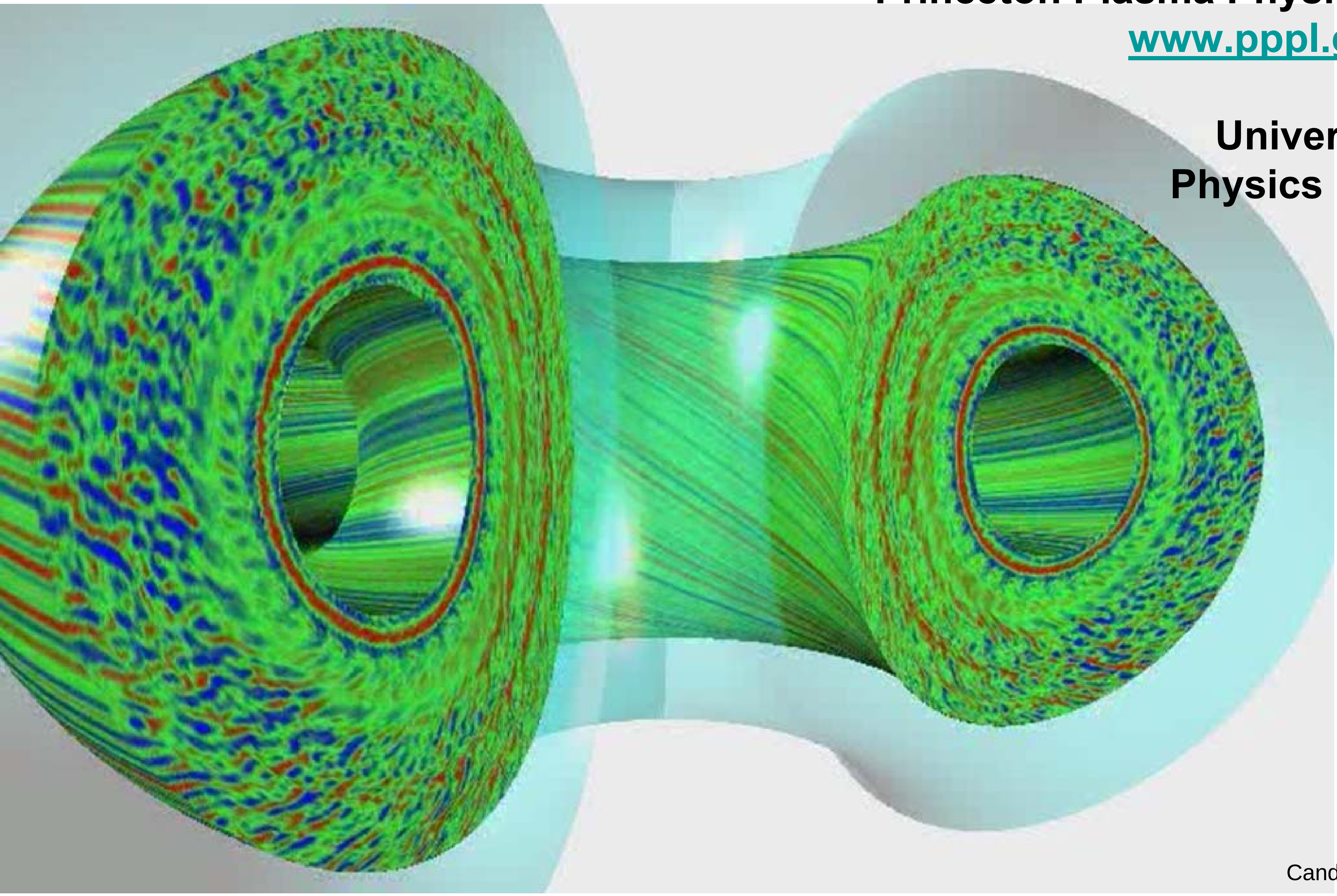
Status of Research on Fusion Energy and Plasma Turbulence

Greg Hammett
Princeton Plasma Physics Lab (PPPL)
www.pppl.gov/~hammett

University of Ottawa
Physics Dept. Seminar
Nov. 29, 2007



Candy, Waltz (General Atomics)

Acknowledgments:

Center for Multiscale Plasma Dynamics http://www.cmpd.umd.edu

& Plasma Microturbulence Project http://fusion.gat.com/theory/pmp

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

DOE Scientific Discovery Through Advanced Computing

GYRO Simulation movies from:

J. Candy, R. Waltz (General Atomics) http://fusion.gat.com/theory/Gyro

W. Dorland (Maryland), S. Cowley (UCLA), M. Kotschenreuther (U. Texas)

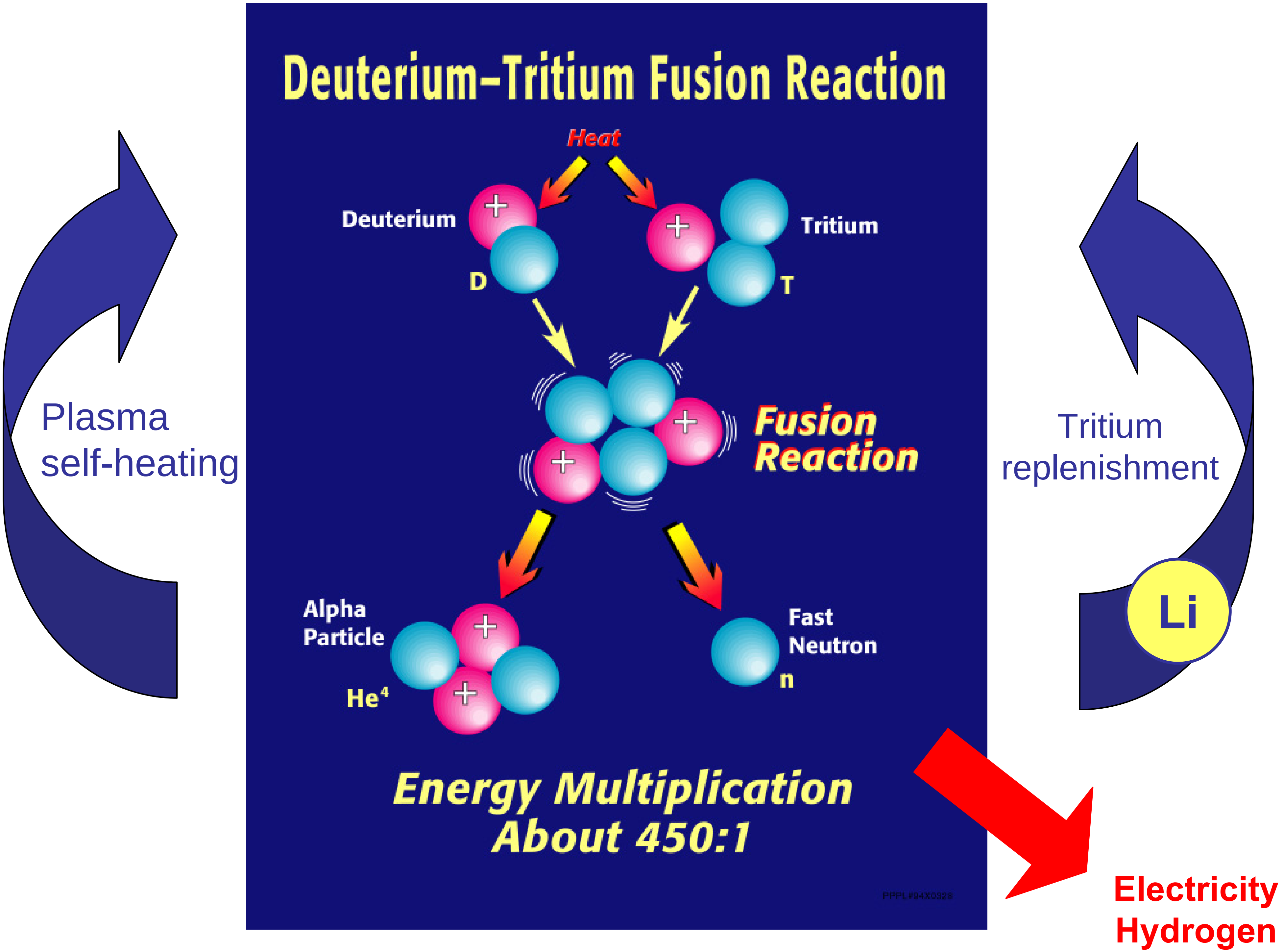
W. Nevins (LLNL)

R. Goldston, R. Nazikian, D. Meade, E. Synakowski, D. Stotler, M. Zarnstorff (PPPL)

J. Ongena (JET)

The Plasma Microturbulence Project

- A DOE, Office of Fusion Energy Sciences, SciDAC (Scientific Discovery Through Advanced Computing) project (~2001-2004)
- devoted to studying plasma microturbulence through direct numerical simulation
- 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 …


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

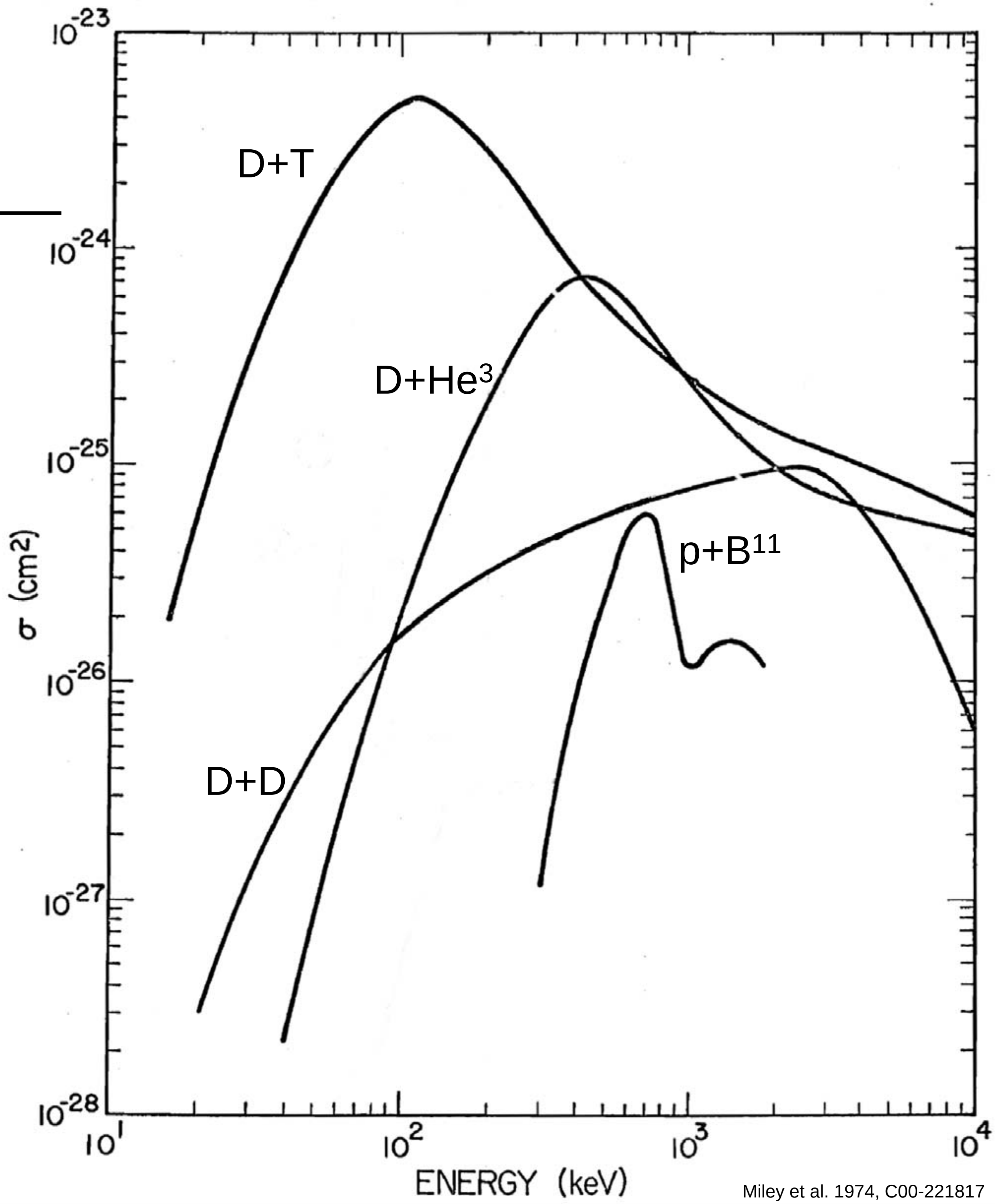
Major Fusion Cross-sections

D + T →
He^4(3.5 MeV) + n(14.1 MeV)

