Current Status of Fusion Energy Research & Related Plasma Turbulence Studies

Greg Hammett, Princeton Plasma Physics Lab (PPPL)
http://w3.pppl.gov/~hammett
http://online.kitp.ucsb.edu/online/jet+disk05/hammett/

Kavli Institute For Theoretical Physics, May 19, 2005

Acknowledgments:

Center for Multiscale Plasma Dynamics

& Plasma Microturbulence Project

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

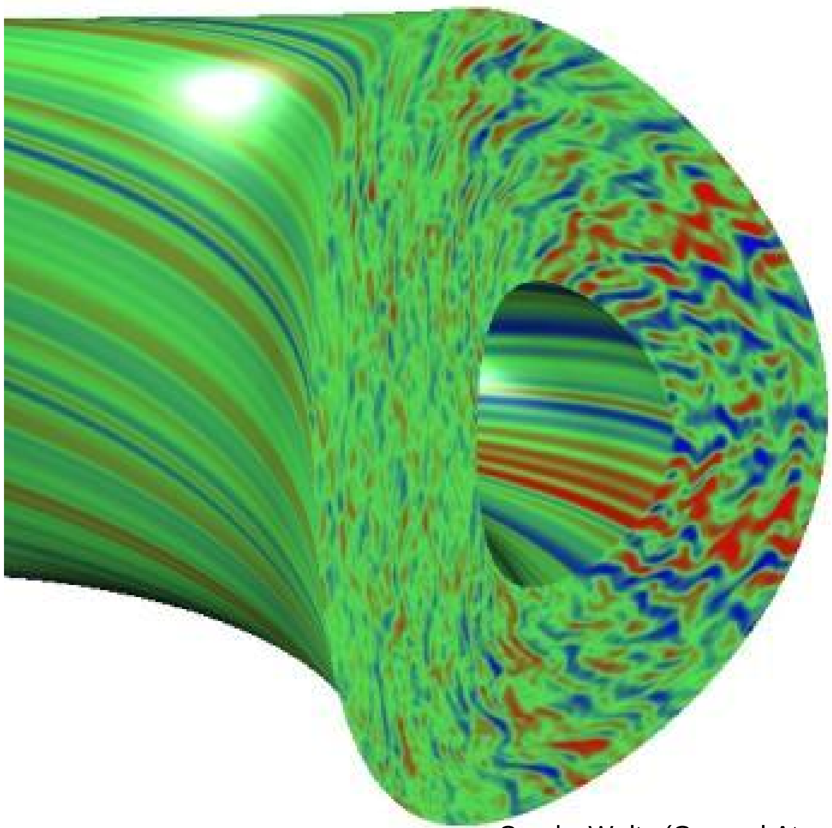
DOE Scientific Discovery Through
Advanced Computing

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

J. Candy, R. Waltz (General Atomics)

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

R. Goldston, 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 …

Current Status of Fusion Energy Research & Related Plasma Turbulence Studies

- Why Fusion?
  - Progress in fusion research
  - Global warming issues, projections of need for CO2-free energy
- Simple physical pictures of tokamak plasma turbulence & how to reduce it (reversed magnetic shear, sheared flows, plasma shaping…)
- Present design for ITER (proposed international fusion burning plasma experiment) much better than in 1996
- Remaining uncertainties: quantitative scaling of turbulent losses to larger sizes, turbulence suppression mechanisms, edge boundary layer, power loads to material wall?

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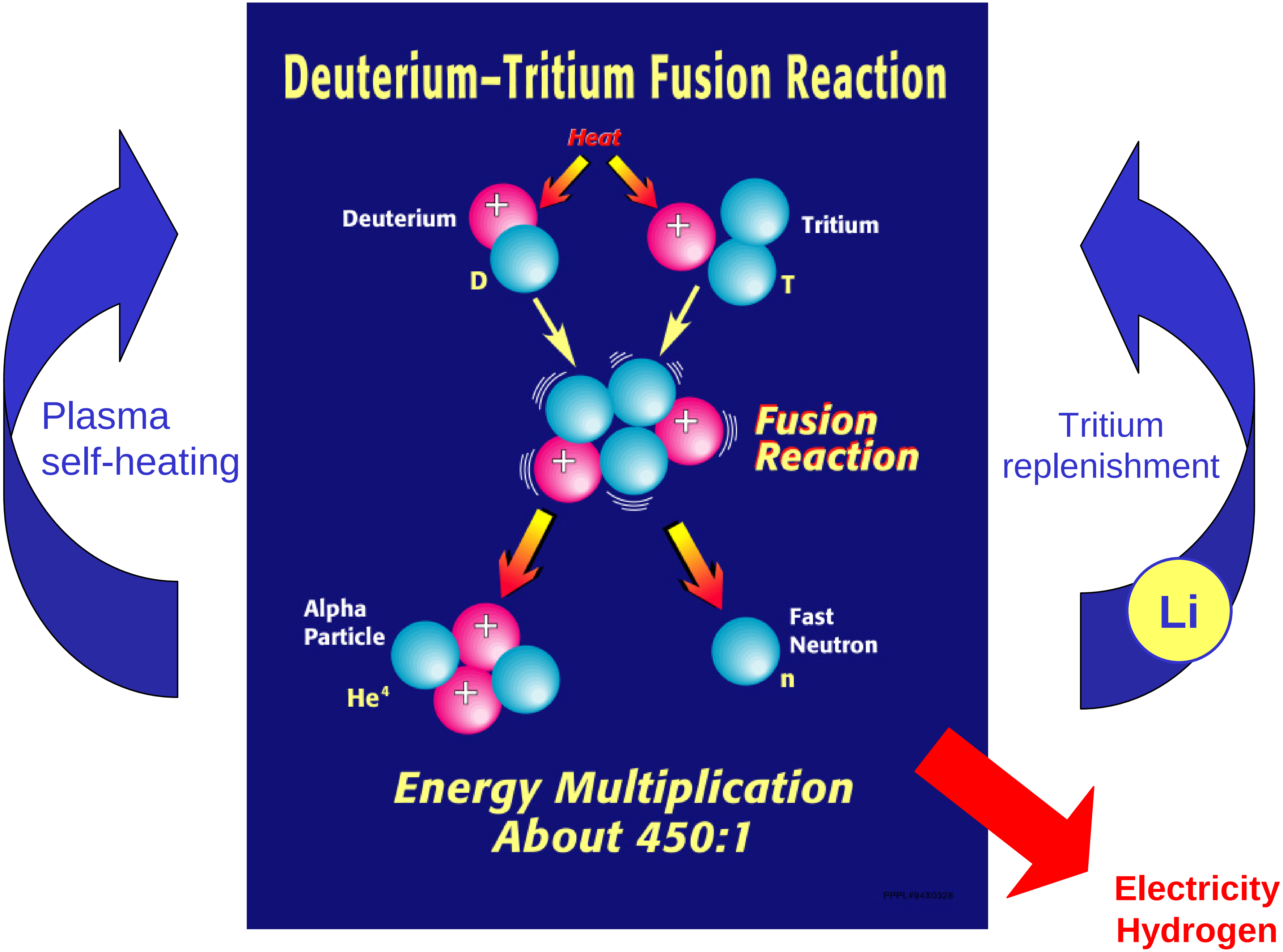
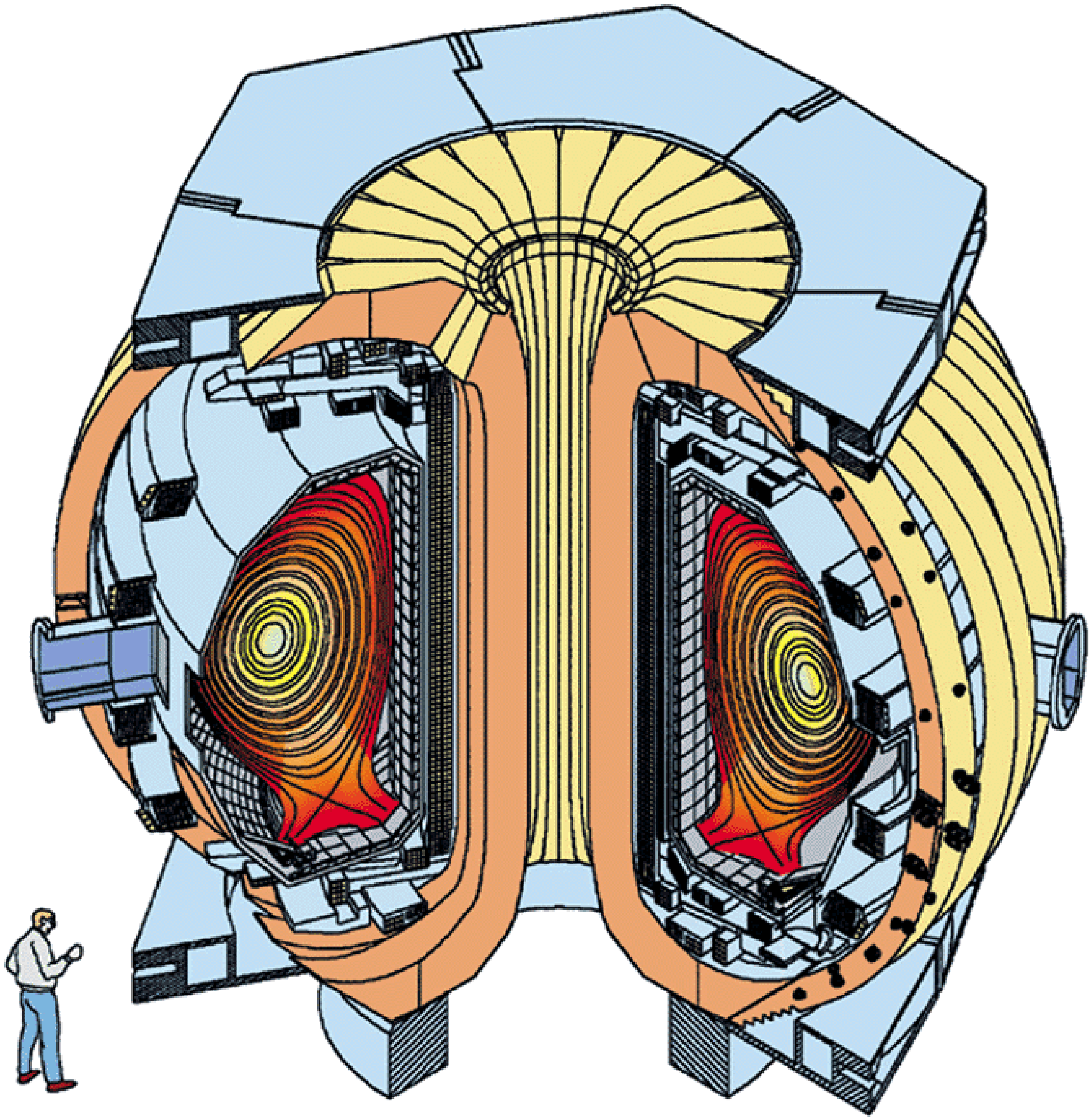

Deuterium–Tritium Fusion Reaction
Heat
Deuterium
D
Tritium
T
Fusion Reaction
Alpha Particle
He4
Fast Neutron
n
Energy Multiplication
About 450:1
Plasma self-heating
Tritium replenishment
Li
Electricity
Hydrogen

