheared flows and negative magnetic shear / Shafranov shift





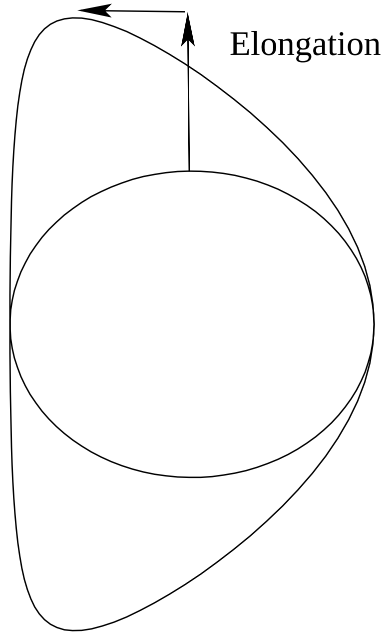
Synakowski, Batha, Beer, et.al. Phys. Plasmas 1997

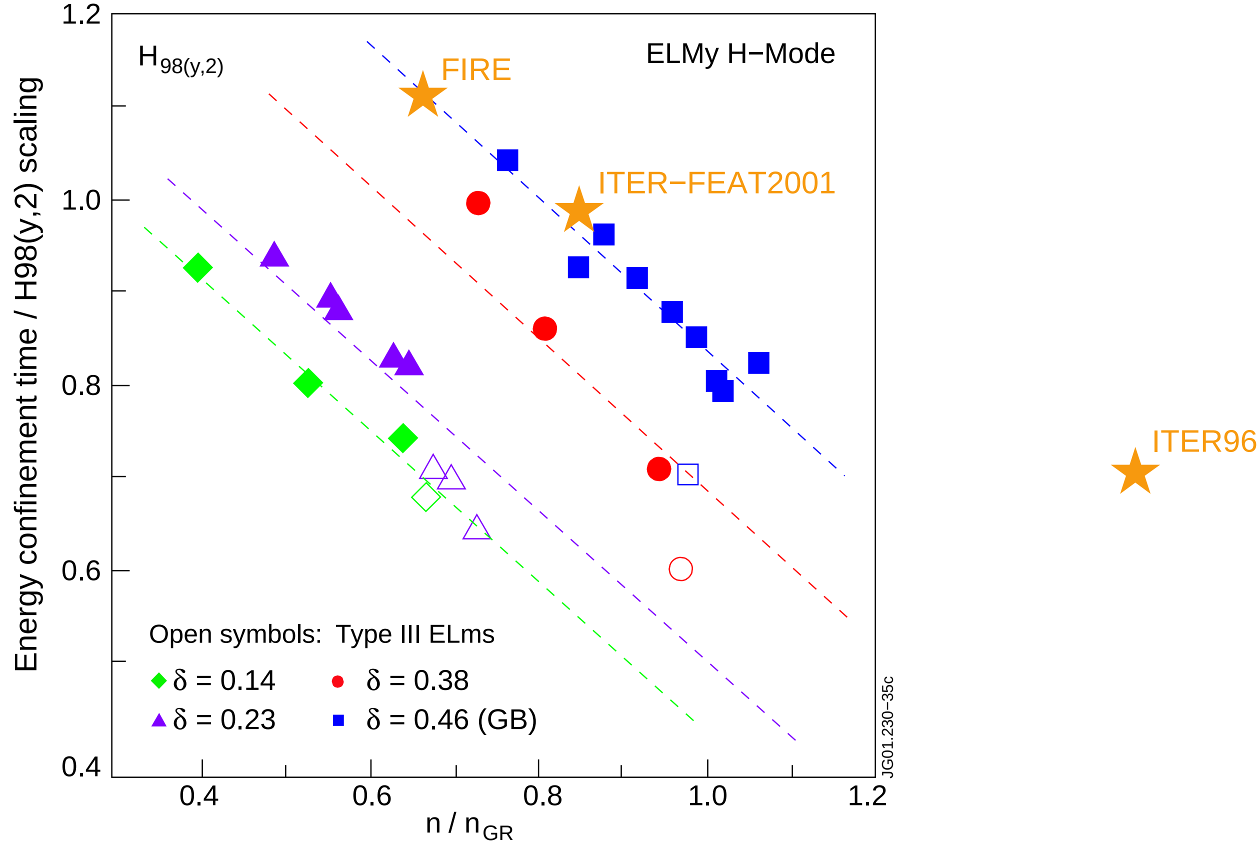
Internal transport barrier forms when the flow shearing rate $\partial v_\theta/\partial r >\sim$ the linear growth rate γ_{lin}^{max} of the instabilities that usually drive the turbulence.

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

Advanced Tokamak Regime: Plasma pressure $>$ doubles, $P_{fusion} \propto (pressure)^2$

Stronger plasma shaping improves performance





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

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

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

Improvements in new fusion designs ↓ uncertainties

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

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

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

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

FIRE pushes to even stronger shaping and reduced size with high magnetic field cryogenic CuBe (achievable with future superconductors?)

	R m	a m	B T	I_p MA	n_{Gr} $10^{20}/m^3$	$\frac{\langle n_e \rangle}{n_{Gr}}$	κ_x	δ_x	P_{fusion} keV	$P_\alpha/(2\pi R)$
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 (a goal)	5.20	1.30	5.86	12.8	2.41	1.00	2.18	0.84	1760	9.0

Caveats: There are still some remaining uncertainties regarding confinement, edge pedestal scaling, ELMs, disruptions, & heat loads, tritium retention, neoclassical beta limits, but also reasonable possibilities for dealing with potential problems or further improving performance.

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