D + He^3 →
He^4(3.6 MeV) + p(14.7 MeV)

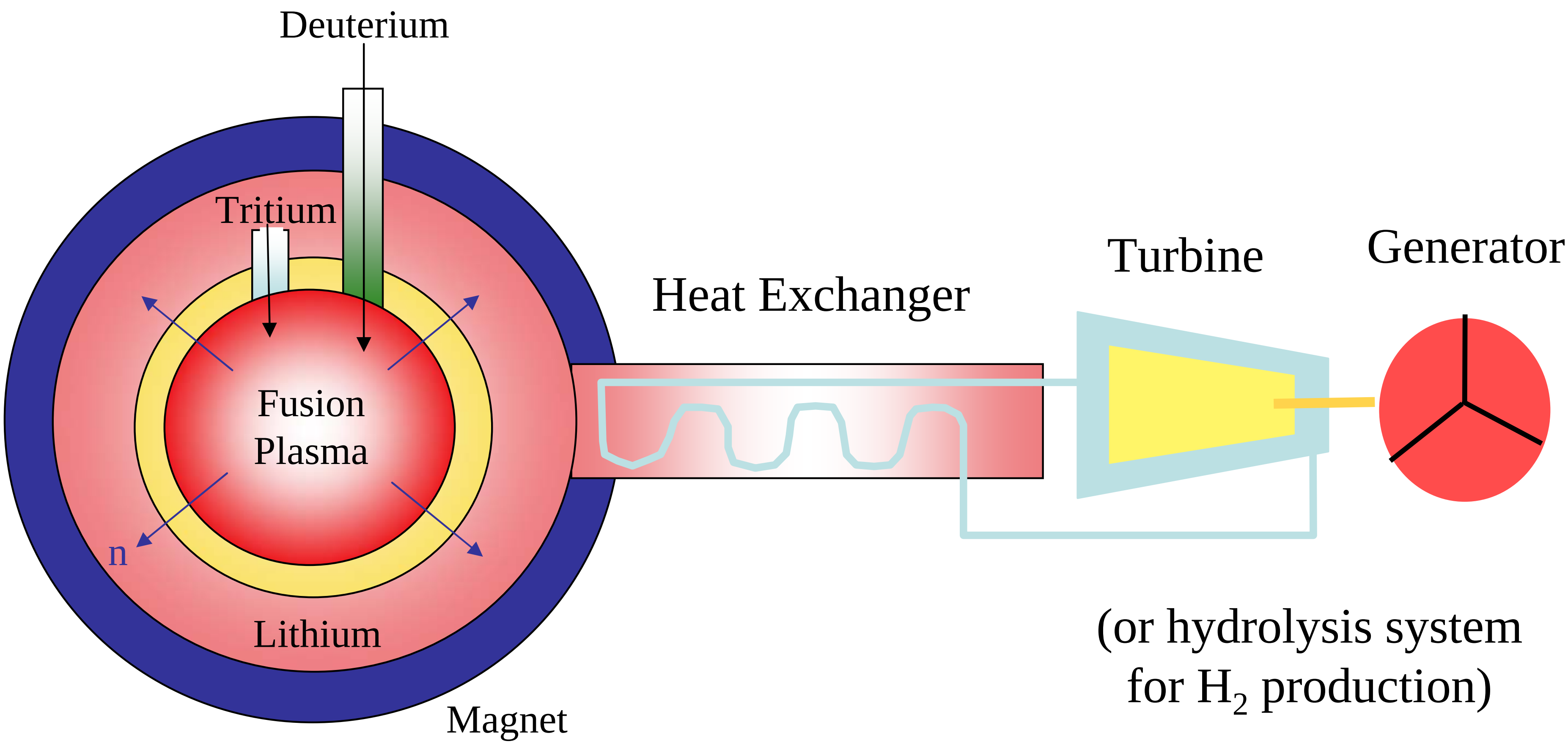
D + D →
He^3 + n +3.3 MeV (50%) or
T + p +4.0 MeV (50%)

p + B^{11} →
3 He^4 + 8.7 MeV



Miley et al. 1974, C00-221817

Magnetic Fusion Power System



Two Approaches to Fusion Power

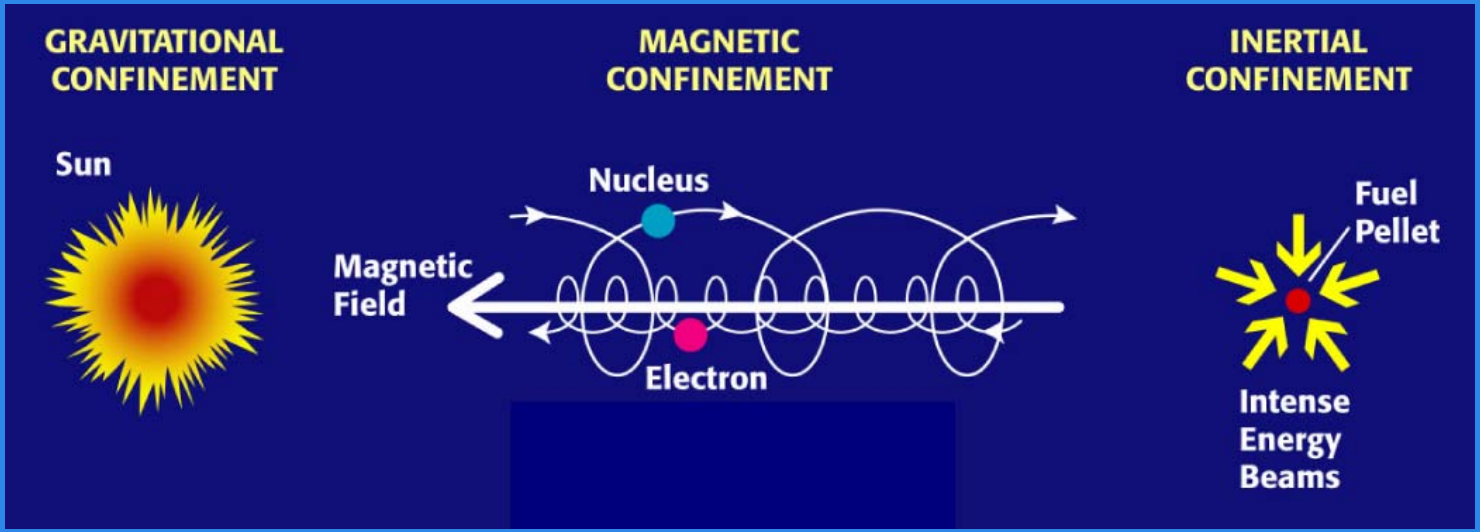
Each has R&D Paths with Plausible Technologies leading to Attractive & Economical Energy

- Inertial Fusion Energy (IFE)
  - Fast implosion of high-density D-T fuel capsules.

    Reaches ~ 200 Gbar from 25-35 fold radial convergence.
  - Several ~ 350 MJ (0.1 ton TNT) explosions per second.
- Magnetic Fusion Energy (MFE)
  - Strong magnetic pressure (100's atm) confine low-density (10's atm) plasma.
  - Particles confined within "toroidal magnetic bottle" for at least ~ 10 km and 100's of collisions per fusion event.
  - Fusion power density (~10 MW/m^3 and 20,000 × solar) allows plasma to be sustained for continuous power.

M.E. Mauel, AAAS05, http://fire.pppl.gov/aaas05_annual.html

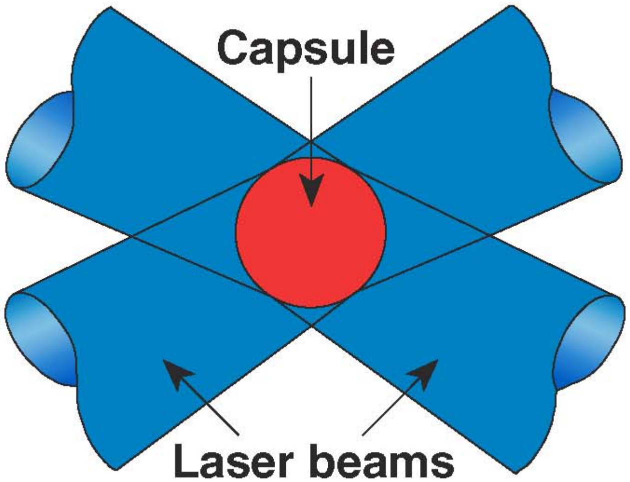
Three Types of Fusion Power

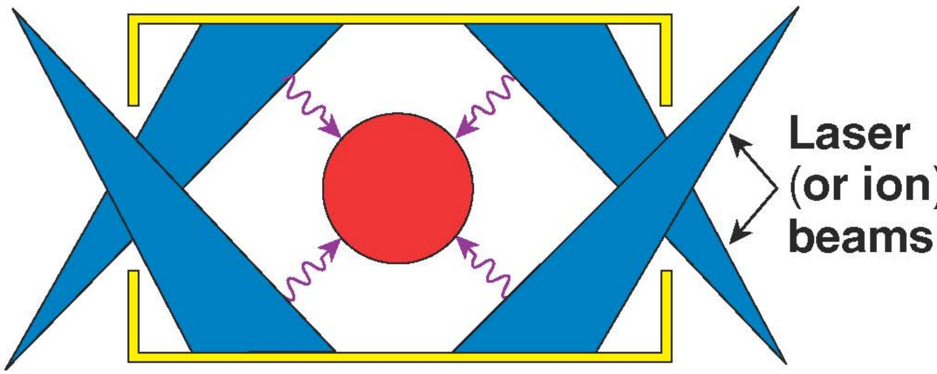


T_i (keV)	~ 1 - 2	10	10
n (m^{-3})	~ 10^{32}	3 X 10^{20}	6 X 10^{30}
R (m)	~ 10^{8}	1	10^{-4}
τ_E (sec)	> 10^{13}	2	10^{-10}

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

The fundamental physics of direct- and indirect-drive ICF implosions is the same





Key physics issues are common to both

- Energy coupling
- Drive uniformity
- Hydrodynamic instabilities
- Compressibility

Direct-drive cryogenic implosions provide essential information for ICF physics.