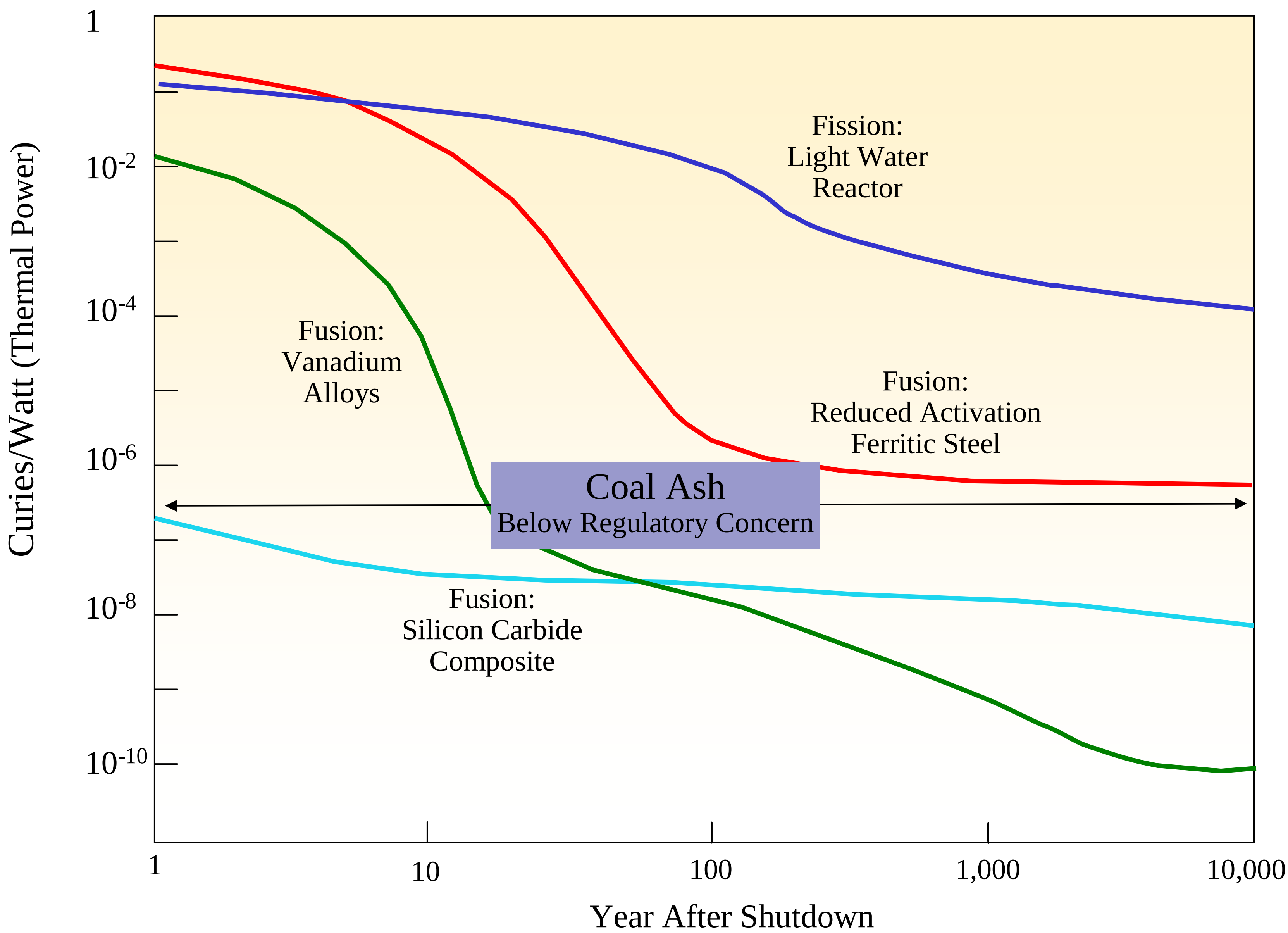
Cut-away view of aTokamak



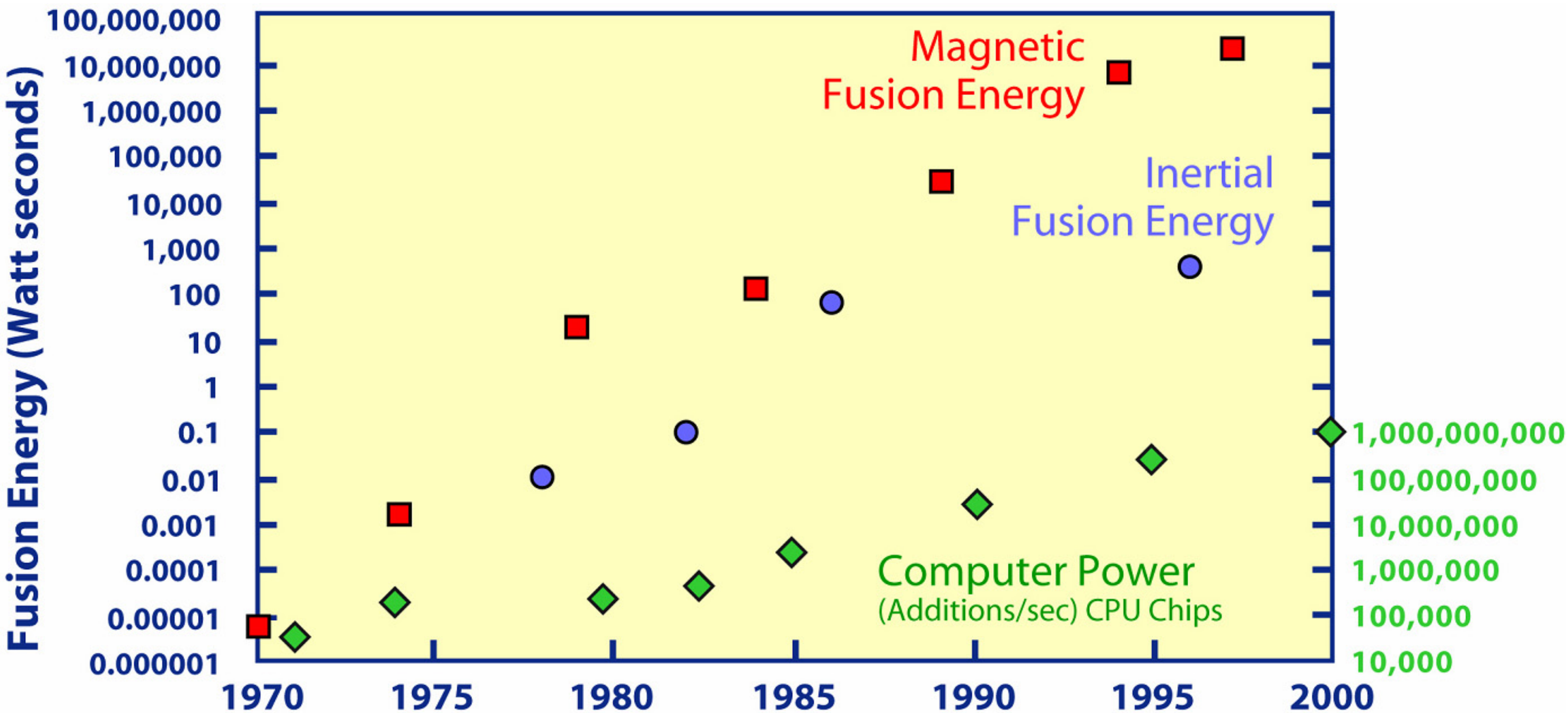
Fusion can be an Attractive Domestic Energy Source

- Abundant fuel, available to all nations
  - Deuterium and lithium easily available for thousands of years
- Environmental advantages
  - No carbon emissions, short-lived radioactivity
- Can't blow up, resistant to terrorist attack
  - Less than a minute's worth of fuel in the chamber
- Low risk of nuclear materials proliferation
  - No fissile or fertile materials required
- Compact relative to solar, wind and biomass
  - Modest land usage
- Not subject to daily, seasonal or regional weather variation, no requirement for local CO_2 sequestration.
  - Not limited in its contribution by need for large-scale energy storage or extreme-distance transmission
- Cost of power estimated similar to coal, fission
- Can produce electricity and hydrogen
  - Complements other nearer-term energy sources

Comparison of Fission and Fusion Radioactivity After Shutdown

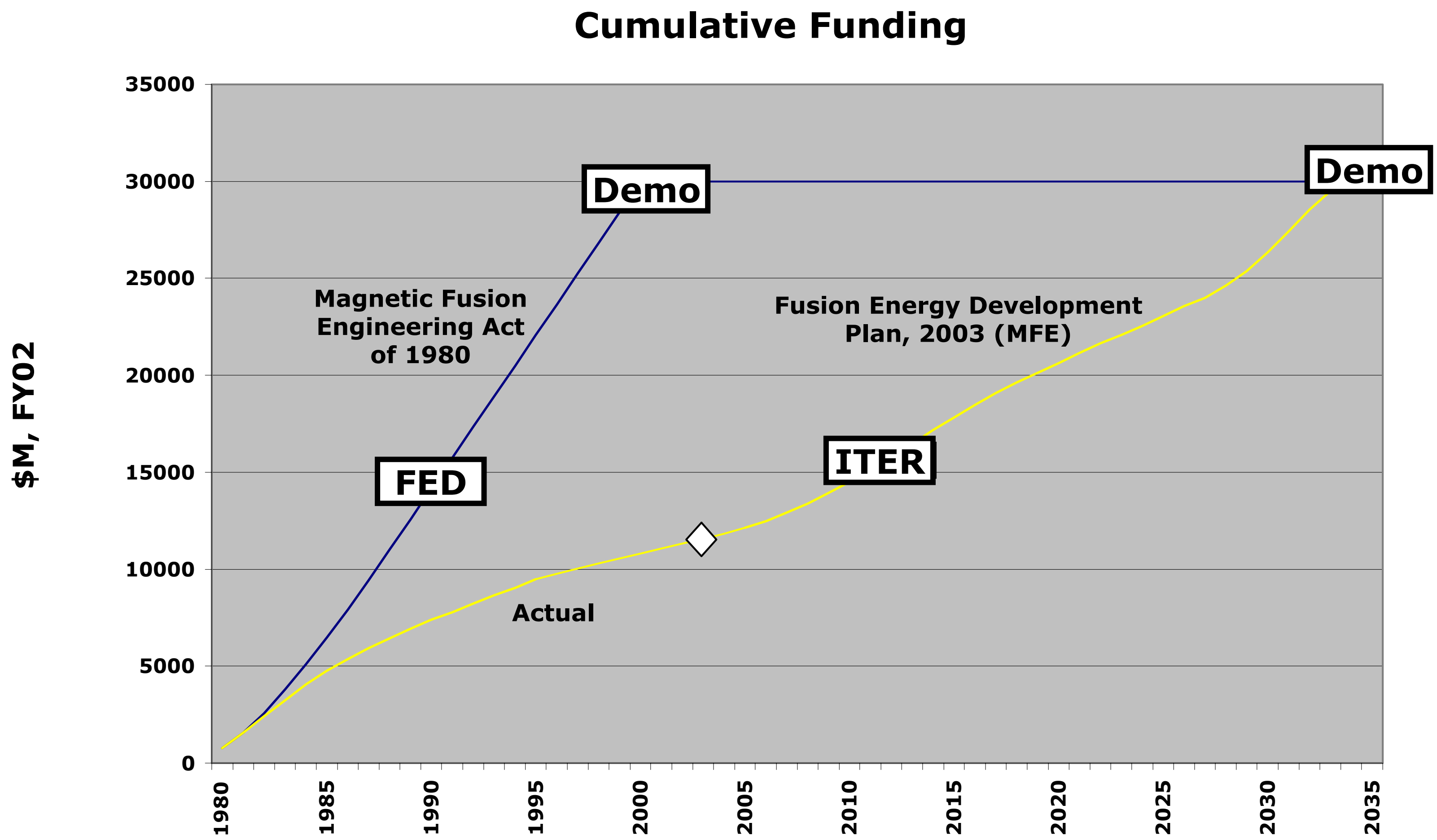


Progress in Fusion Energy has Outpaced Computer Speed



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

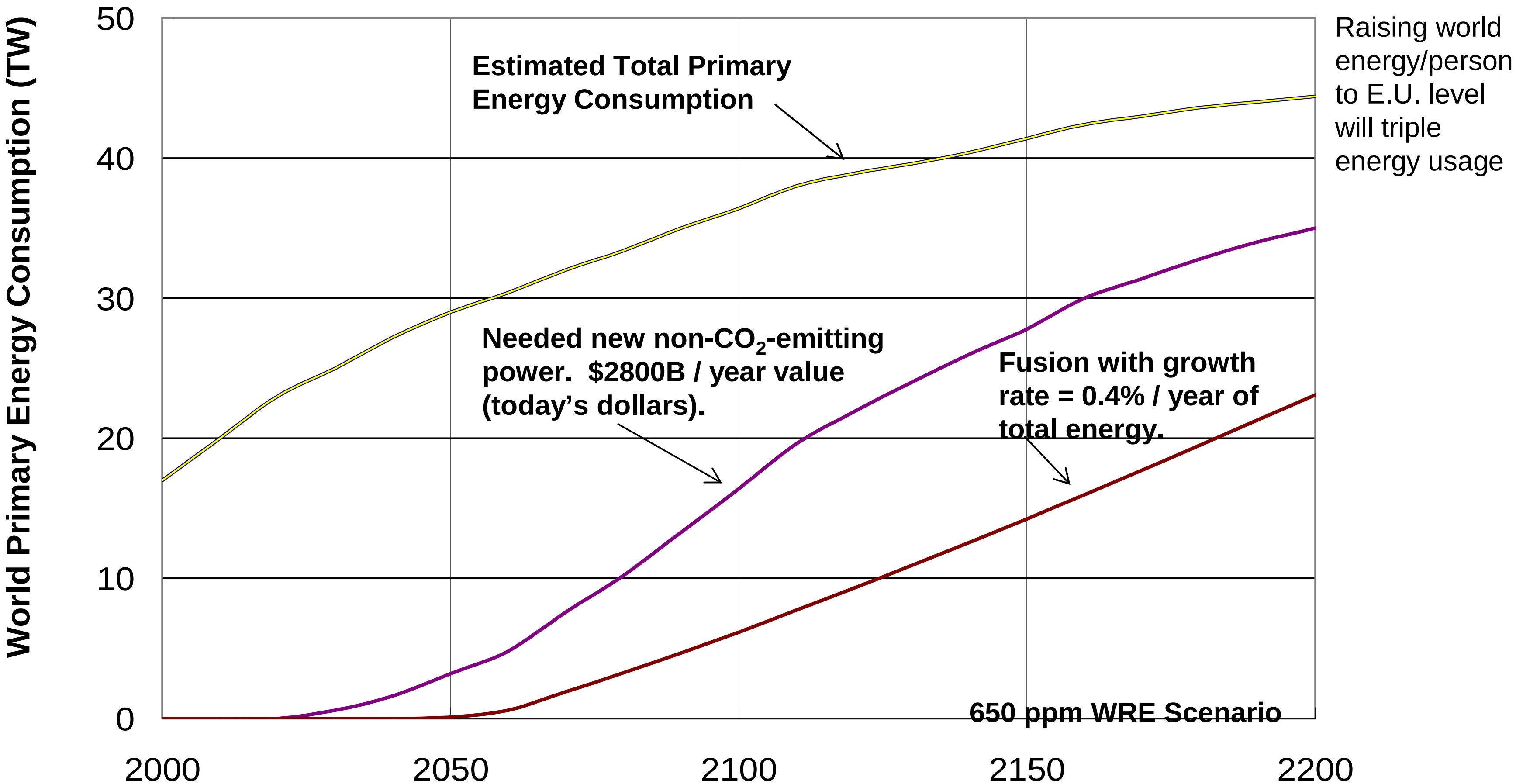


On budget,
if not on time.

$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.

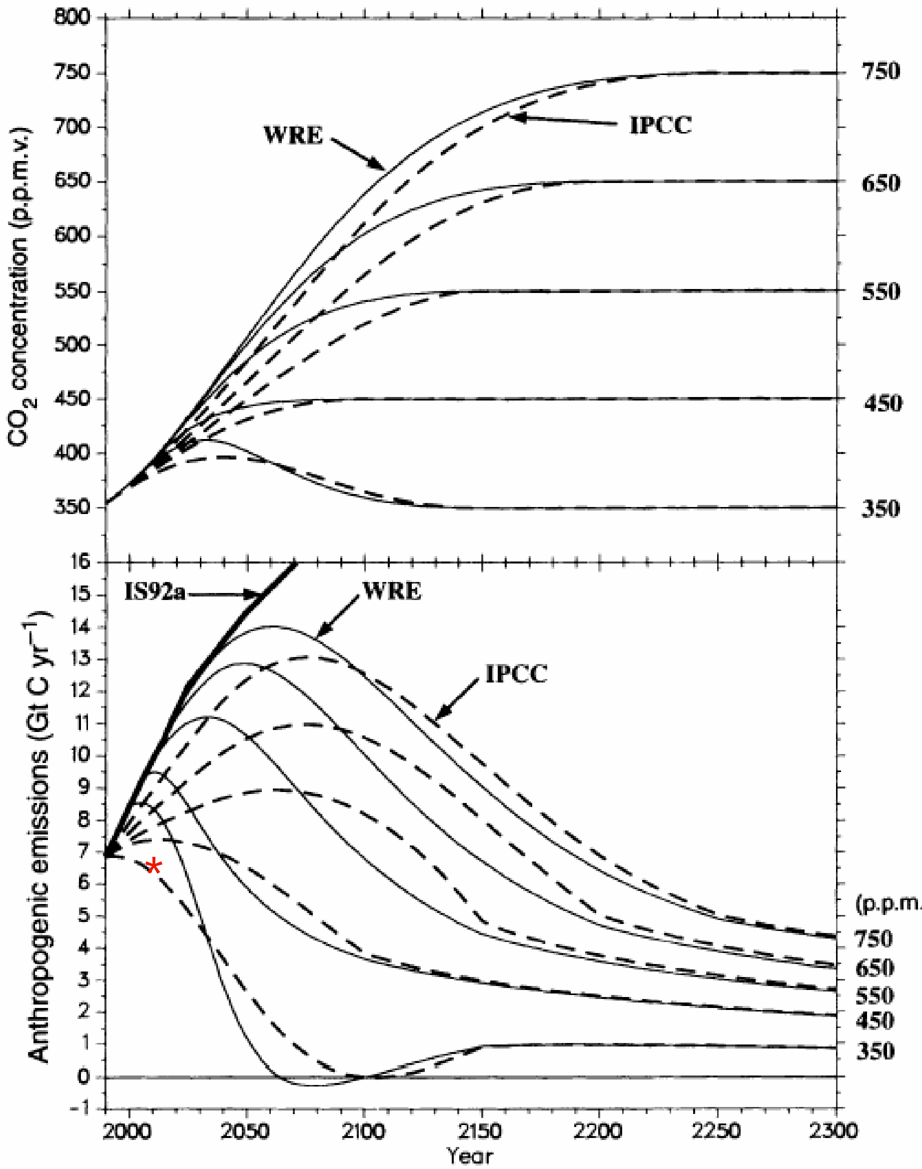
The Value of Fusion-Produced Energy is 12,000x Greater than the Development Cost

Return on investment still ~40:1 payoff after discounting for Net Present Value, 20% advantage over other energy sources, 50% chance of success, 1/3 payoff to U.S.