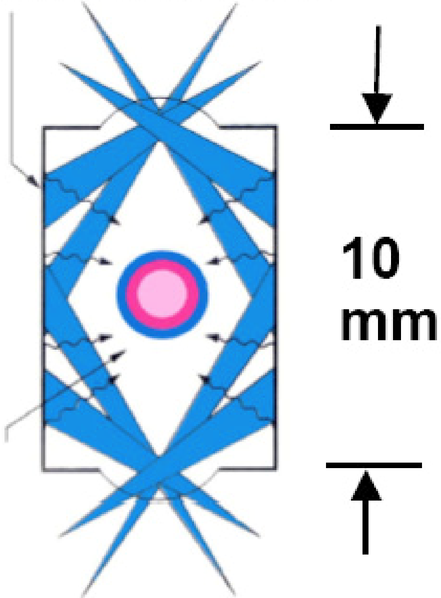
E6426o

R.L. McCrory, APS 2007 http://fire.pppl.gov/aps07_mccrory_icf.pdf

There are two principal approaches to compression in Inertial Confinement Fusion

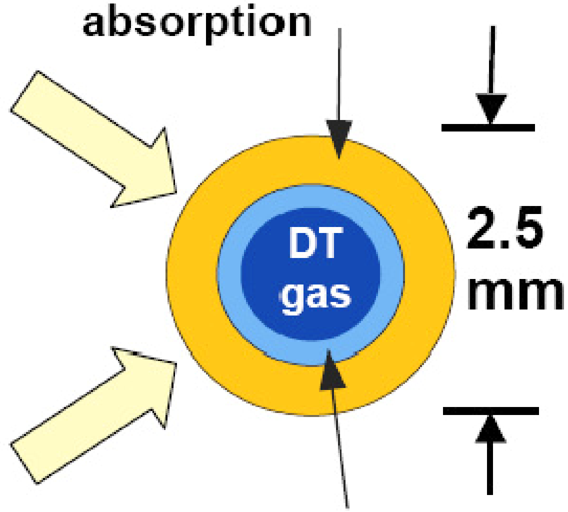
NIC
The National Ignition Campaign

Indirect Drive

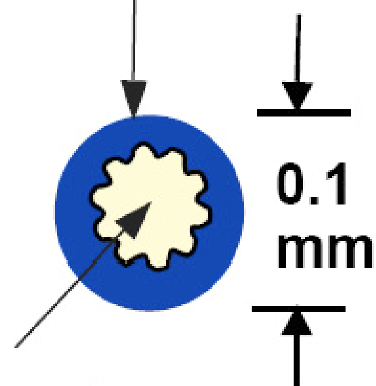


Direct Drive

Inertial Confinement Fusion uses direct or indirect drive to couple driver energy to the fuel capsule



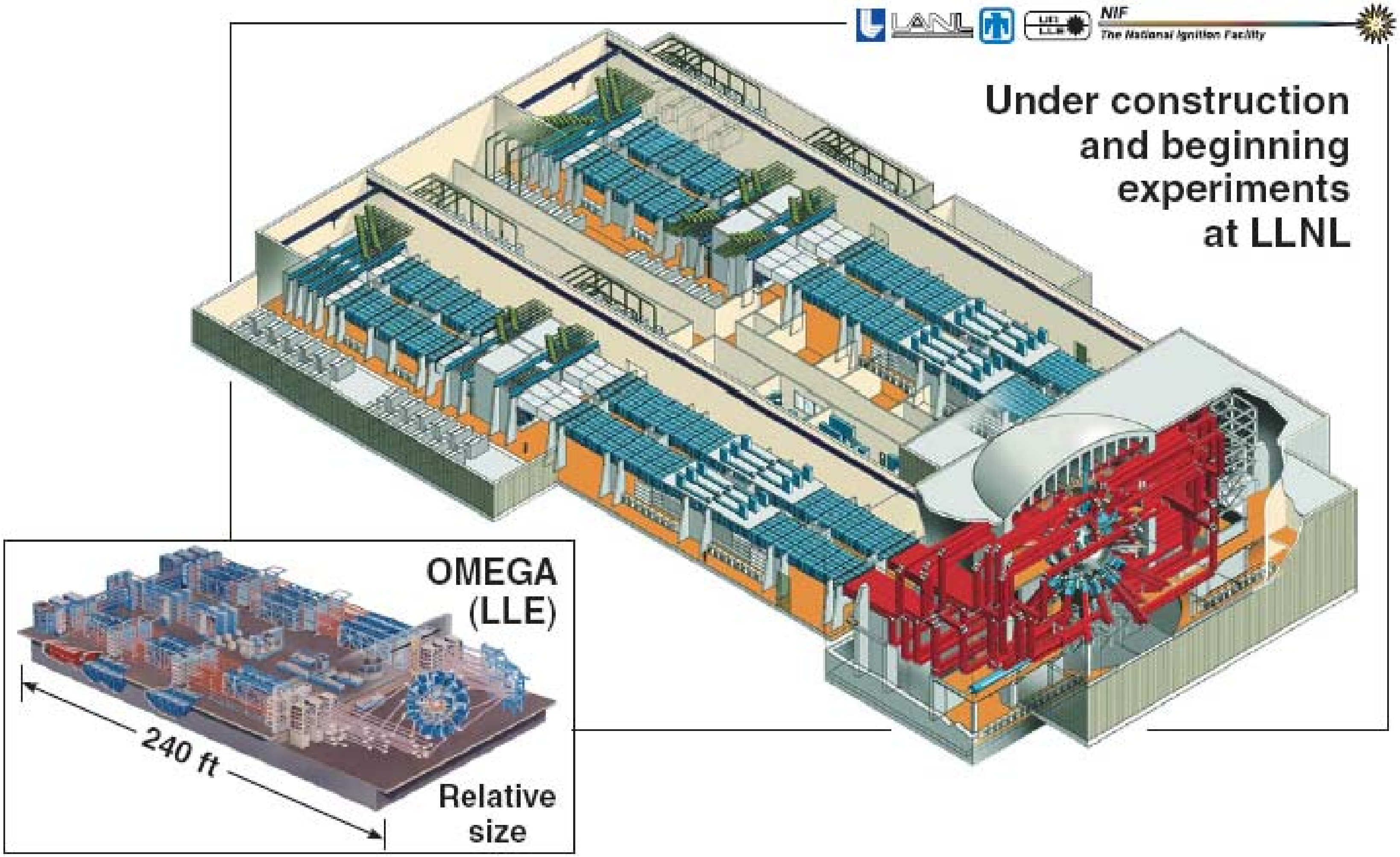
Spherical ablation with pulse shaping results in a rocket-like implosion of near Fermi-degenerate fuel



Spherical collapse of the shell produces a central hot spot surrounded by cold, dense main fuel

J. Lindl, APS 2007, http://fire.pppl.gov/aps07_lindl_maxwell.pdf

The 1.8-MJ National Ignition Facility (NIF) will demonstrate ICF ignition and modest energy gain



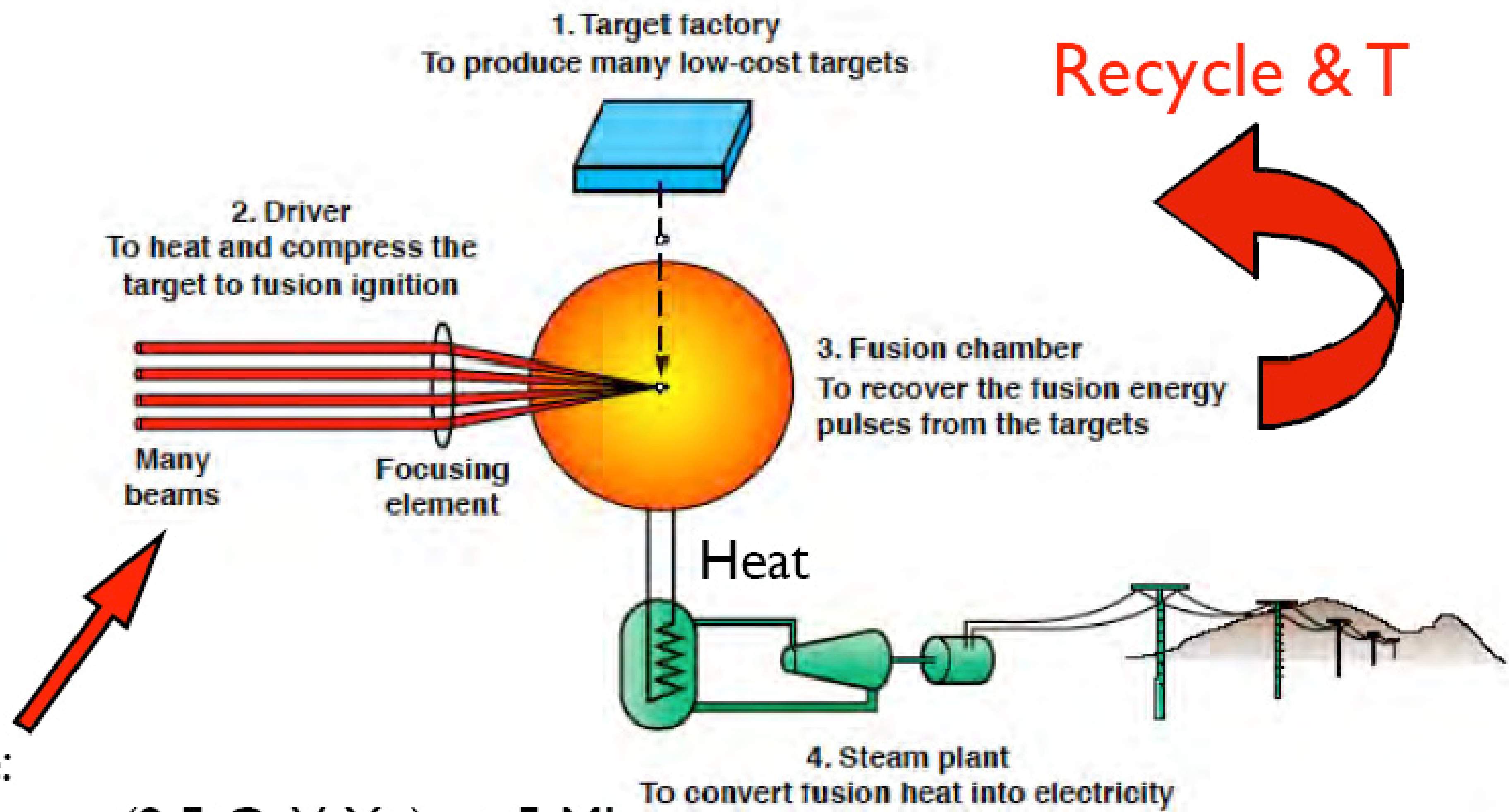
OMEGA experiments are integral to an ignition demonstration on the NIF.

TC4680m

R.L. McCrory, APS 2007 http://fire.pppl.gov/aps07_mccrory_icf.pdf

IFE

< \$0.50/capsule



Example:

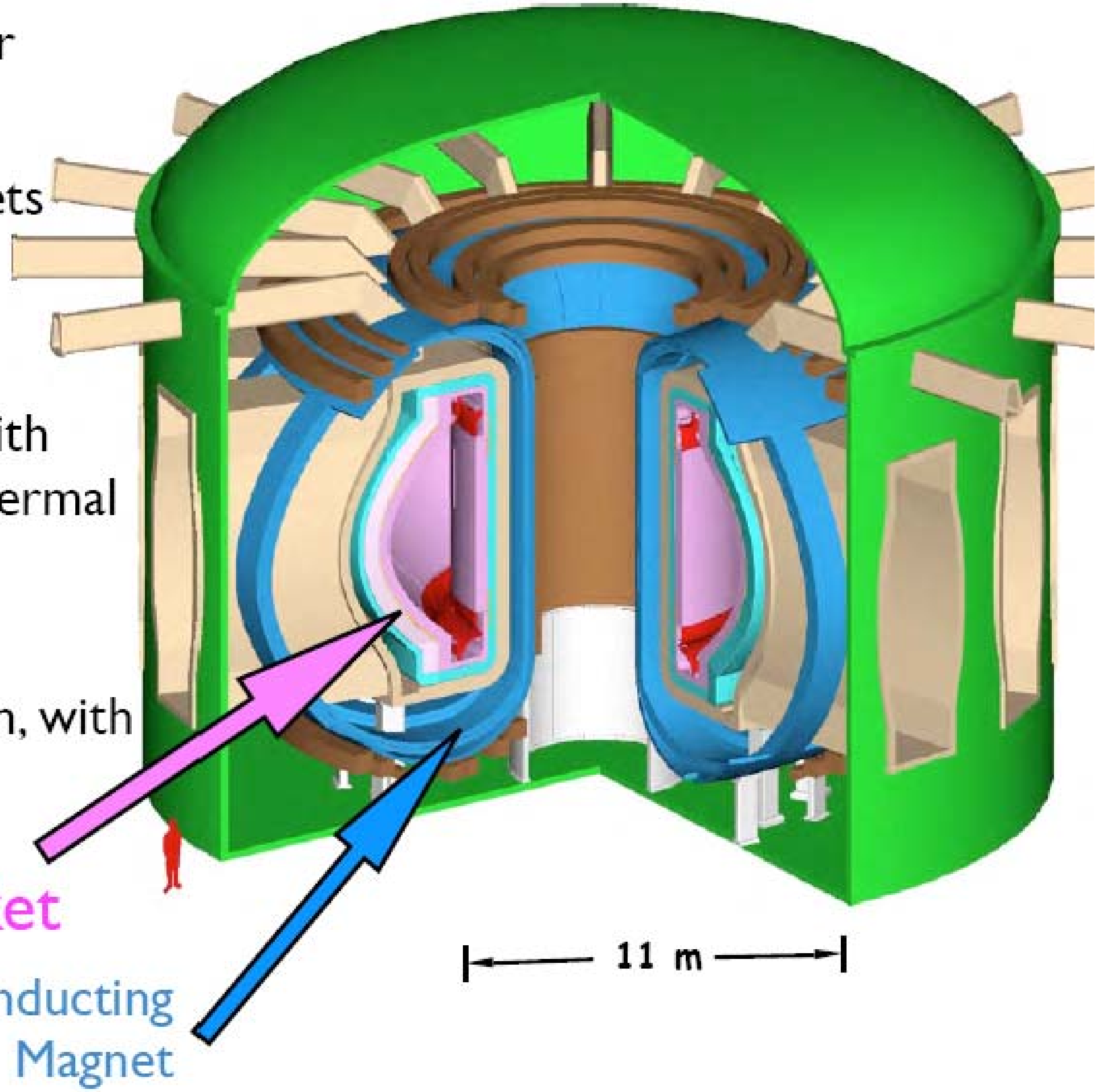
~ 100 beams (2.5 GeV Xe) ⇒ 5 MJ

(About the length of SLAC ~2.5 km)

M.E. Mauel, AAAS05, http://fire.pppl.gov/aaas05_annual.html

MFE

- Toroidal magnetic chamber
- Steady state, Nb_3Sn magnets (Coldest ↔ Hottest)
- SiC blanket (~ 1,100 C) with PbLi coolant yields high thermal efficiency.
- Modular, "easy" to maintain, with 85% availability
- 1 GWe



M.E. Mauel, AAAS05, http://fire.pppl.gov/aaas05_annual.html

Fusion's Materials Challenge

- Unlike fission, the by-products of fusion are not inherently radioactive. Fusion has low proliferation risks.
- When fabricated from low activation materials, fusion does not produce long-lived radioactive waste.
- Fusion's **materials challenge** is to develop long-life, high-strength materials with high neutron-irradiated fracture toughness and good helium swelling resistance.
- **Good options exist**: Ferritic/martensitic steels, Vanadium alloys, and SiC/SiC composites

M.E. Mauel, AAAS05, http://fire.pppl.gov/aaas05_annual.html

$$\text{Fusion Power} \propto n_D n_T \langle \sigma v \rangle V \; 17.6\text{ MeV}$$

$$\propto n^2 \quad T^2$$

$$\propto p^2 \quad \propto \beta^2 B^4$$

Key performance parameter:

$$\beta = \frac{\text{plasma pressure}}{\text{magnetic field pressure}} = \frac{p}{B^2/8\pi}$$

$\beta \sim 3\%$ standard tokamak

$\sim 9\%$ advanced tokamak (mod. j profile, steady state?)

$\sim 50\%$ spherical torus (But B weaker)

$\sim 4-7\% \uparrow ?$ new quasi-axisymmetric stellarators

Lawson Power Balance Criterion

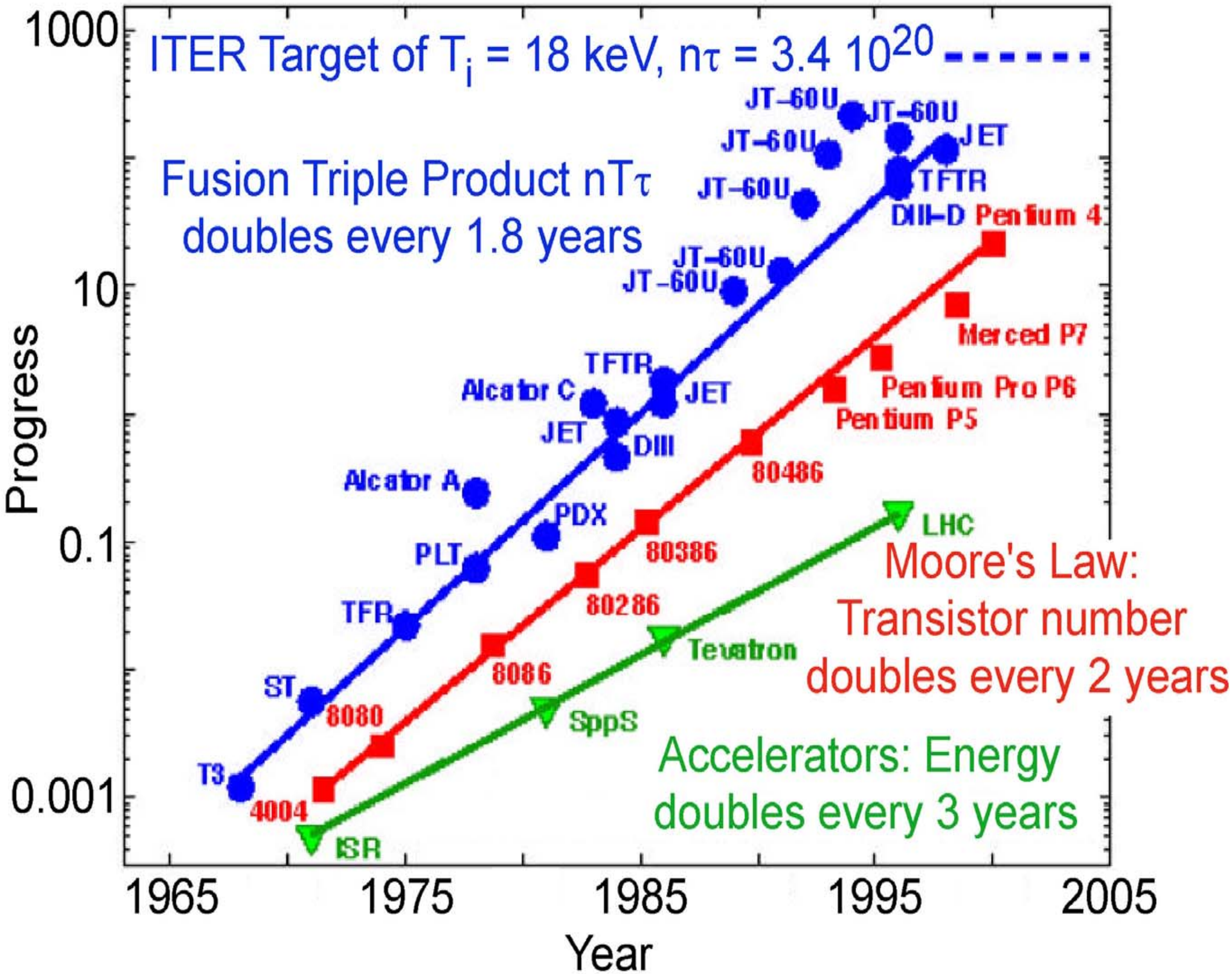
(Simplified)

Key ratio : $\dfrac{\text{Fusion Power}}{\text{Heating Power needed to sustain Plasma}}$

$$\simeq \frac{n^{\cancel{2}}\, T^{\cancel{2}}\, \cancel{V}}{\left(\dfrac{3}{2}\,\dfrac{\cancel{n}\, k\, \cancel{T}\, \cancel{V}}{\tau_E}\right)} \propto n\, T\, \tau_E$$

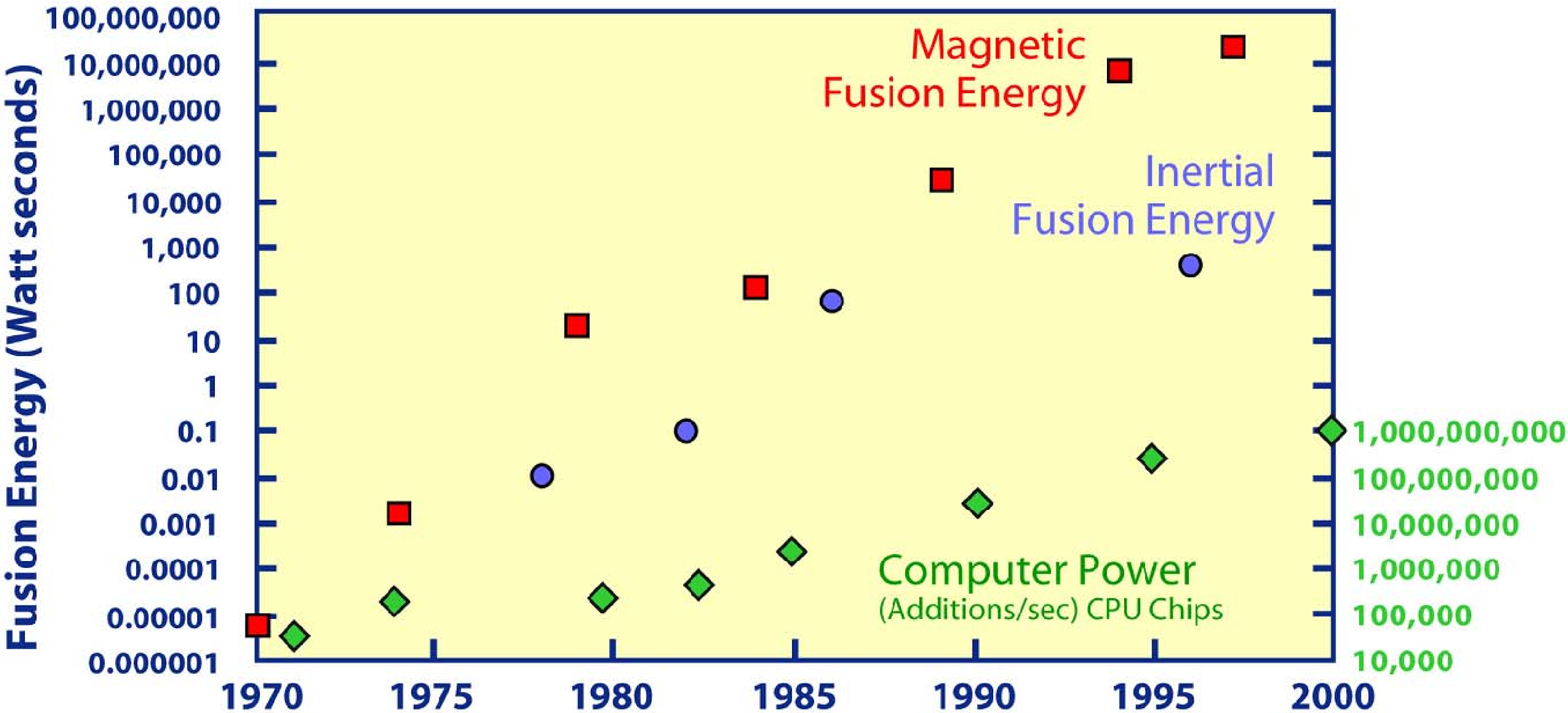
$$Q = \frac{\text{Output Fusion Power}}{\text{Input Power to Heat Plasma}} \propto \frac{5}{\left(\dfrac{C}{n\, T\, \tau_E} - 1\right)}$$