Total value ~ $296T at $0.02 per kWhr thermal ($FY2002)

Large CO2 Emissions cuts needed to stabilize CO2 & associated global warming



twice preindustrial

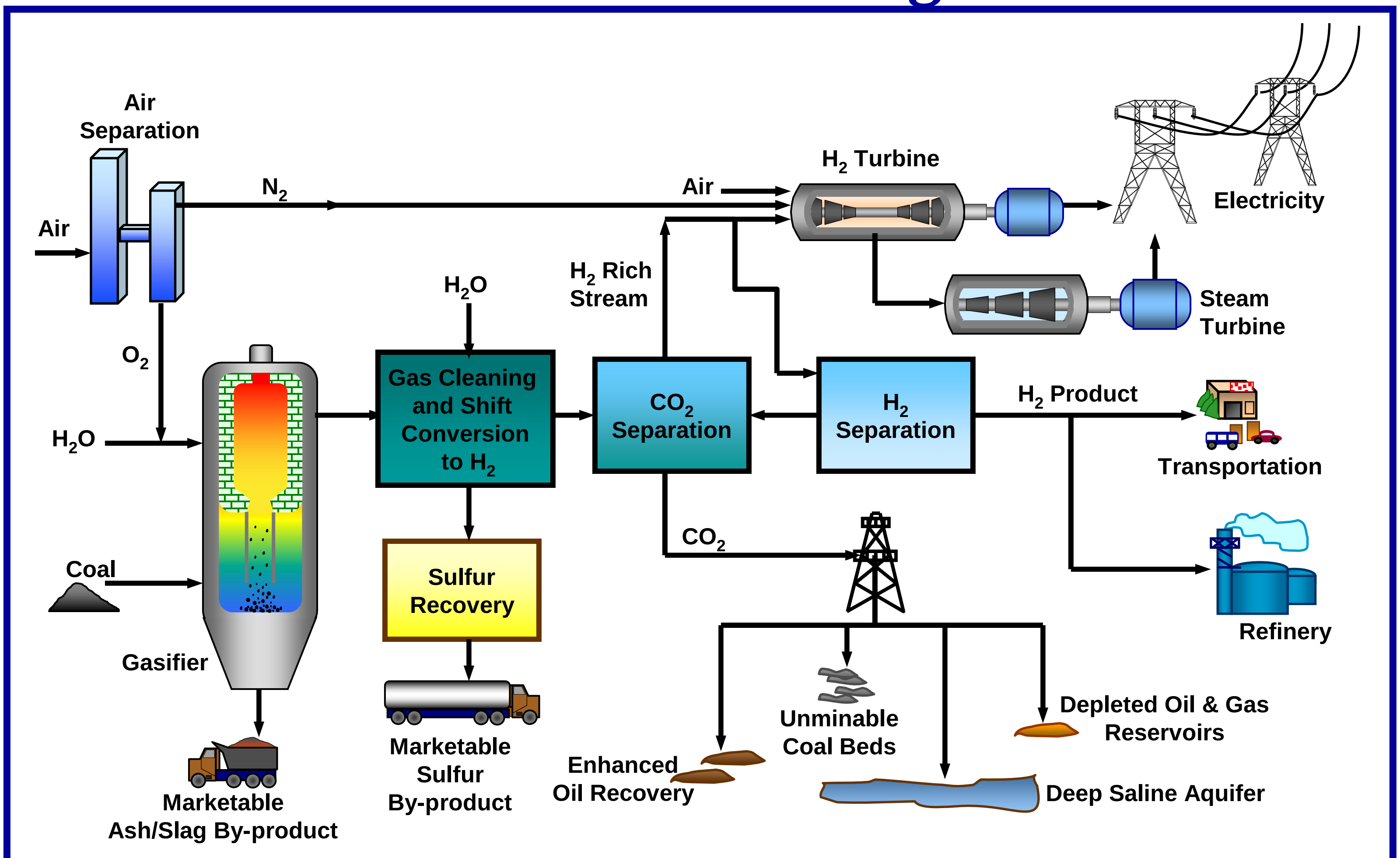
Raising world energy/person to E.U. level will triple energy usage

* Kyoto Accords: 2012 target 10% below 1990

Wigley, Richels, & Edmonds, Nature 379 (1996) 240.

GWH: Adequate reductions in CO2 over next 50 years probably possible with improved efficiency, windmills, fission, CO2 sequestration, etc. But after 50 years, need fusion, or fission breeders, or ??

Future Gen Flow Diagram

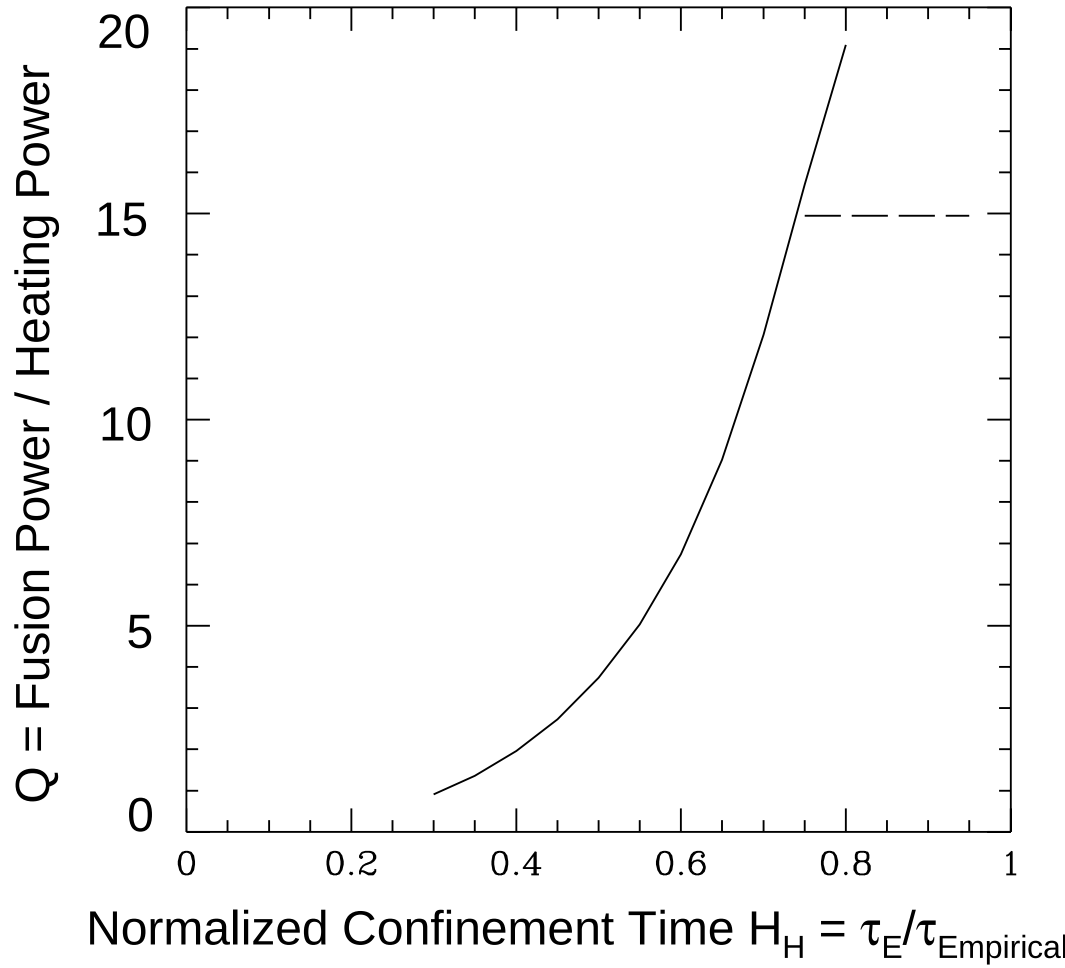


From Gary J. Stiegel, http://wvodyssey.nrcce.wvu.edu/2004/post_event/ppt/Stiegel_gasification.ppt

Fusion performance depends sensitively on confinement

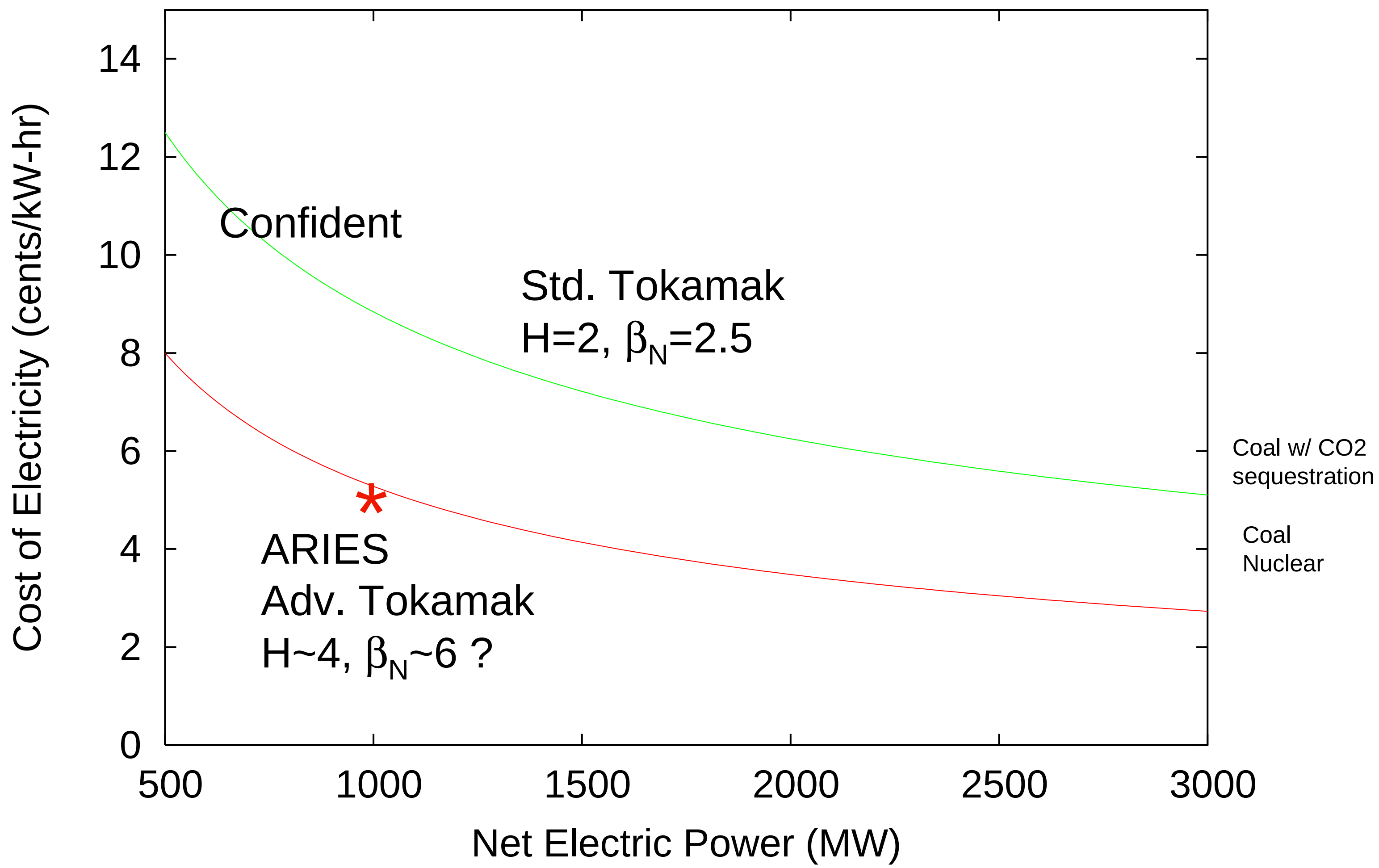
Sensitive dependence on turbulent confinement causes some uncertainties, but also gives opportunities for significant improvements, if methods of reducing turbulence extrapolate to larger reactor scales.

$$\frac{dE}{dt} = P_{ext} + P_{fusion} - \frac{E}{\tau_E}$$



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



From Galambos, Perkins, Haney, & Mandrekas 1995 Nucl.Fus. (very good), scaled to match ARIES-AT reactor design study (2001), http://aries.ucsd.edu/ARIES/

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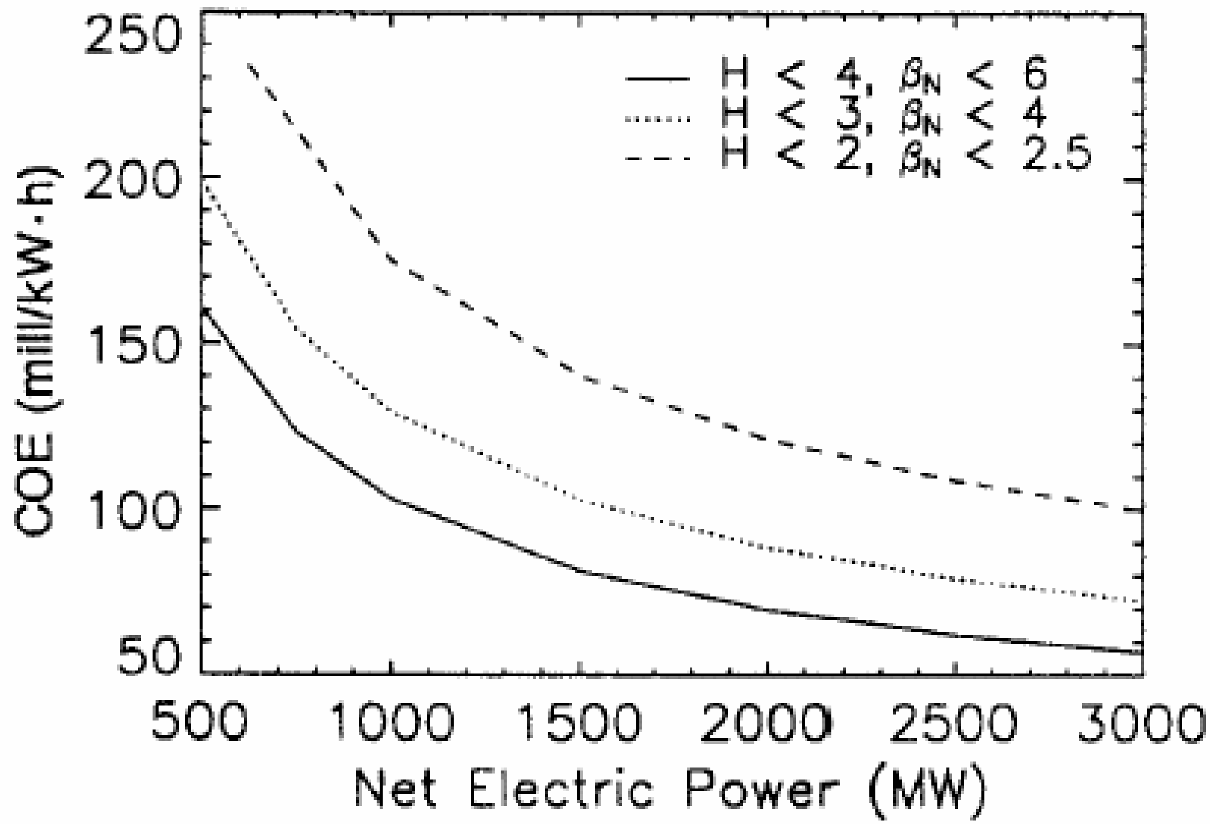
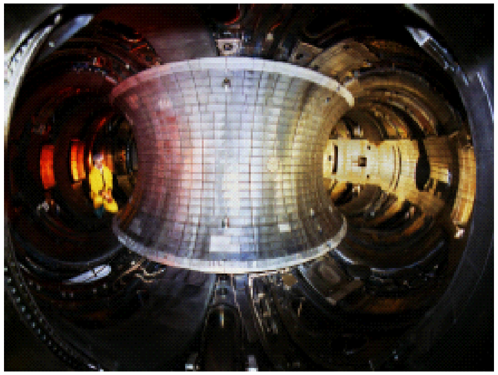


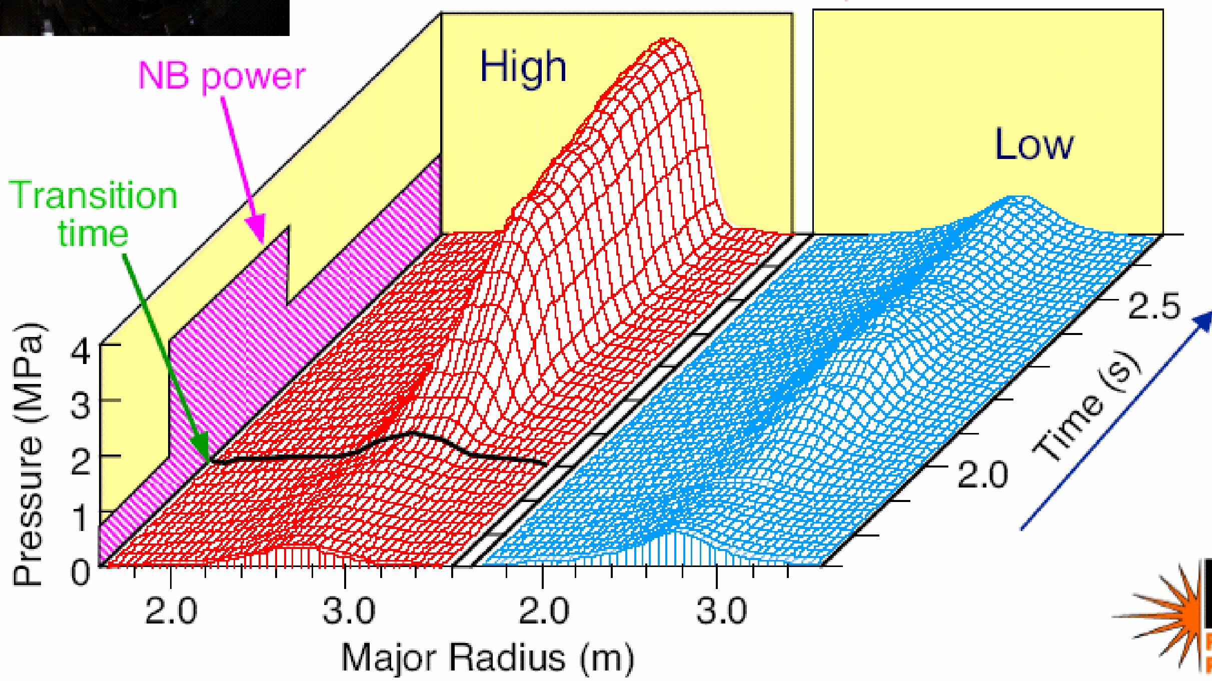
FIG. 4. Minimum COE steady state reactor parameters versus the net electric output. Cases are shown for three physics levels: (a) present day levels that would be sustainable in a non-transient manner in a conservatively designed system ($H \leq 2, \beta_N \leq 2.5$), (b) moderately improved physics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

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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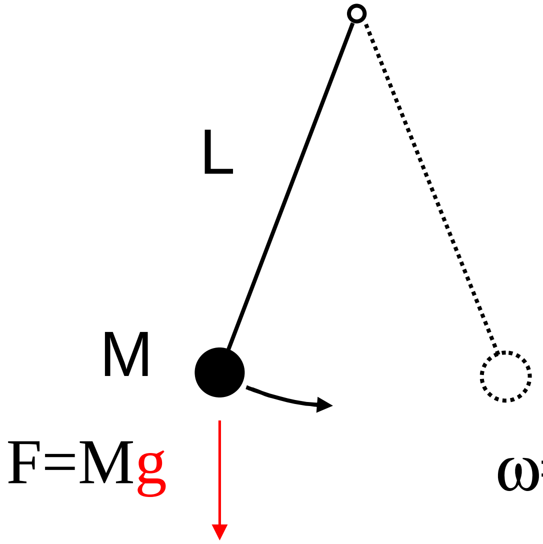
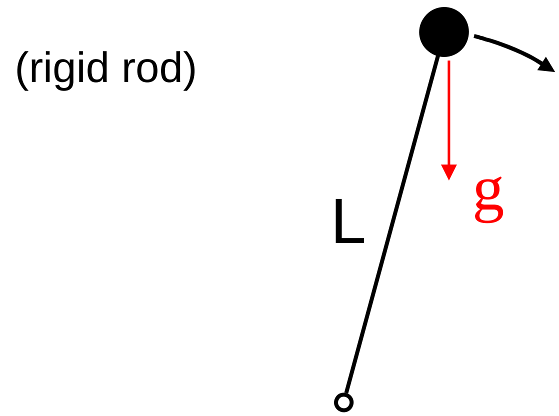
Stable Pendulum



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

Unstable Inverted Pendulum

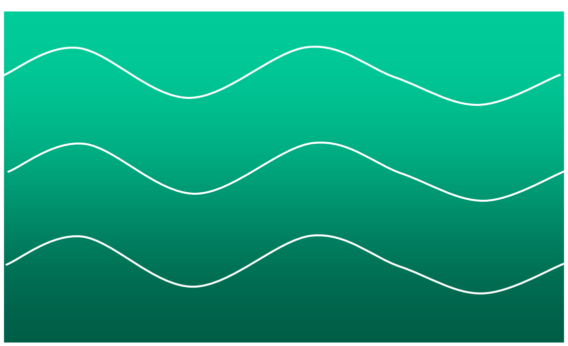


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

Instability

Density-stratified Fluid

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

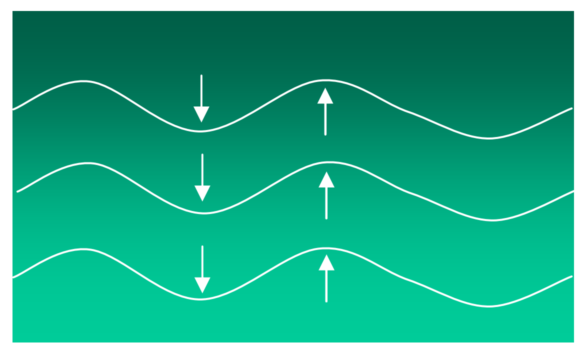


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

$\Rightarrow$Rayleigh-Taylor Instability

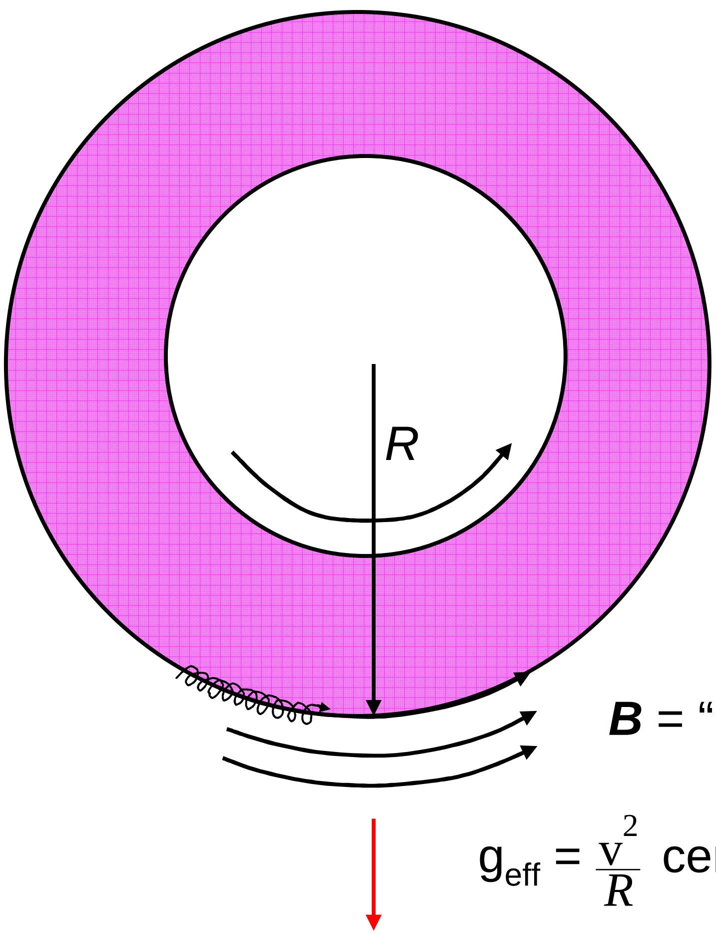
$\rho=\exp(y/L)$



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:

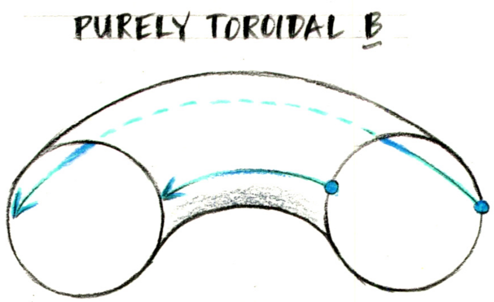
$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{v_t^2}{RL}} = \frac{v_t}{\sqrt{RL}}$$

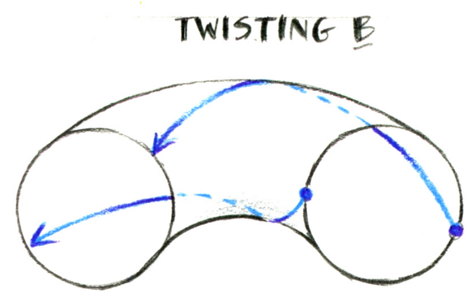
Similar instability mechanism
in MHD & drift/microinstabilities

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

The Secret for Stabilizing Bad-Curvature Instabilities

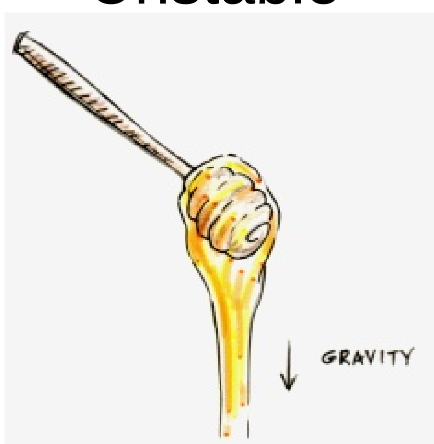
Twist in ***B*** carries plasma from bad curvature region to good curvature region:

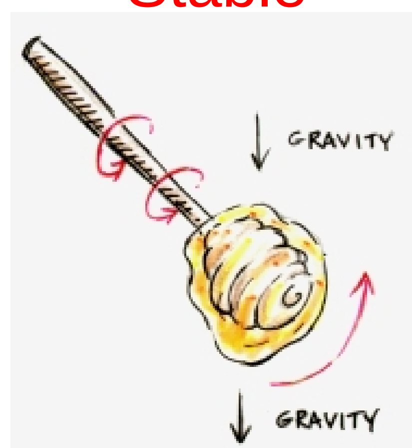




Unstable

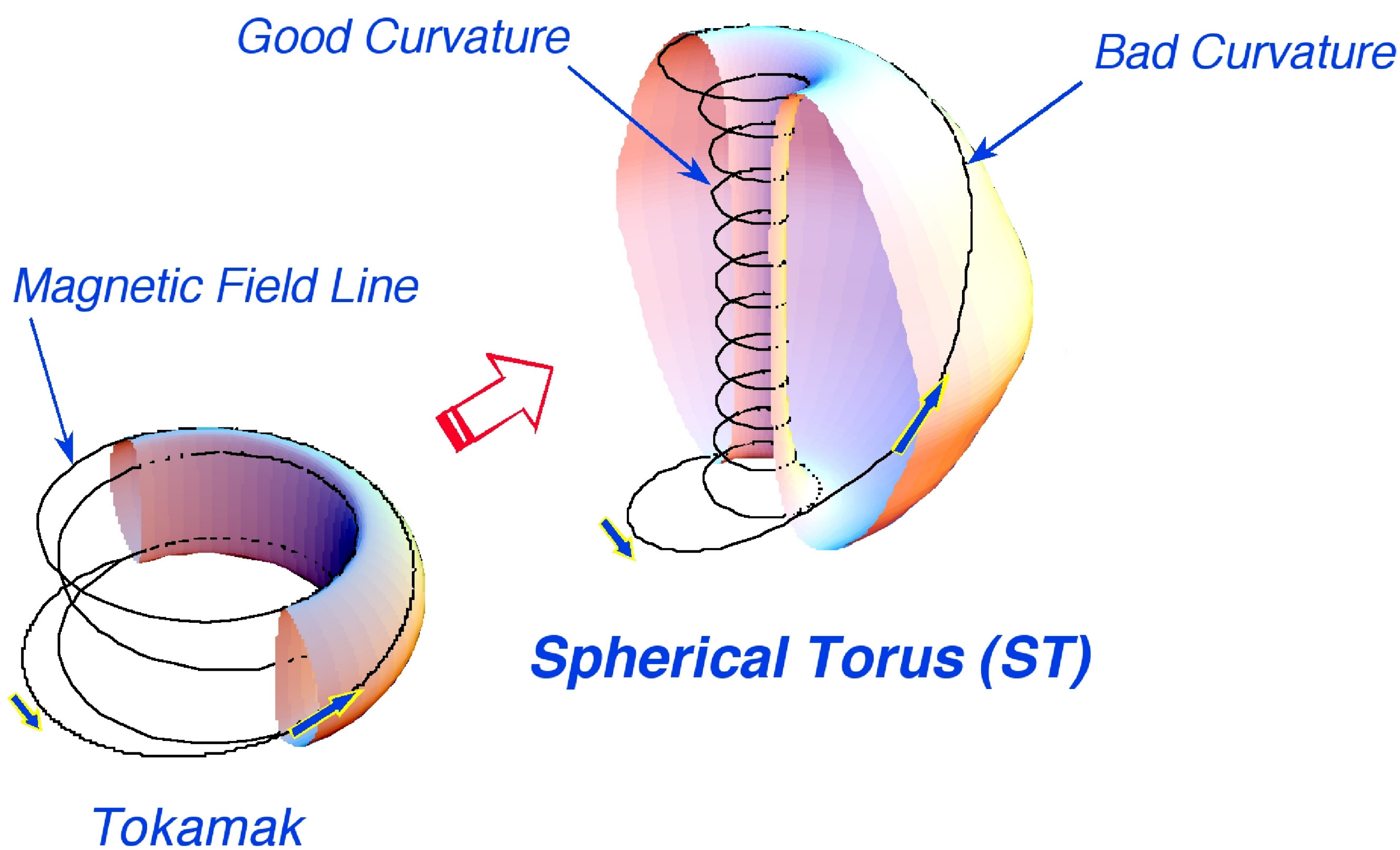
Stable



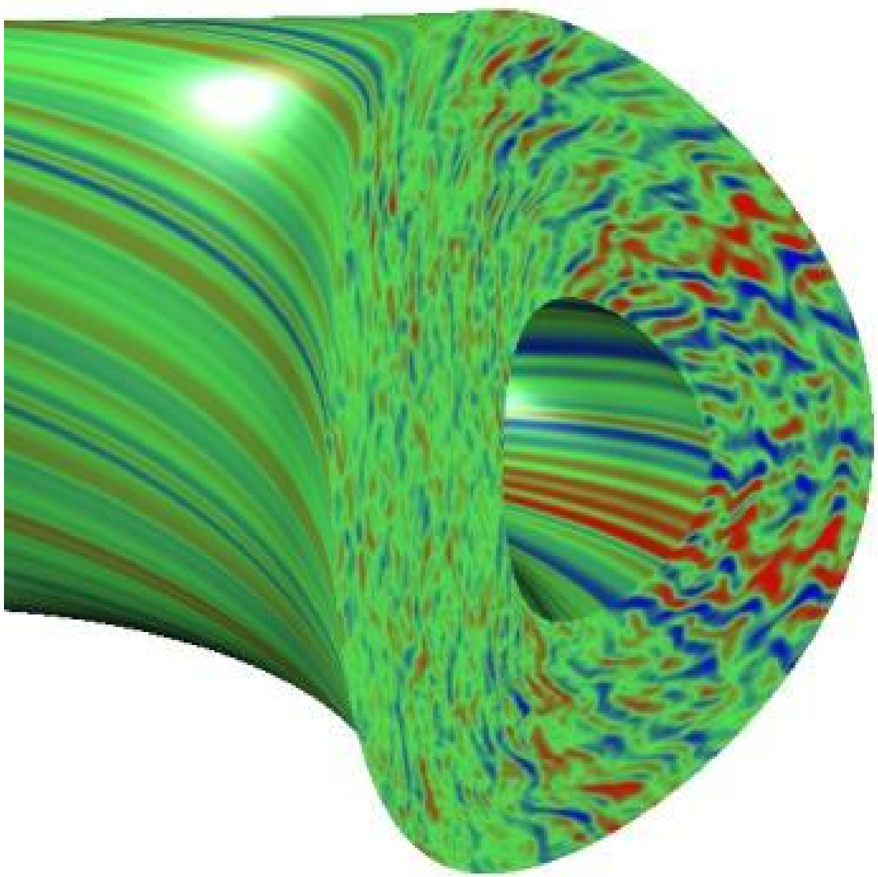


Similar to how twirling a honey dipper can prevent honey from dripping.