Progress in Fusion Energy Outpaced Computers



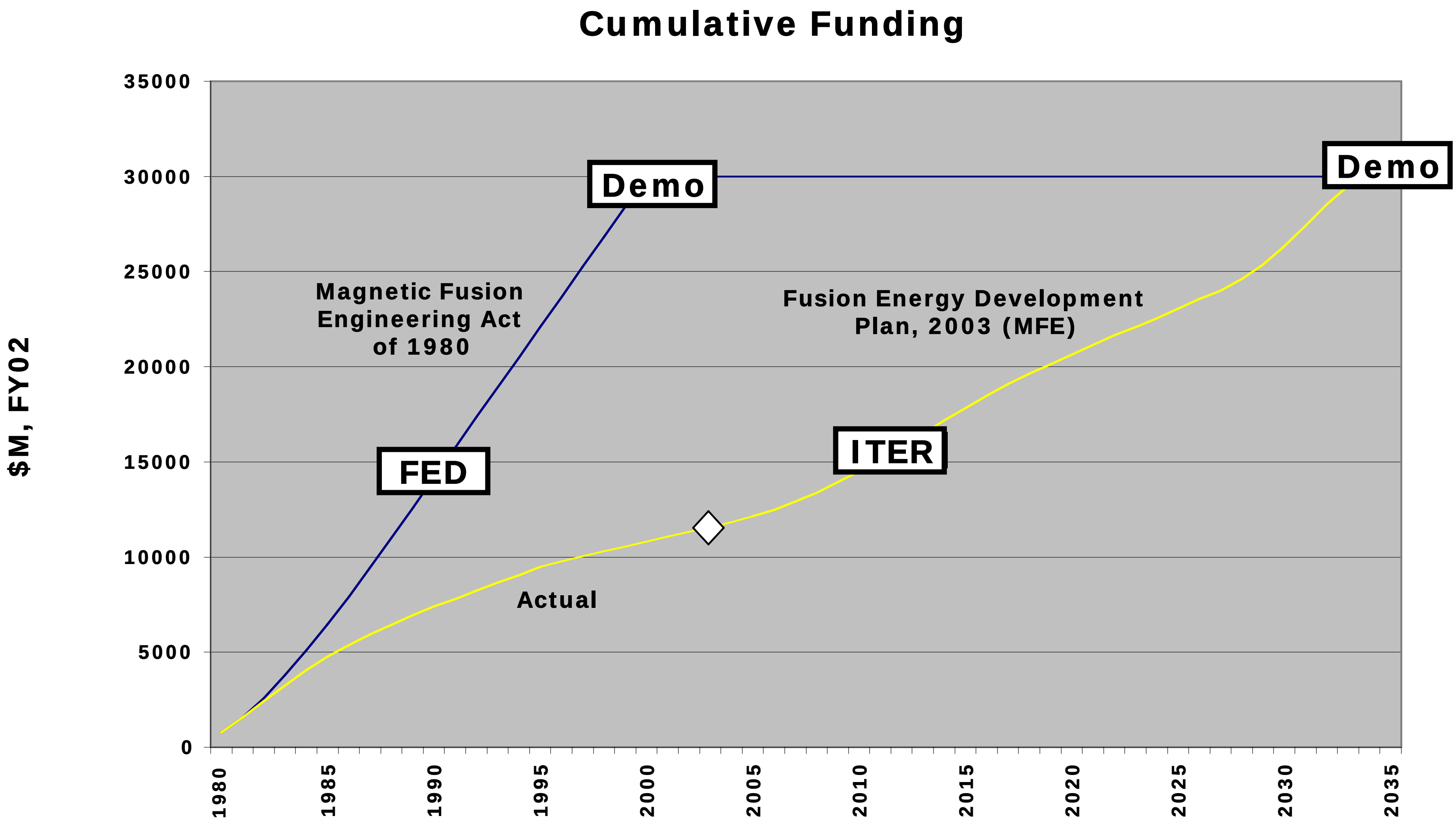
J.B. Lister

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.

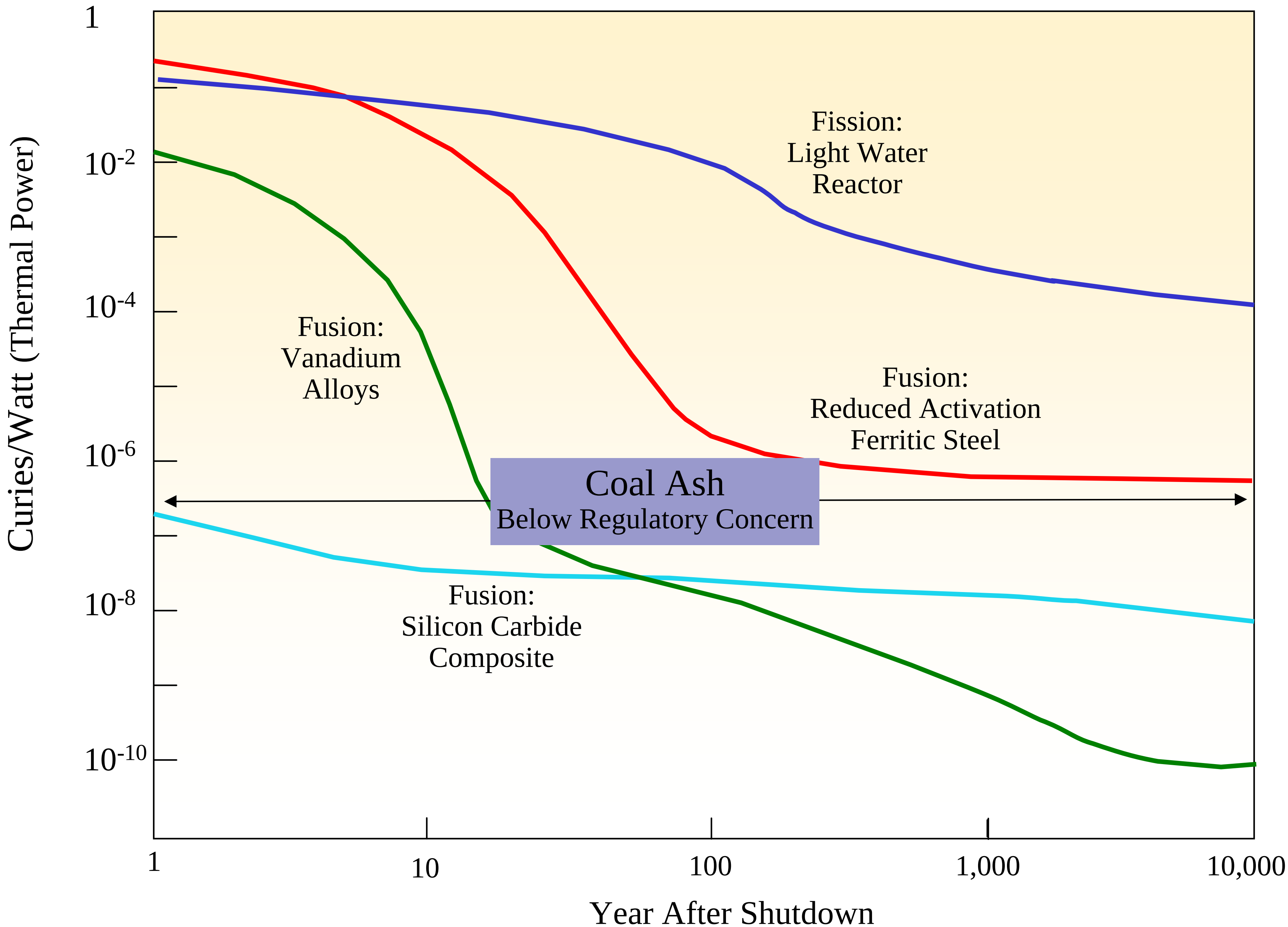
$30B development cost tiny compared to >$100 Trillion energy needs of 21st century and potential costs of global warming. Still 40:1 payoff after discounting 50+ years.

based on slide from R.J. Goldston

Fusion can be an Attractive Domestic Energy Source

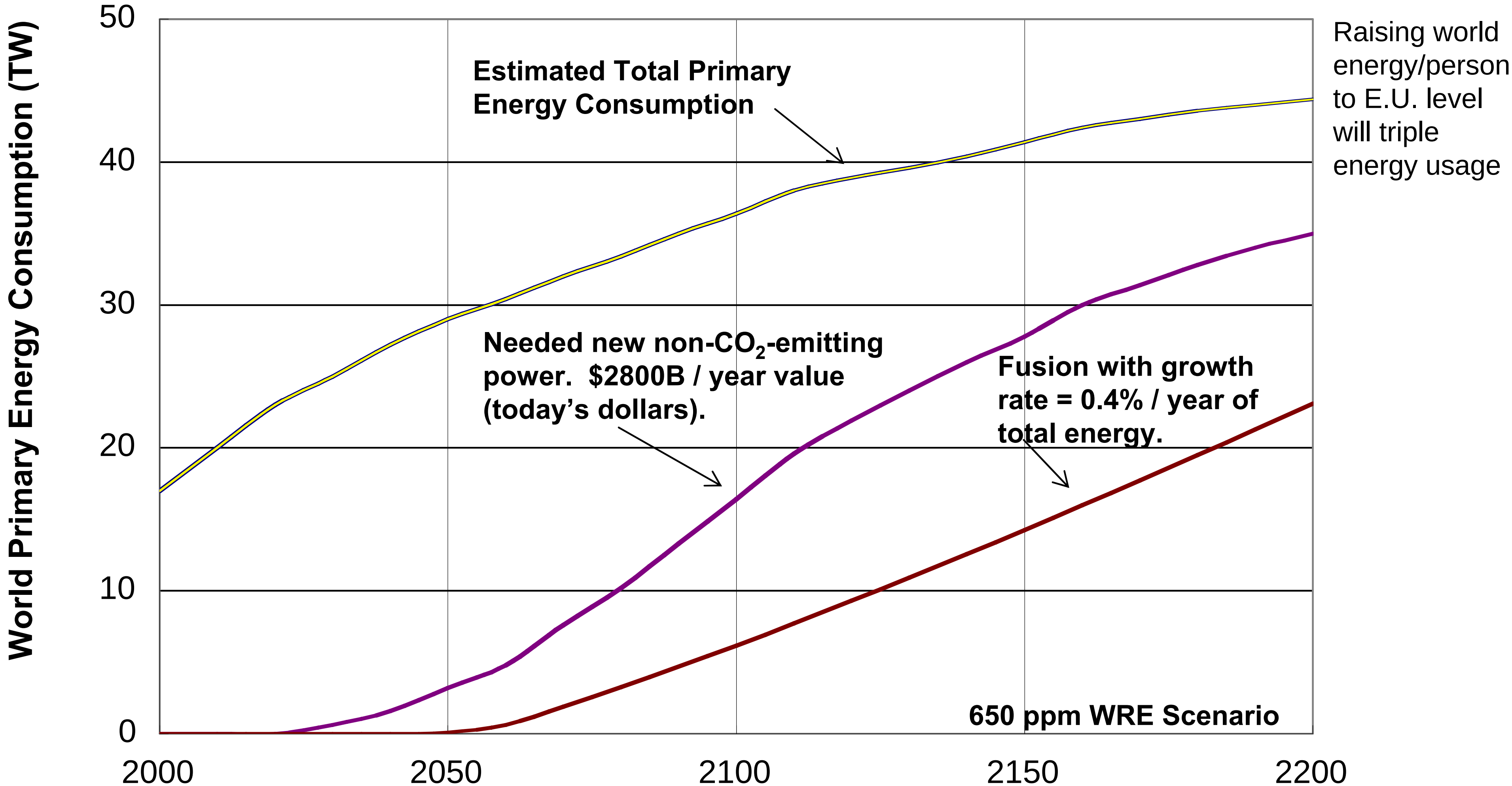
- Abundant fuel, available to all nations
  - Deuterium and lithium easily available for thousands of years
- Environmental advantages
  - No carbon emissions, short-lived radioactivity
- Can't blow up, resistant to terrorist attack
  - Less than a minute's worth of fuel in the chamber
- Low risk of 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