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



Understanding Turbulence That Affects the Performance of Fusion Device

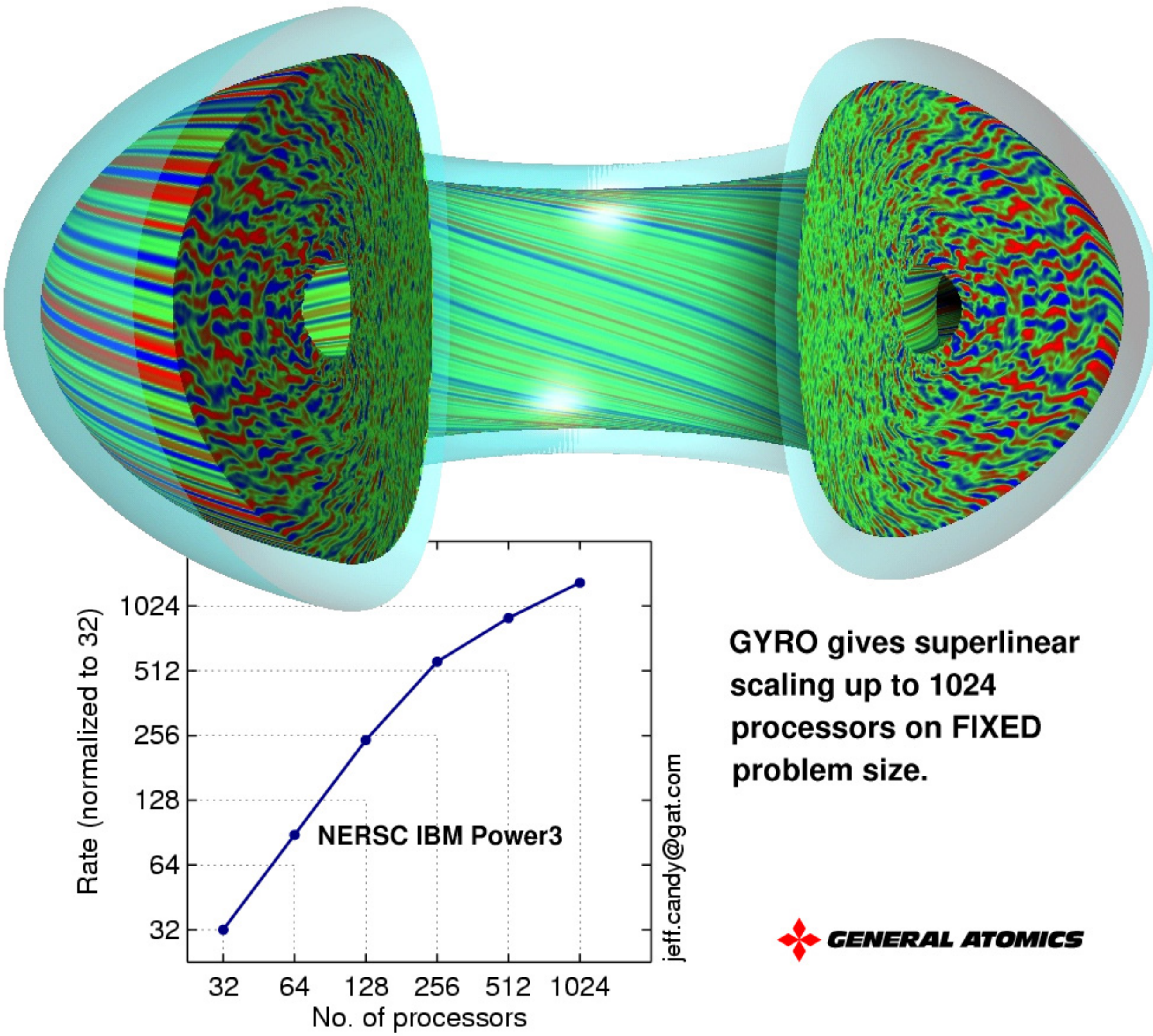


Central temp ~ 10 keV ~ 10^8 K

Large temperature gradient
$\rightarrow$ turbulent eddies
$\rightarrow$ cools plasmas
$\rightarrow$ determines plasma size needed for fusion ignition

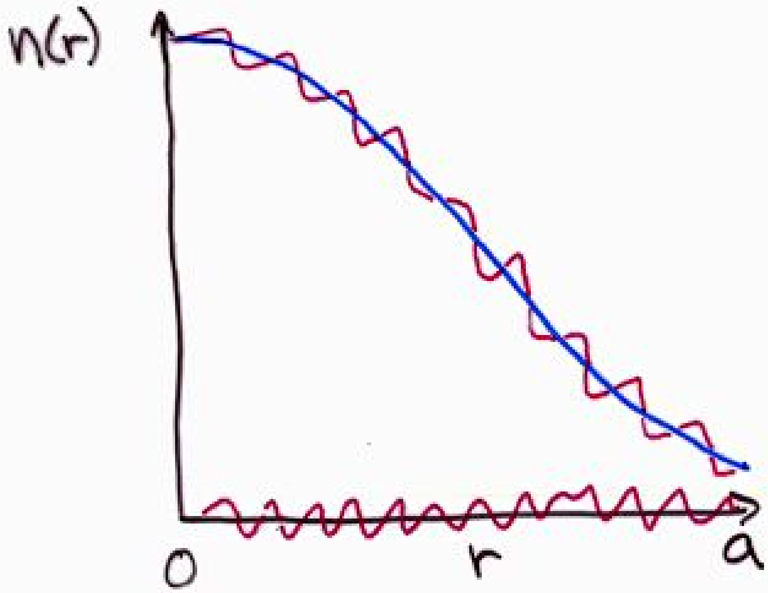
Major progress in last decade: detailed nonlinear simulations (first 3-D fluid approximations, now 5-D $f(\vec{x}, v_{||}, v_{\perp}, t)$) & detailed understanding

(Candy & Waltz, GA 2003)



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.

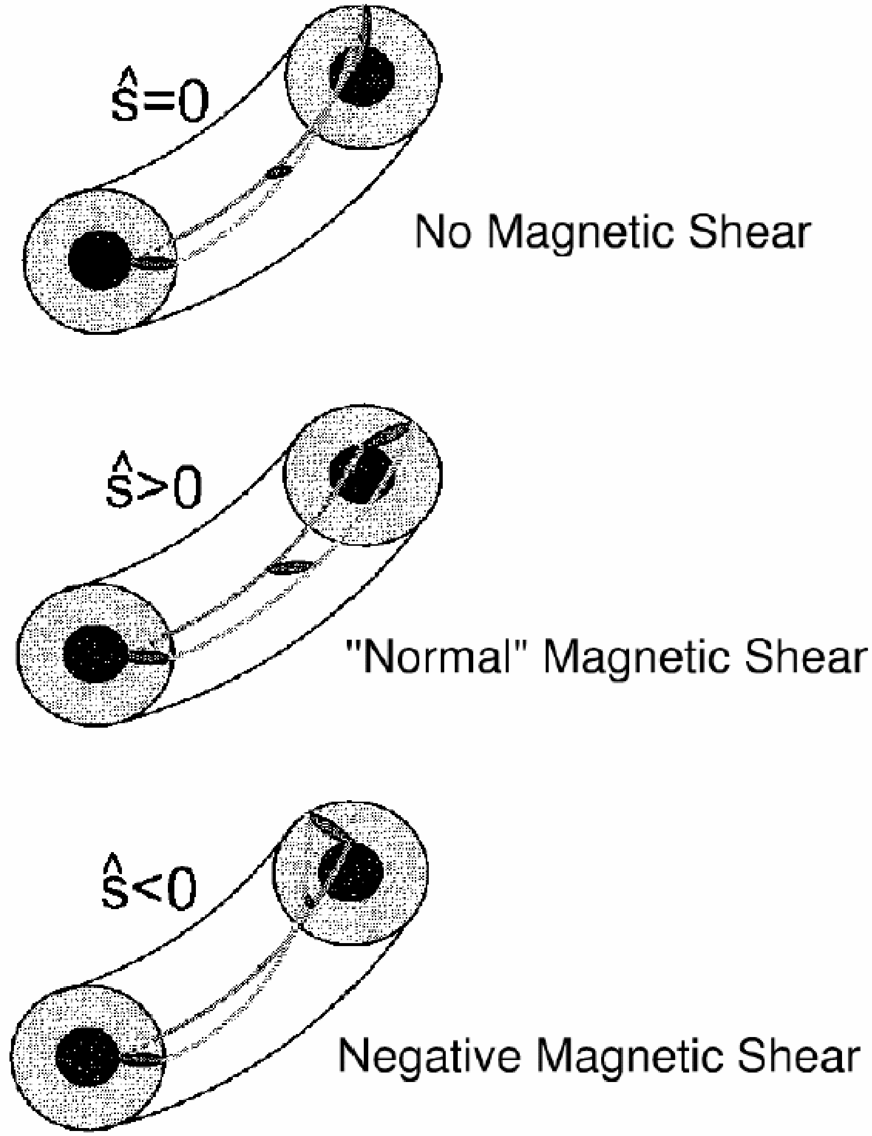
Simple picture of reducing turbulence by negative magnetic shear

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

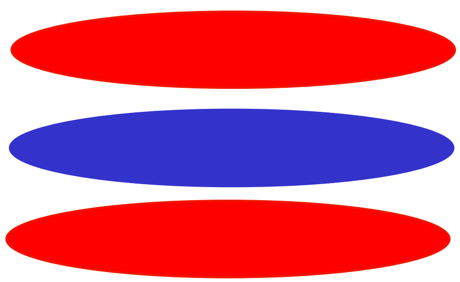


Antonsen, Drake, Guzdar et al. Phys. Plasmas 96

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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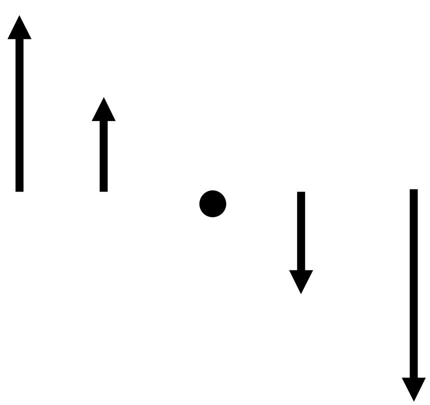
Sheared Flows



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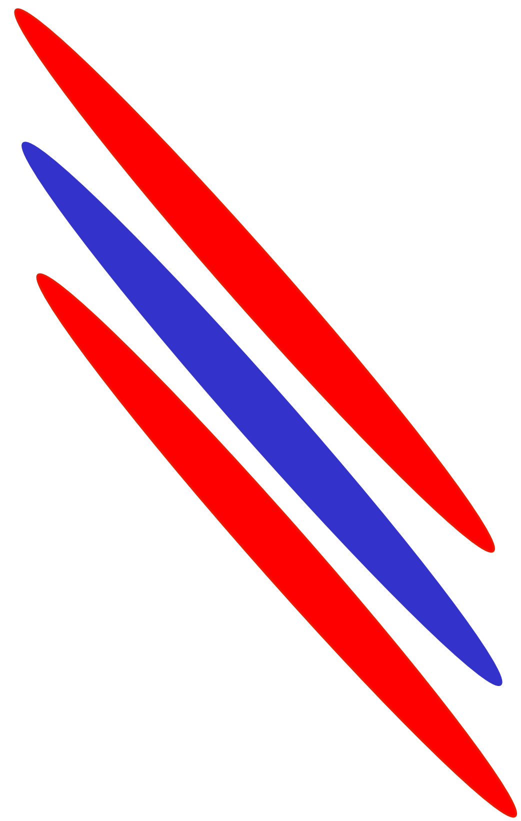
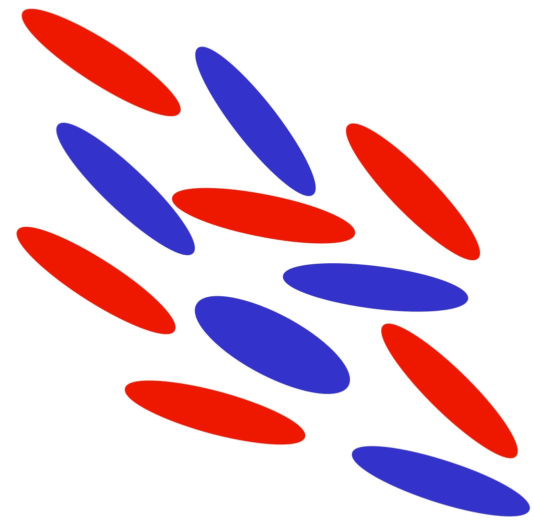
Sheared Eddies
Less effective