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

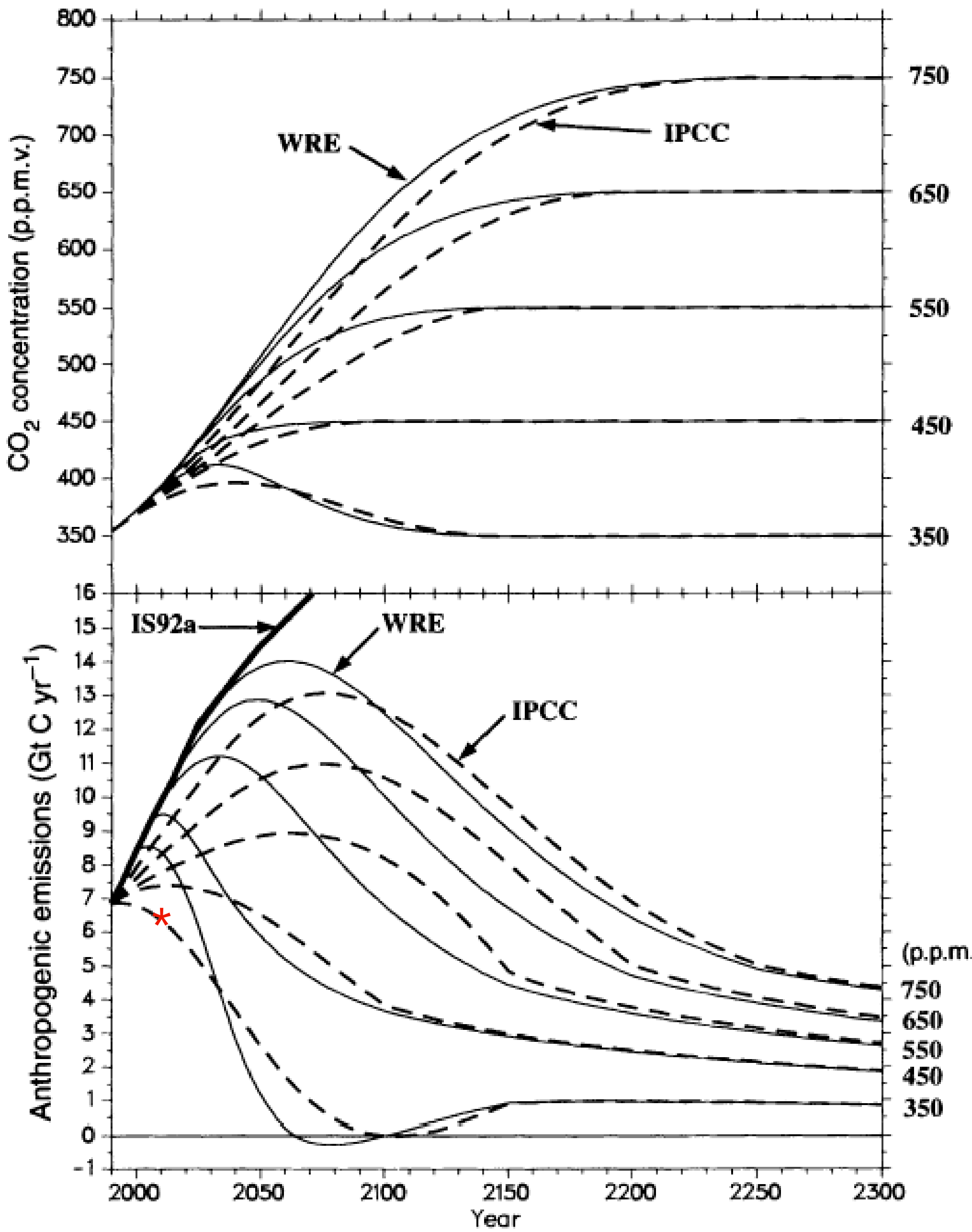
Return on investment still ~40:1 payoff after discounting for Net Present Value, 20% advantage over other energy sources, 50% chance of success, 1/3 payoff to U.S.



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

based on slide from R.J. Goldston

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



twice preindustrial

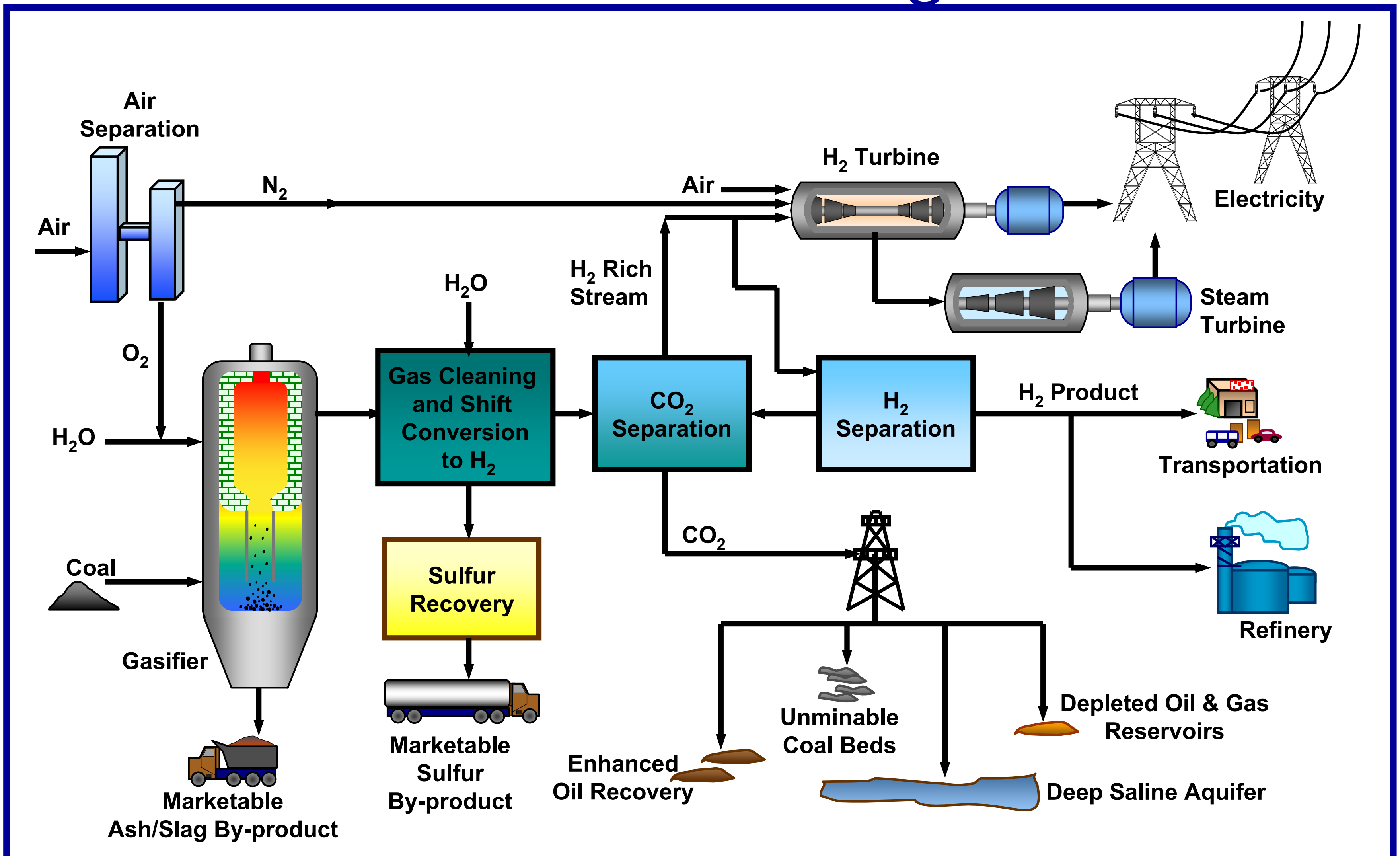
Raising world energy/person to E.U. level will triple energy usage

* Kyoto Accords: 2012 target 10% below 1990

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

GWH: Adequate reductions in CO_2 over next 50 years probably possible with improved efficiency, windmills, fission, CO_2 sequestration, etc. But after 50 years, need fusion, or fission breeders, or ??

Future Gen Flow Diagram

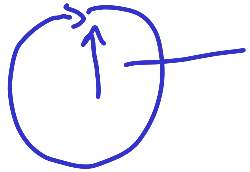


From Gary J. Stiegel, http://wvodyssey.nrcce.wvu.edu/2004/post_event/ppt/Stiegel_gasification.ppt

A Crash Course in Magnetic Confinement (in 3 slides)

$$m\frac{d\mathbf{v}}{dt} = q\left(\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{c}\right) + \text{Collisions}$$

$\mathbf{B}$ ⊙



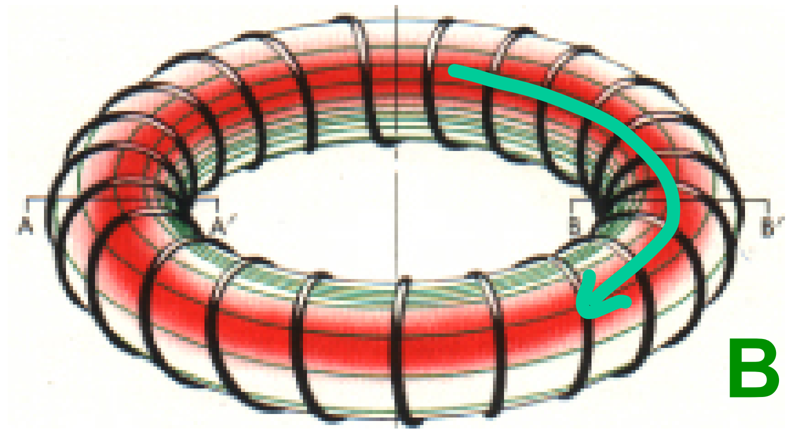
$\rho_\perp \sim 3$ mm for 10 keV Deuterons $B = 5$ T

gyrofrequency ~ 40 MHz

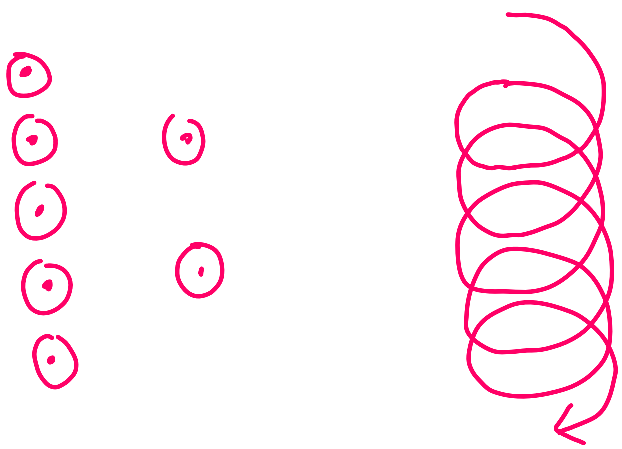
$\lambda_{mfp} \sim 10$ km for $n \sim 10^{20}/m^3$

Particles not confined along $\mathbf{B}$

so wrap into a torus:



<u>Problem:</u> Non-uniform $|\mathbf{B}|$ ⇒ particle drift



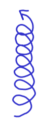
↓ ions drift down

Even worse: Charge imbalance

$\Rightarrow$ Instability

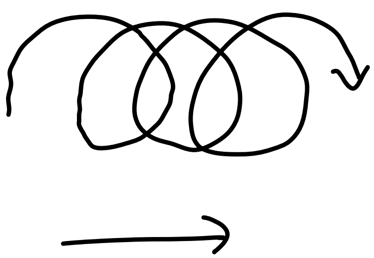
$\leftarrow \nabla B$ $\odot\, \underset{\sim}{B}$

ions drift down

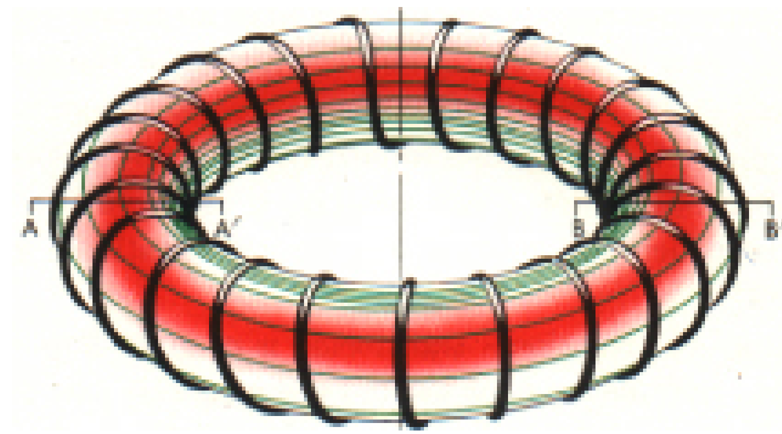


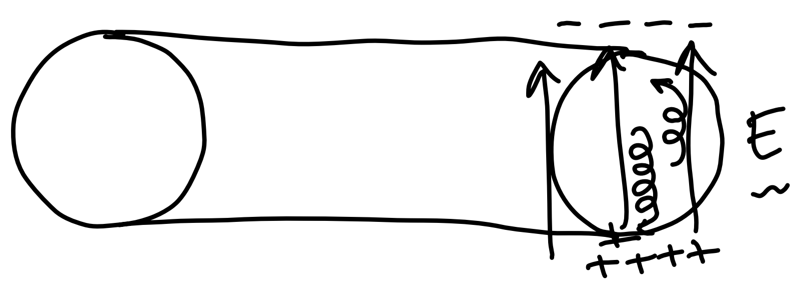
↑ electrons drift up

Particle motion in $\underset{\sim}{E}$ & $\underset{\sim}{B}$:



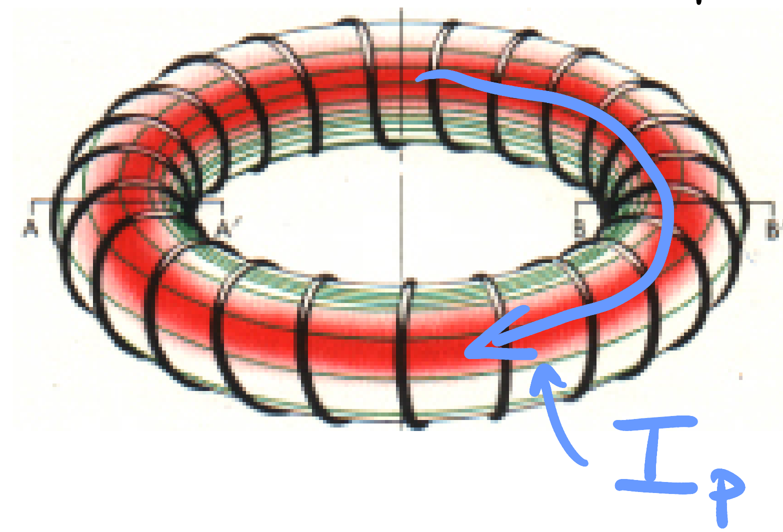
$$\underset{\sim}{v}_{drift} = \frac{c}{B^2}\, \underset{\sim}{E} \times \underset{\sim}{B}$$



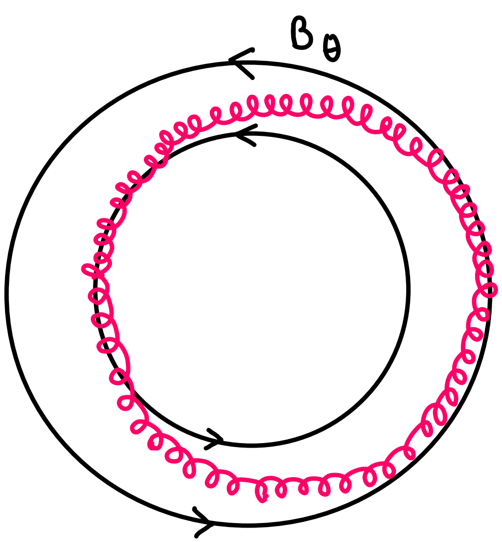


Cure problems by twisting the $\underset{\sim}{B}$ field

Induce a current in plasma:

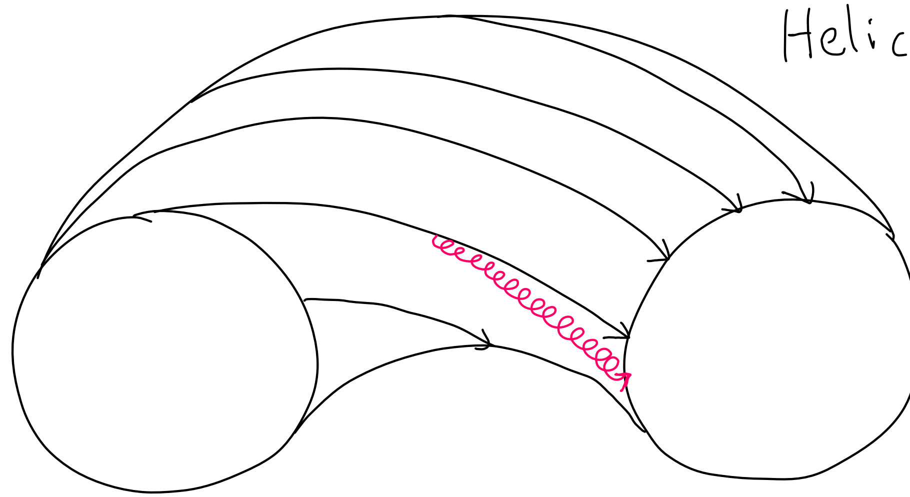


ion motion along twisting $\underset{\sim}{B}$ field + downward drift:



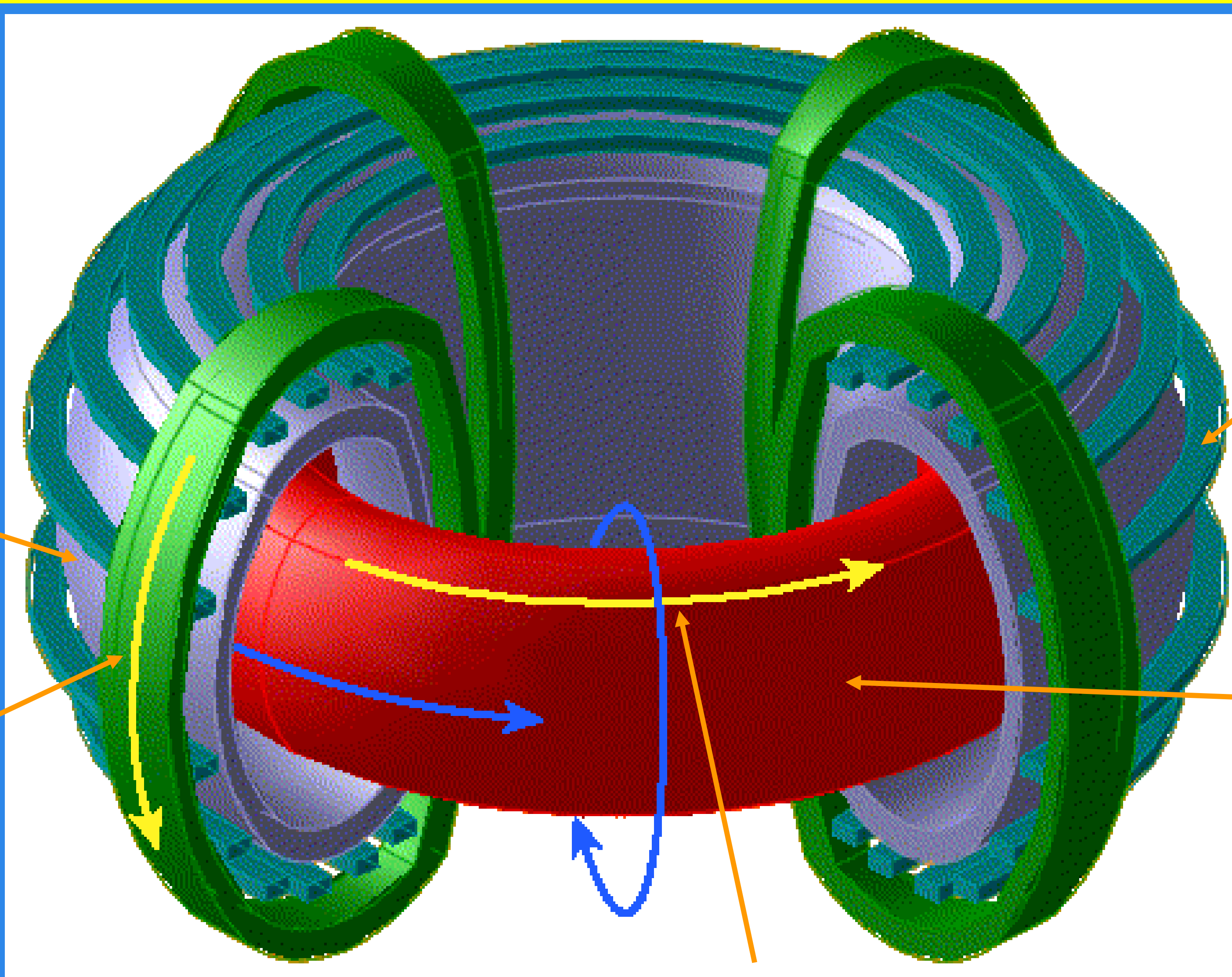
poloidal projection

Helical twist in $\vec{B}$



Perspective view

The Most Successful Magnetic Confinement Configuration is the Tokamak



Stabilizing and shaping magnetic fields are generated by currents in other coils

vacuum vessel

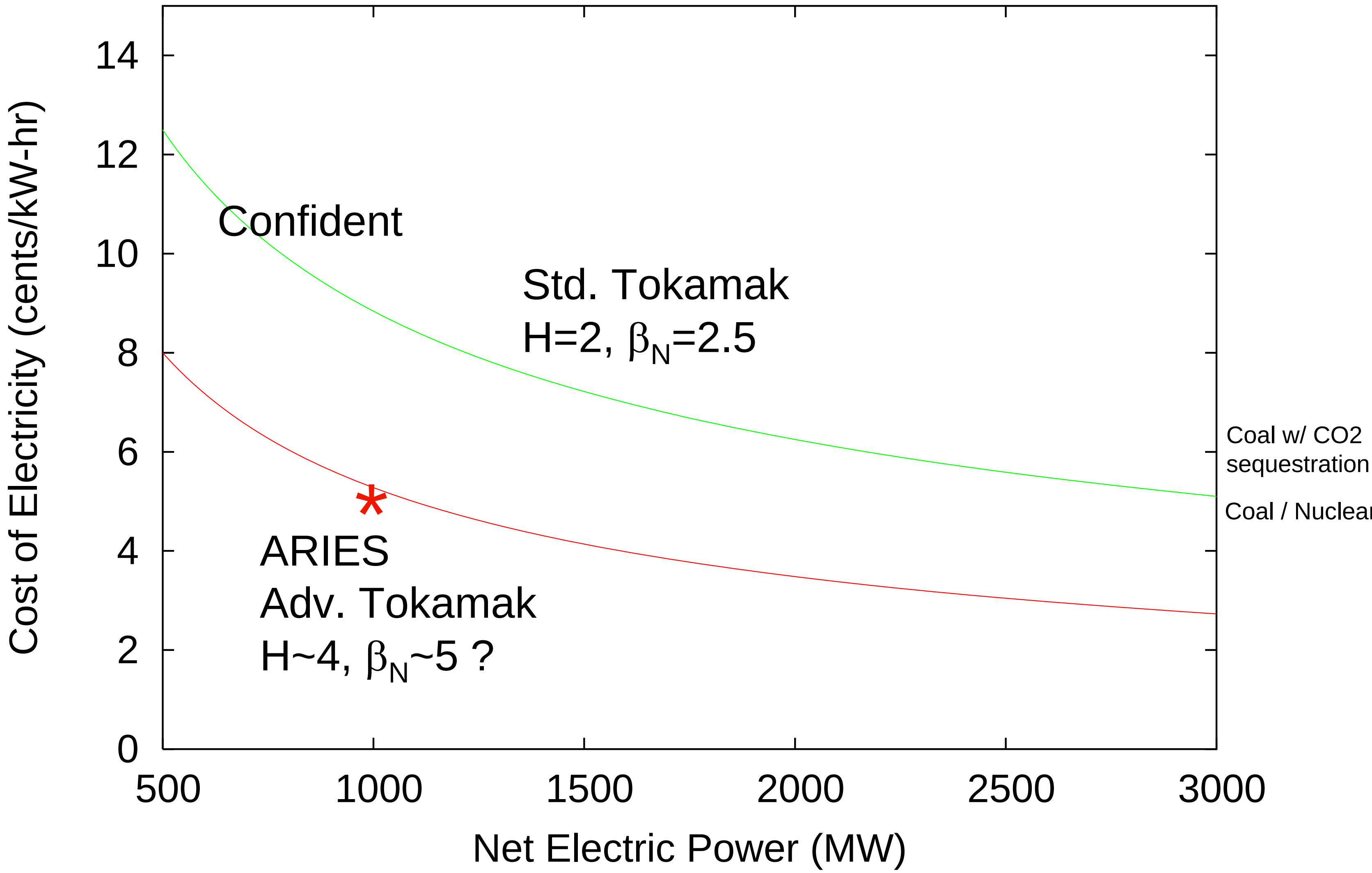
plasma

Current driven through coils distributed around torus creates primary magnetic field

An external transformer induces a current in plasma around torus that creates a smaller magnetic field