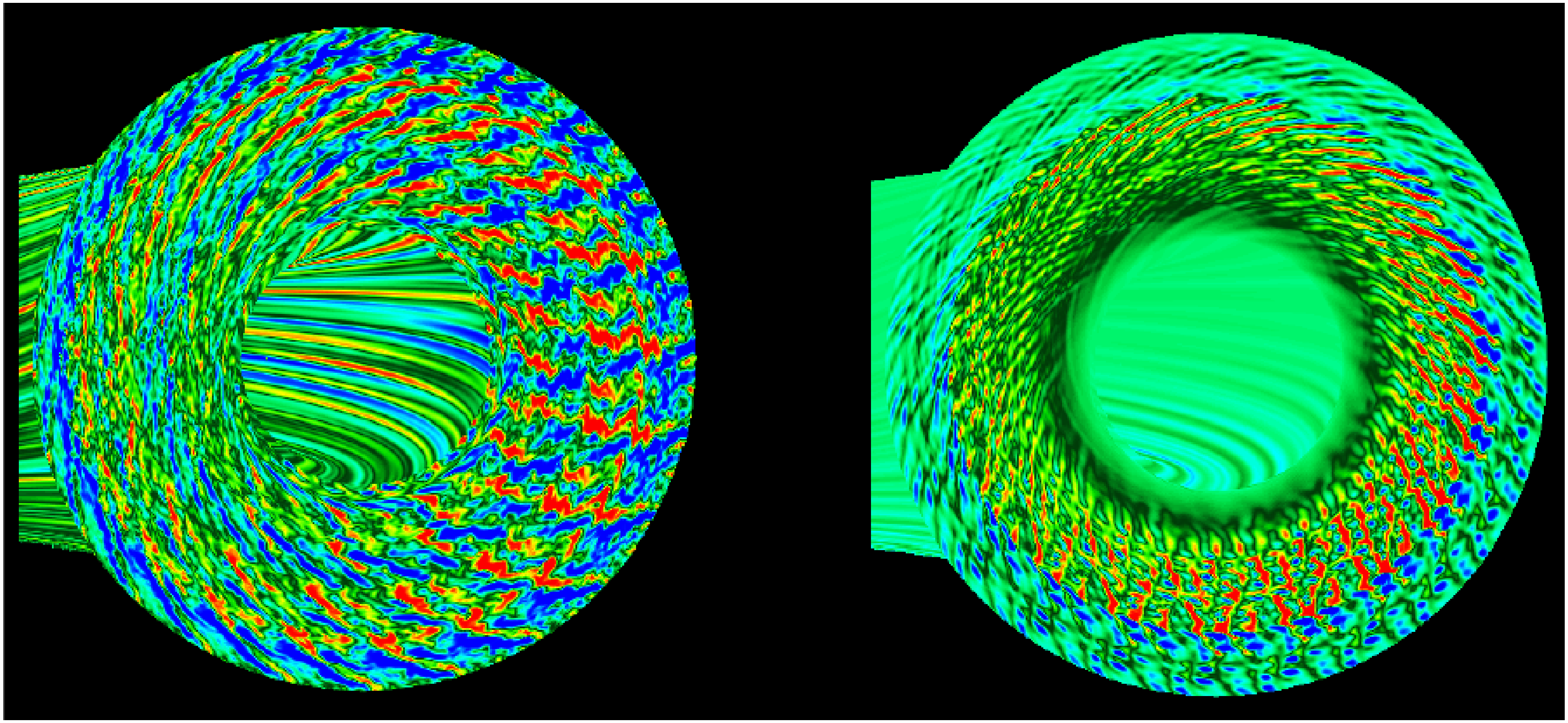


Eventually break up



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

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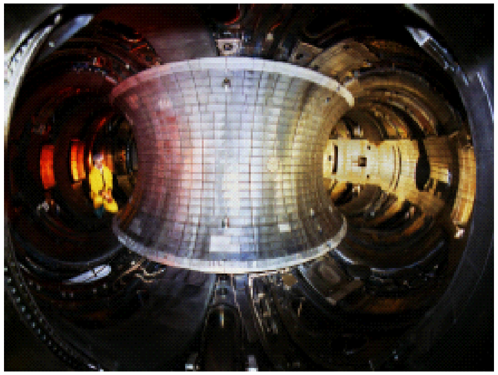

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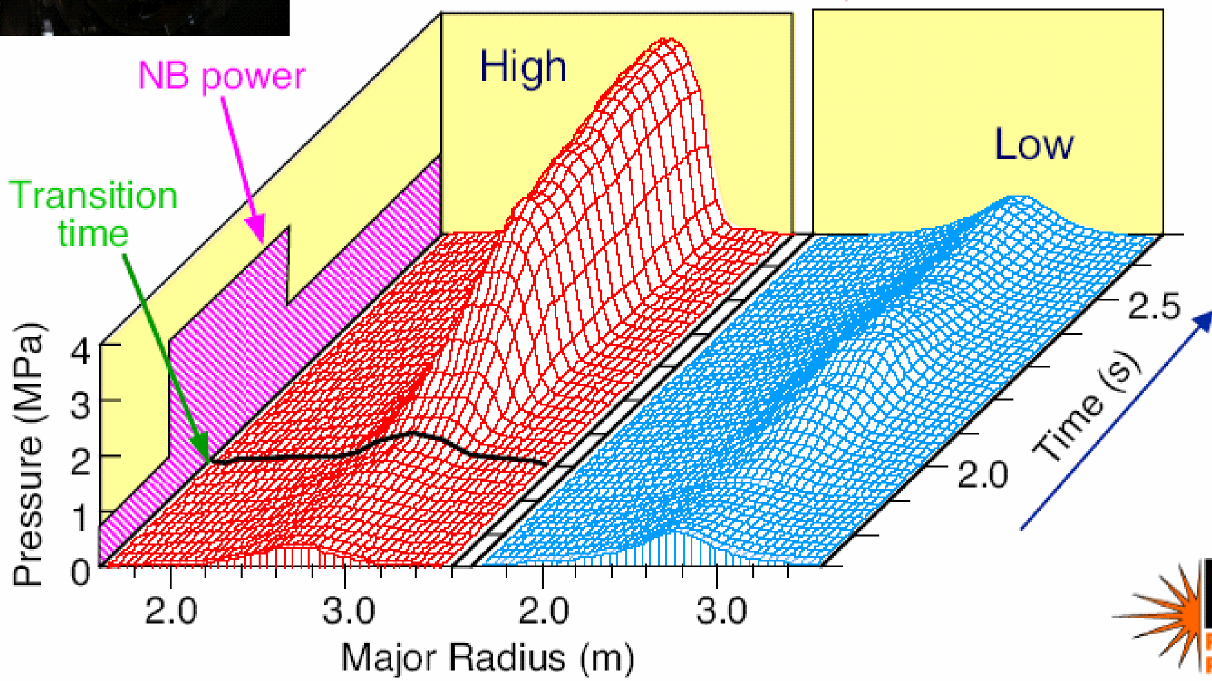

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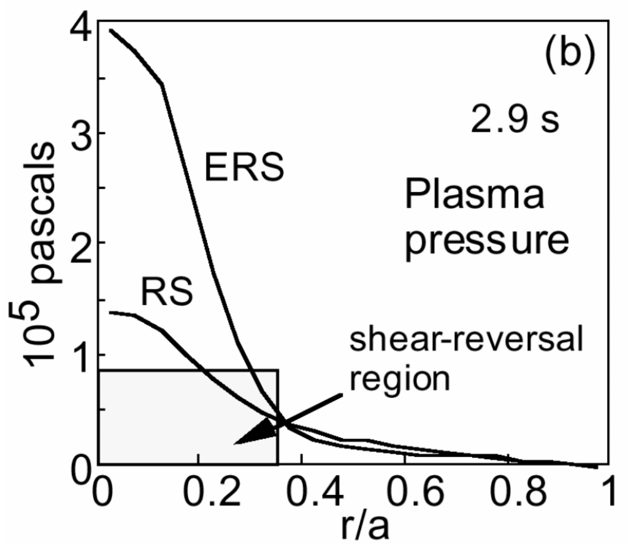
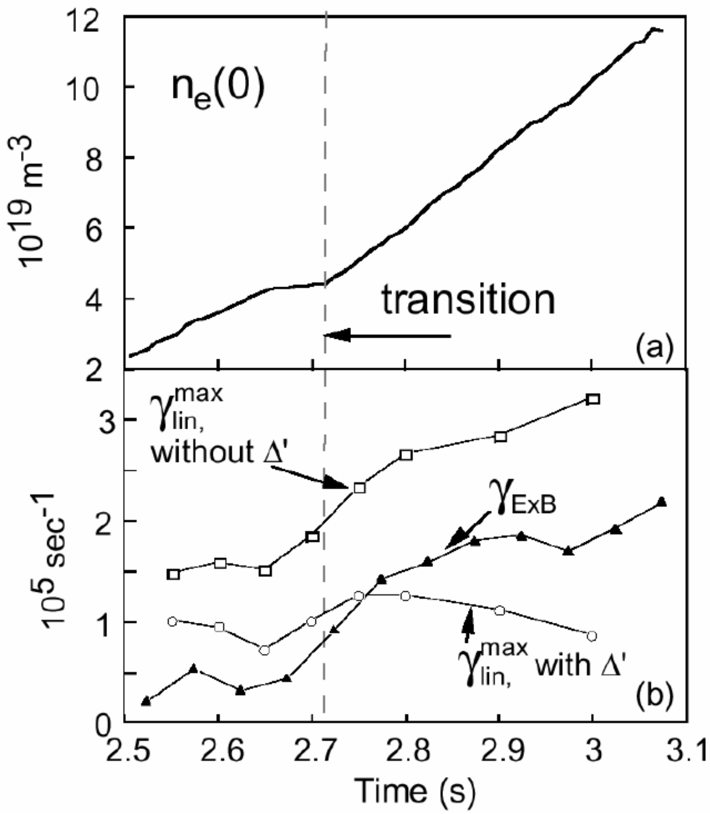
All major tokamaks show turbulence can be suppressed w/ sheared flows & negative magnetic shear / Shafranov shift





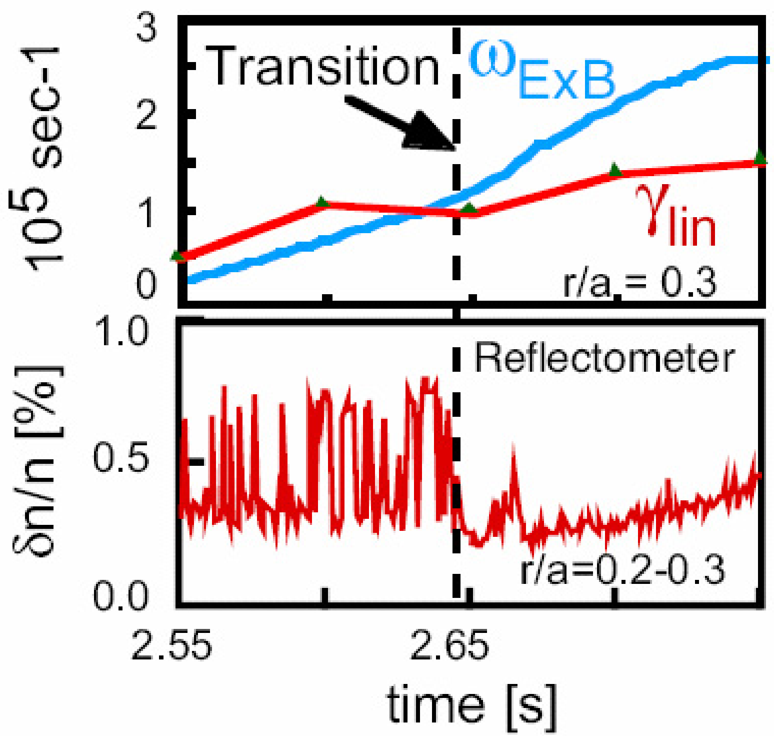
Synakowski, Batha, Beer, et.al. Phys. Plasmas 1997

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.

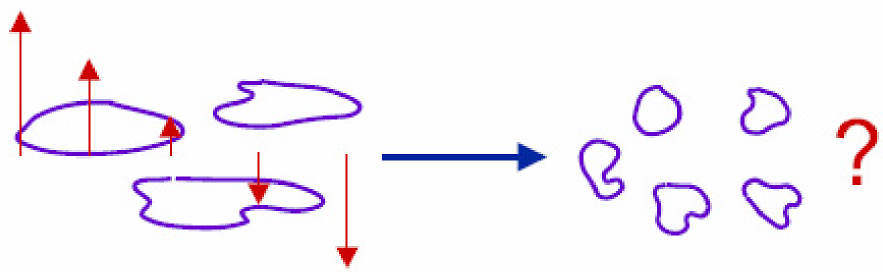
Shafranov shift Δ' effects (self-induced negative magnetic shear at high plasma pressure) also help reduce the linear growth rate.

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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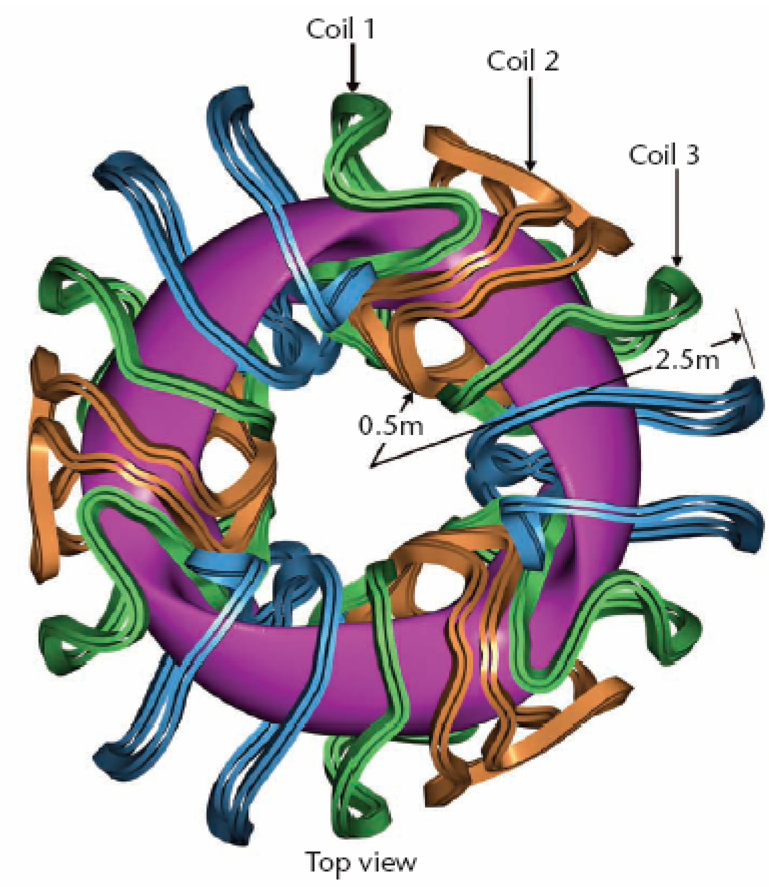
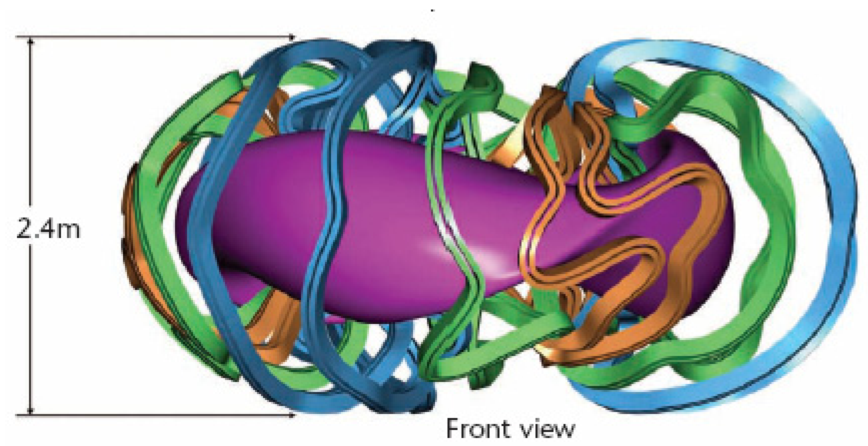
Improved Stellarators Being Built

- Magnetic field twist and shear provided by external coils, not plasma currents. More stable?
- Computer optimized designs much better than 1950-60 slide rules?
- Quasi-toroidal symmetry allows plasma to spin toroidally: shear flow stabilization?





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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

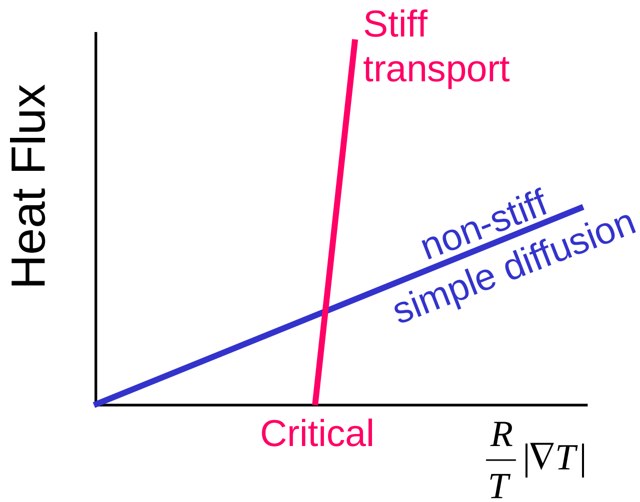
$$\chi_i = \rho_i^2 \frac{v_{ti}}{R} \left(\frac{R}{L_T} - \frac{R}{L_{T,crit}(p_j)} \right) F(p_j) \left(1 - \frac{\gamma_{shear}}{\gamma_{lin}} \right)$$

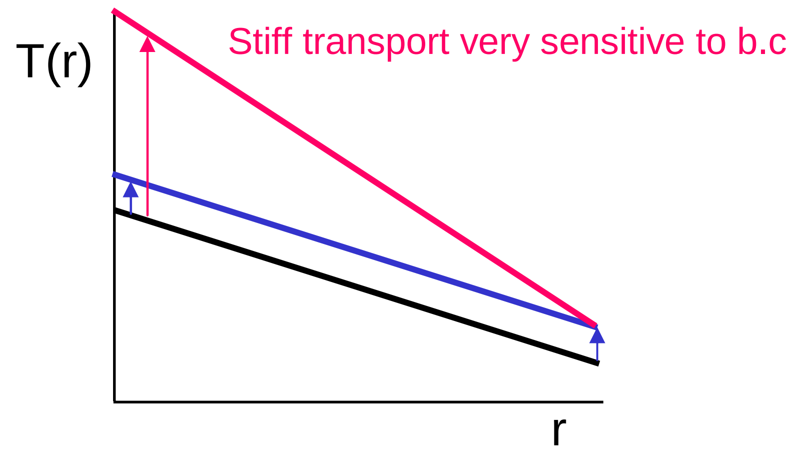
$$\frac{1}{L_T} = -\frac{1}{T}\frac{dT}{dr} \qquad p_j = \left(\frac{R}{L_T}, \frac{R}{L_T}, \frac{T_i}{T_e}, q, \hat{s}, Z_{eff}, nu, \frac{r}{R}, \ldots \right)$$

- 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

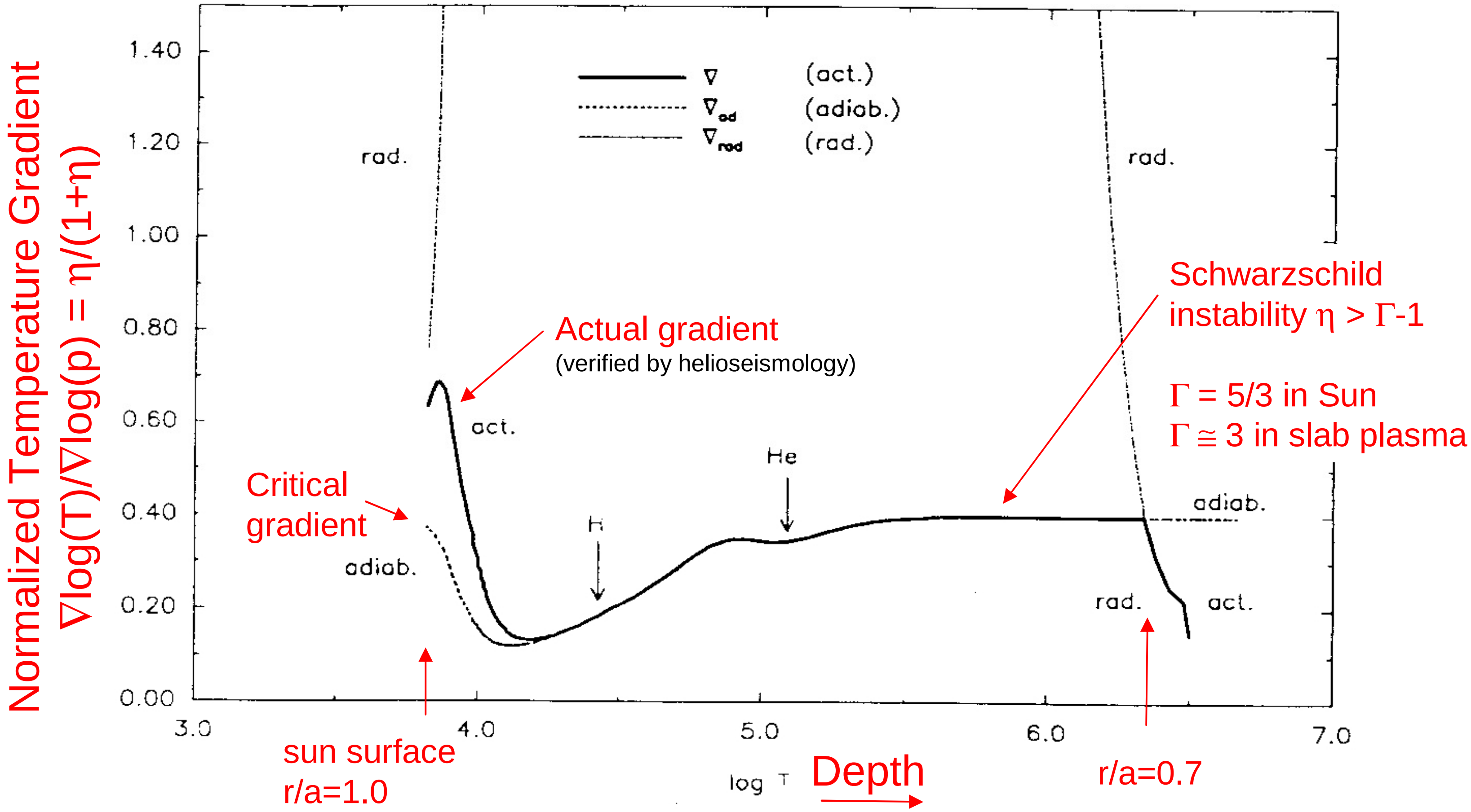


Figure 2: Temperature gradients ∇_{rad}, ∇_{ad}, and ∇ as functions of $\log T$ for a mixing length model of the solar convection zone (Spruit 1977). At the bottom of the convection zone ($\log T \approx 6.3$, depth $\approx 2 \cdot 10^5$ km) the actual temperature gradient changes from $\nabla \approx \nabla_{rad}$ 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 Thesis., in Schüssler '92)

Edge boundary layer very important & uncertain

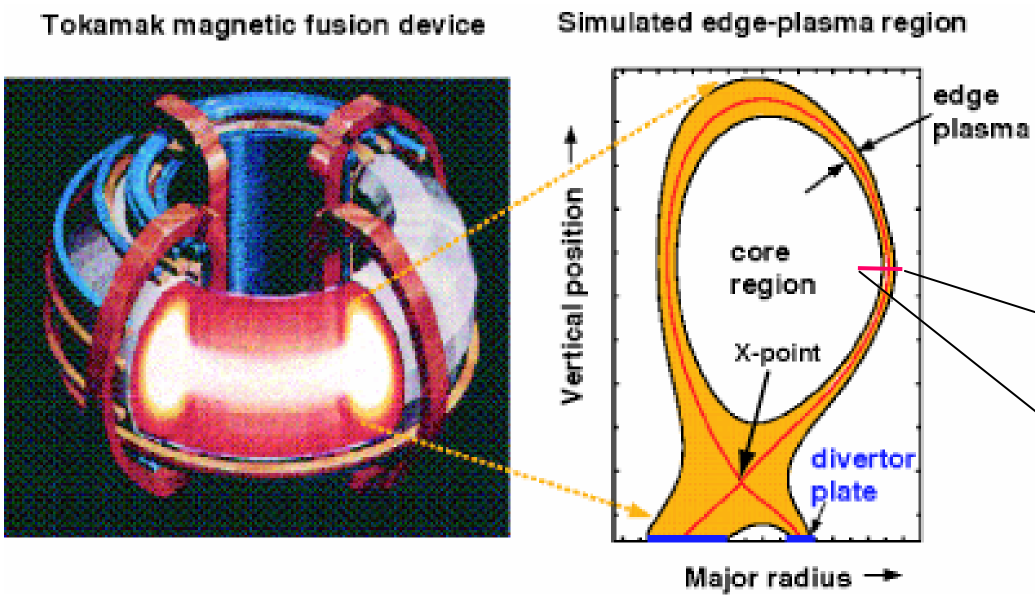


Fig. 2. Schematic views of divertor tokamak and edge-plasma region (magnetic separatrix is the red line and the black boundaries indicate the shape of magnetic flux surfaces).

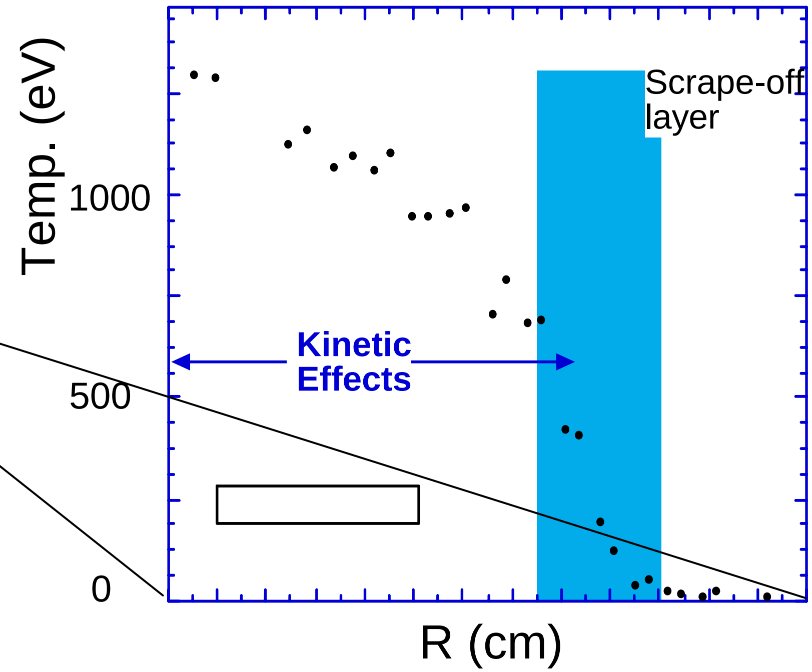


Fig. 1. Edge pedestal temperature profile near the edge of an H-mode discharge in a tokamak.. [For illustrative purposes, see Porter et al.*2000 and refs. therein for further examples.]* Pedestal is shaded region.

- Marginal stability: Tcore $\propto$ Tped

- Periodic instabilites in edge region can dump outer ~5-10% of plasma onto divertor plates. Might be manageable, or divertor erodes, melts?

Current Status of Fusion Energy Research & Related Plasma Turbulence Studies

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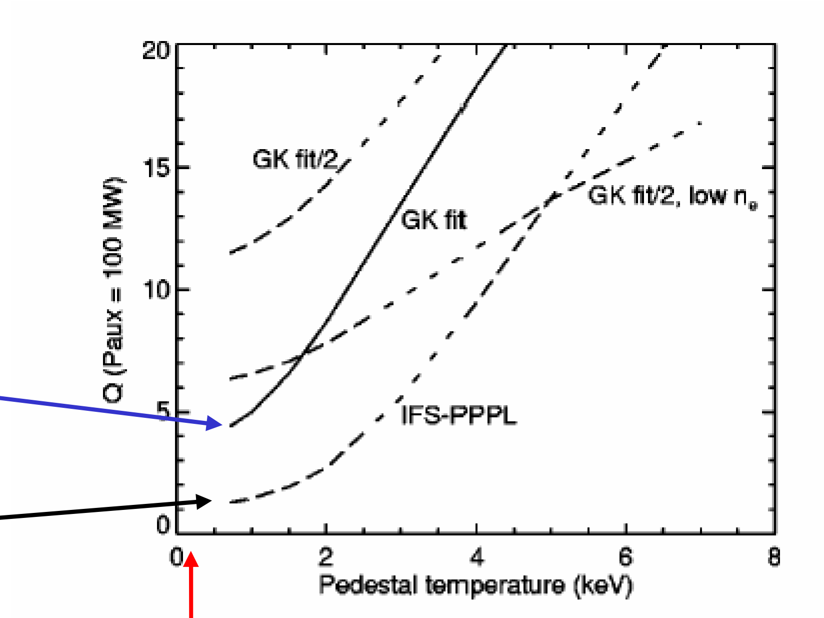
- Remaining uncertainties: quantitative scaling of turbulent losses to larger sizes, turbulence suppression mechanisms, edge boundary layer, power loads to material wall?

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



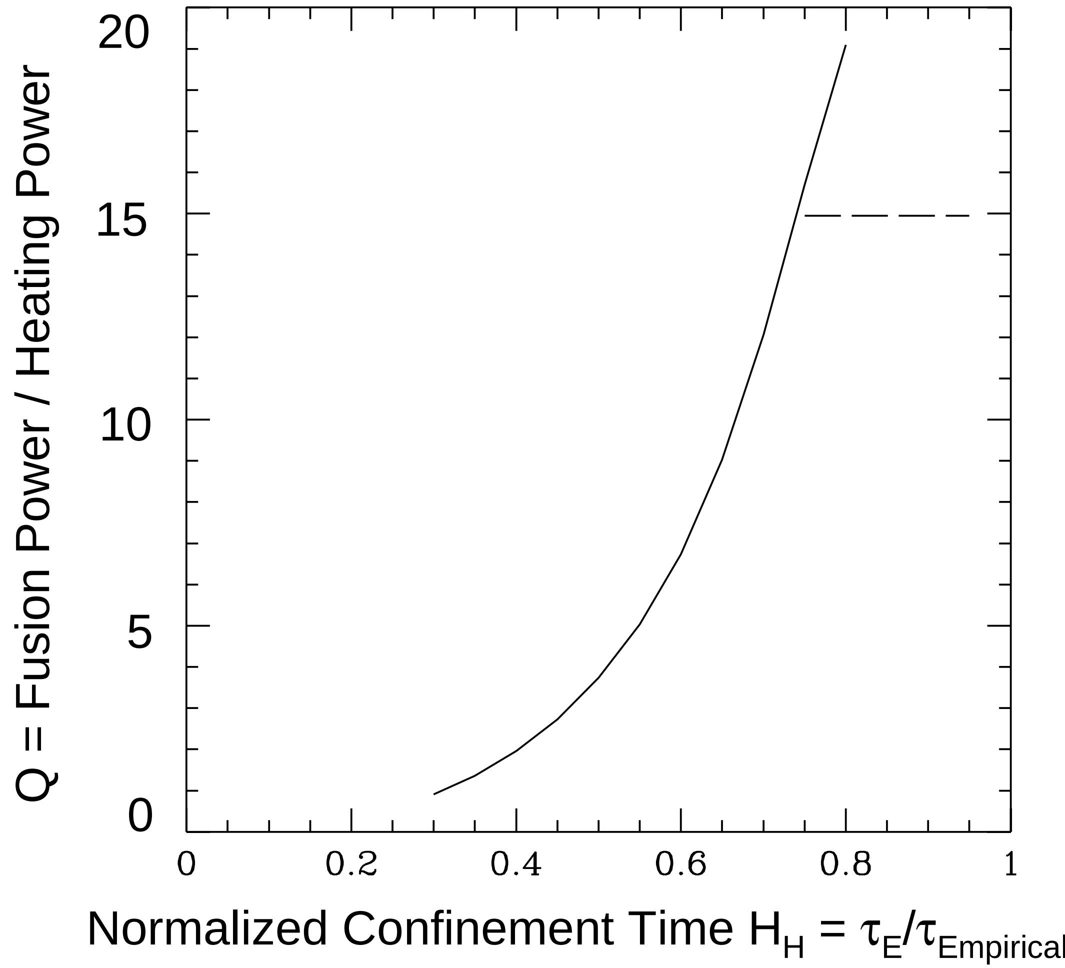
JET 1998 IAEA and ITER 1996 IAEA papers predicted Tped ~ 0.14 keV! for ITER-96

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

Fusion performance depends sensitively on confinement

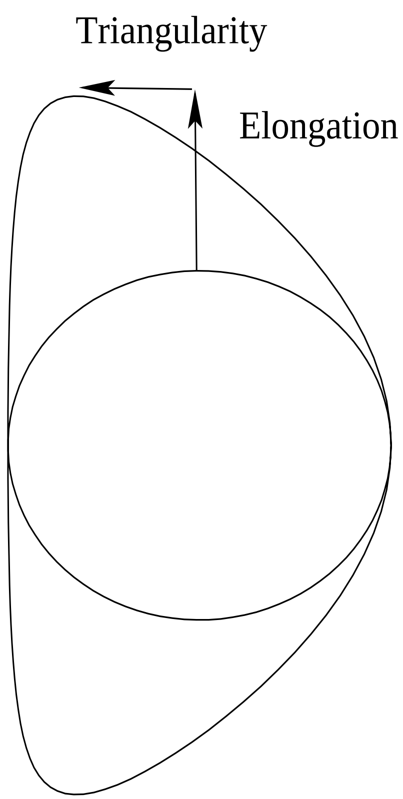
Sensitive dependence on turbulent confinement causes some uncertainties, but also gives opportunities for significant improvements, if methods of reducing turbulence extrapolate to larger reactor scales.

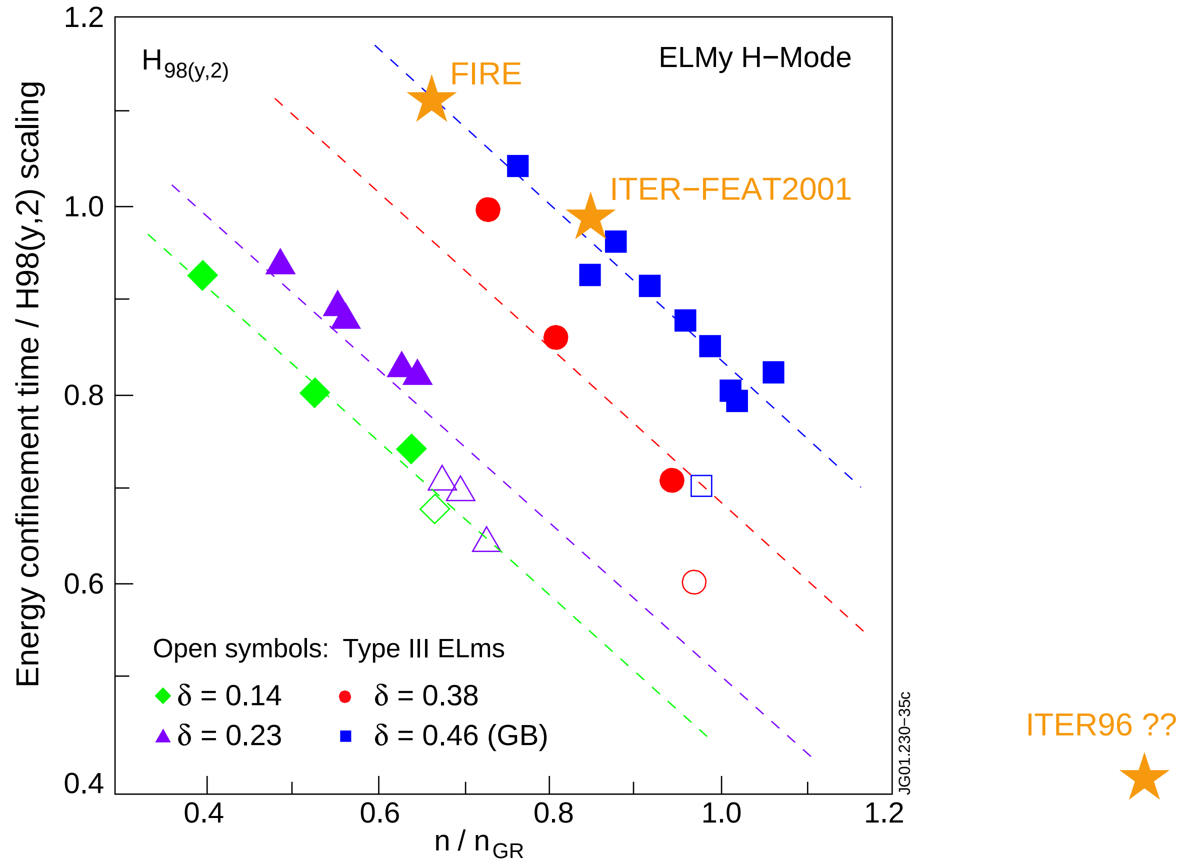
$$\frac{dE}{dt} = P - \frac{E}{\tau_E}$$



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

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.

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 $n\,T\,\tau_E \sim P\,\tau_E^2 \sim P^{-1/3}$

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Selected Further References

- This talk: http://w3.pppl.gov/~hammett &
  http://online.kitp.ucsb.edu/online/jet+disk05/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 refs: http://w3.pppl.gov/~hammett/papers/
- "ENDING THE ENERGY STALEMATE: A Bipartisan Strategy to Meet America's Energy Challenges", The National Commission on Energy Policy, December 2004. http://www.energycommission.org/
- “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

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.

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

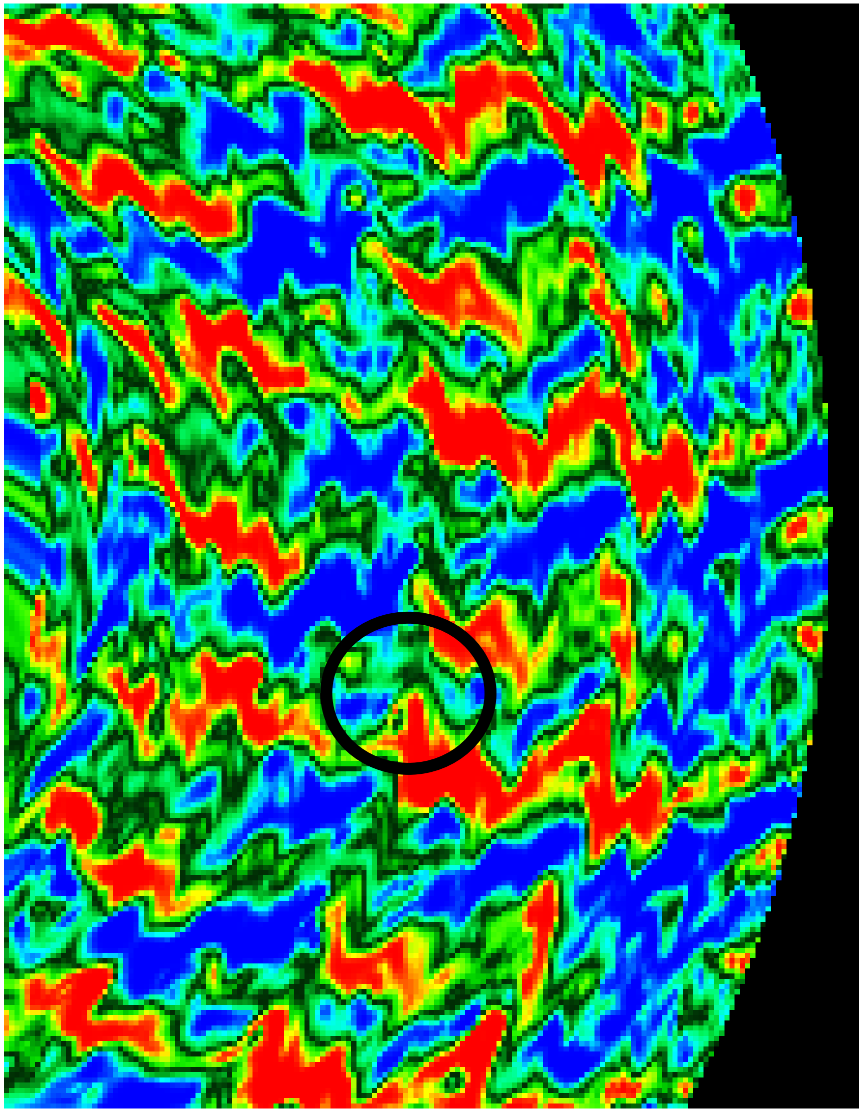
Bessel Functions represent averaging around particle gyro-orbit

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.

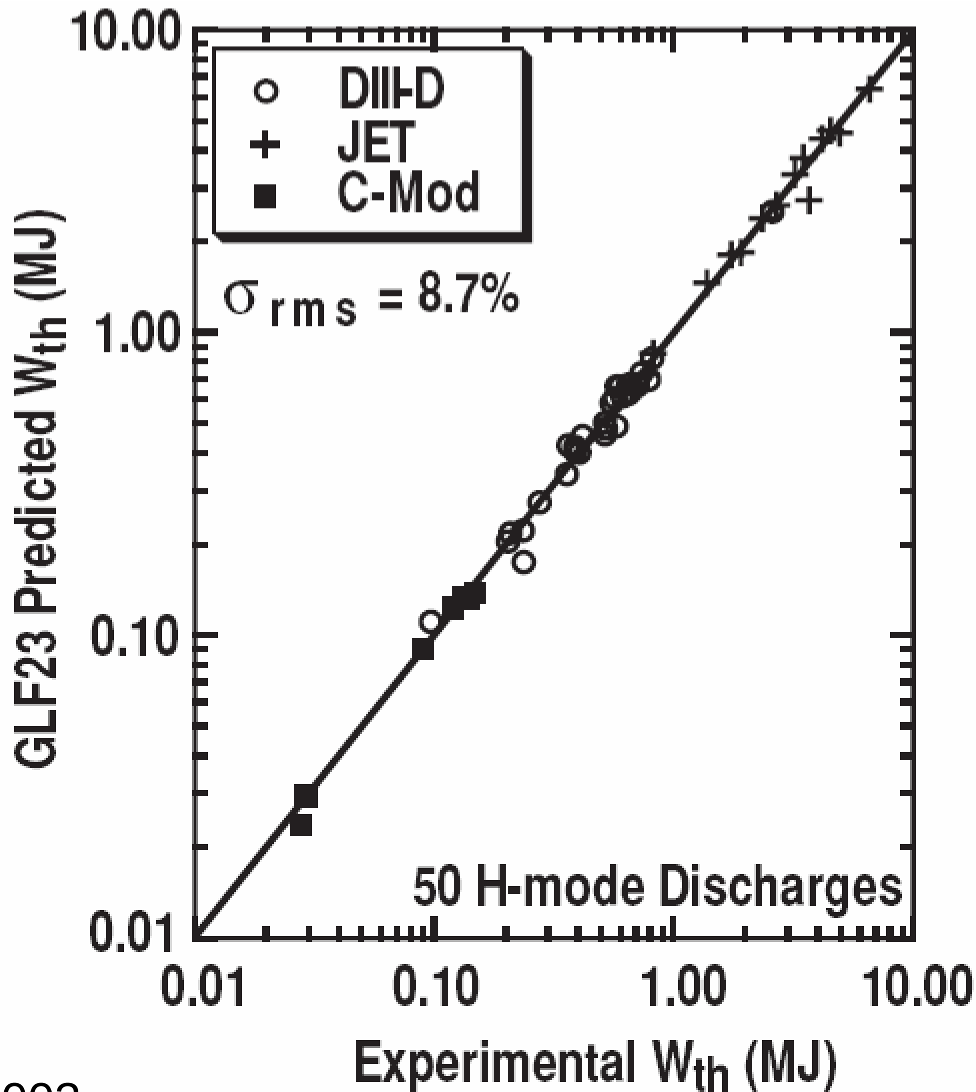
$$\chi = J_0(k_\perp \rho)\,\Phi$$

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



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

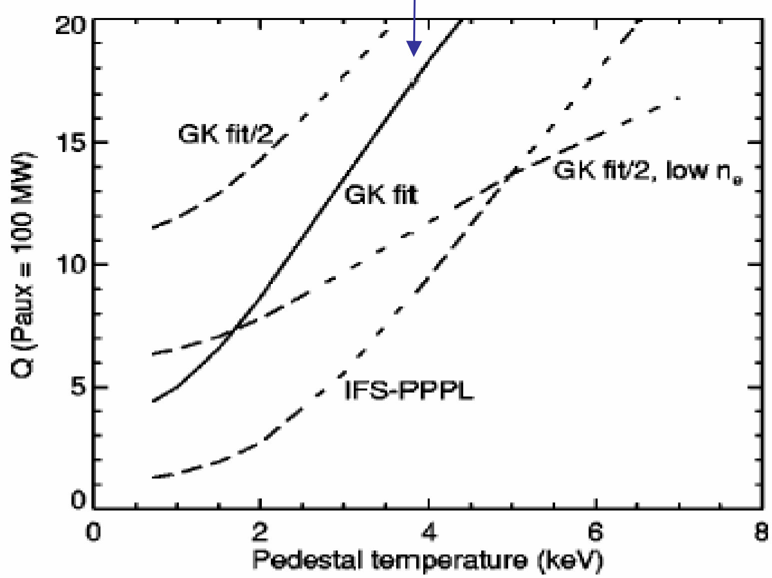
Caveats: core turbulence simulations use observed or empirical boundary conditions near edge. Need more complicated edge turbulence code to make fully predictive & sufficiently accurate. Edge very challenging: wider range of time and space scales, atomic physics, plasma-wall interactions…



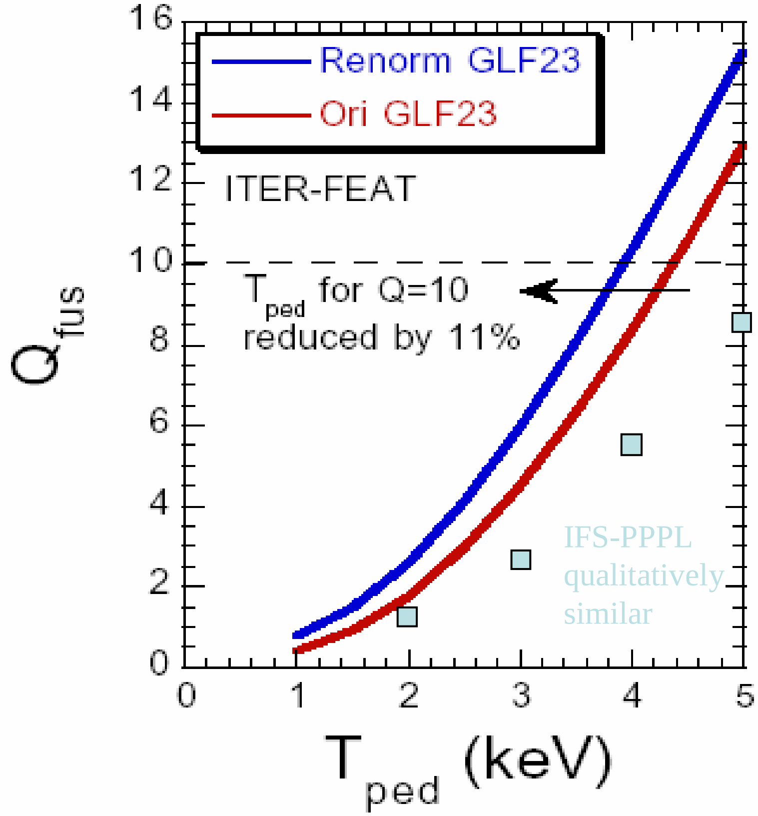
Kinsey, Bateman, et al., Nucl. Fus. 2003

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.