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

↓ 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/

↓ turbulence & ↑ β could significantly improve fusion

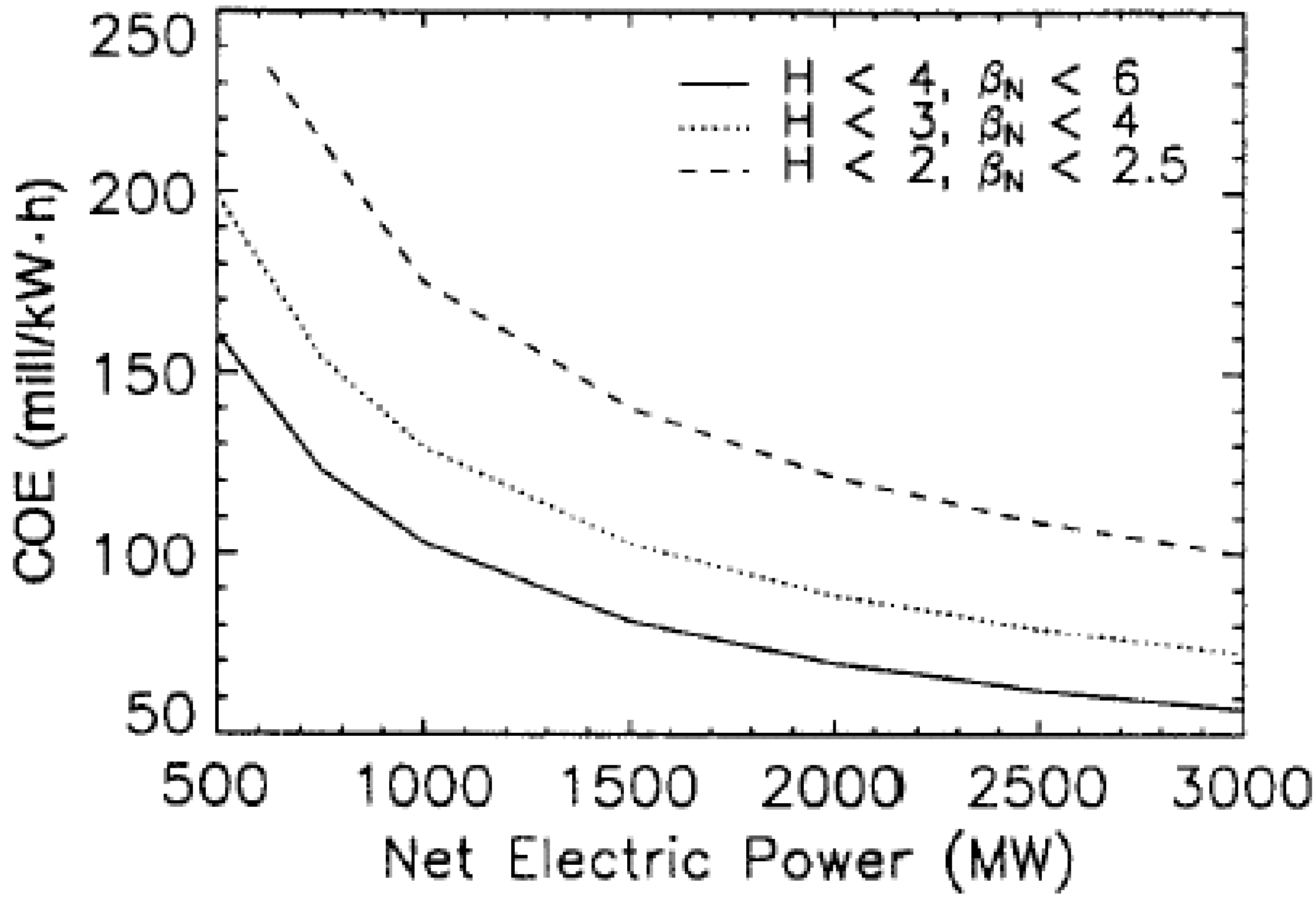
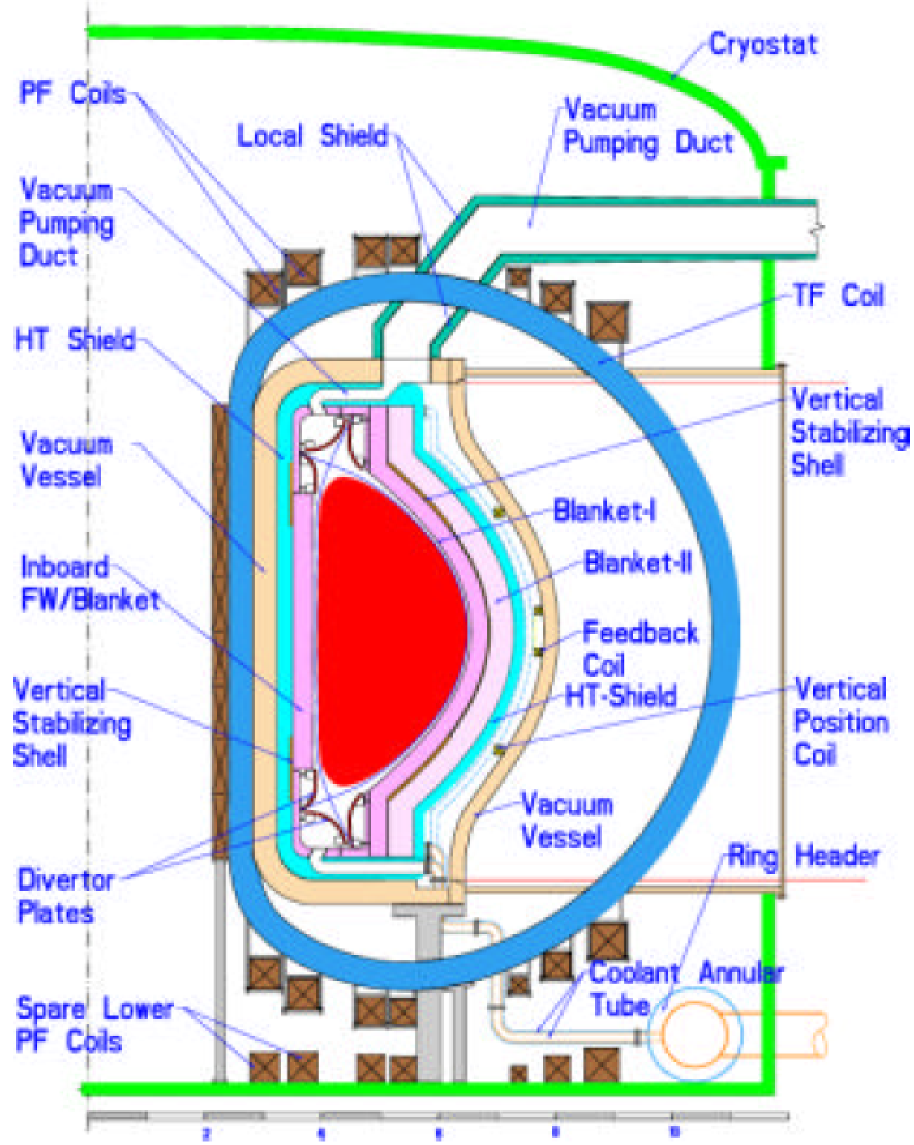


FIG. 4. Minimum COE steady state reactor parameters versus the net electric output. Cases are shown for three physics levels: (a) present day levels that would be sustainable in a non-transient manner in a conservatively designed system ($H \leq 2, \beta_N \leq 2.5$)*, (b) moderately improved physics*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

Galambos, Perkins, Haney, & Mandrekas 1995 Nucl. Fus.

Table 1: Major Parameters of ARIES-AT

Plasma aspect ratio	4.0
Major toroidal radius (m)	5.2
Plasma minor radius (m)	1.3
Plasma elongation, κ_x	2.2
Plasma triangularity, δ_x	0.84
Toroidal β_N	5.4*
Toroidal β	9.2 %
Electron density (10^{20} /m^3)	2.3
Greenwald Density (10^{20} /m^3)	2.4
ITER-98H scaling multiplier	1.4
Plasma current (MA)	13
CD power to plasma (MW)	36
On-axis toroidal field (T)	6.0
Peak field at TF coil (T)	11.4
Thermal cycle efficiency	59%
Average neutron load (MW/m^2)	3.3
Fusion power (MW)	1,755
Recirculating power fraction	14%
Net plant efficiency	51%
Cost of electricity (c/kWh)	5



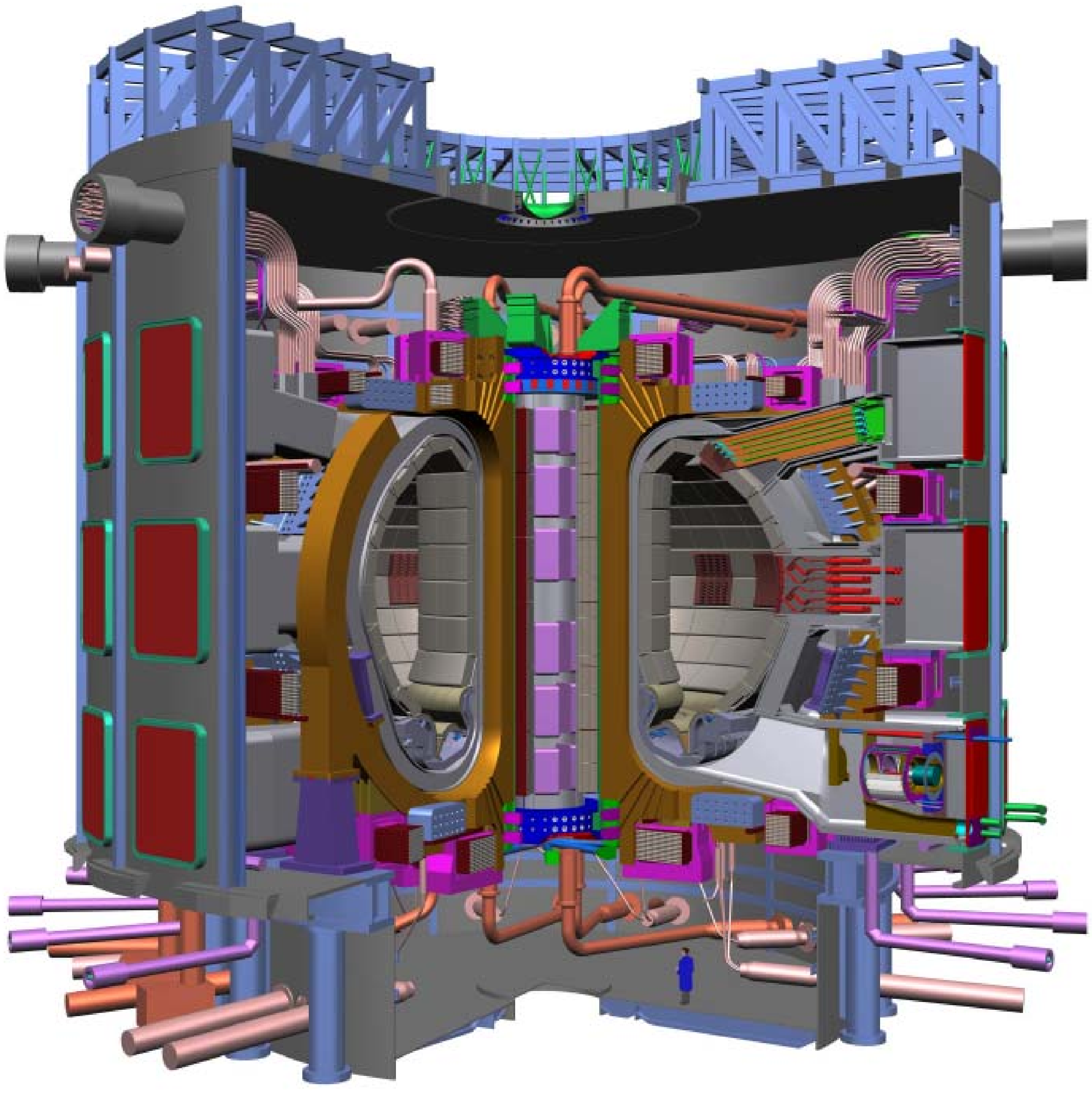


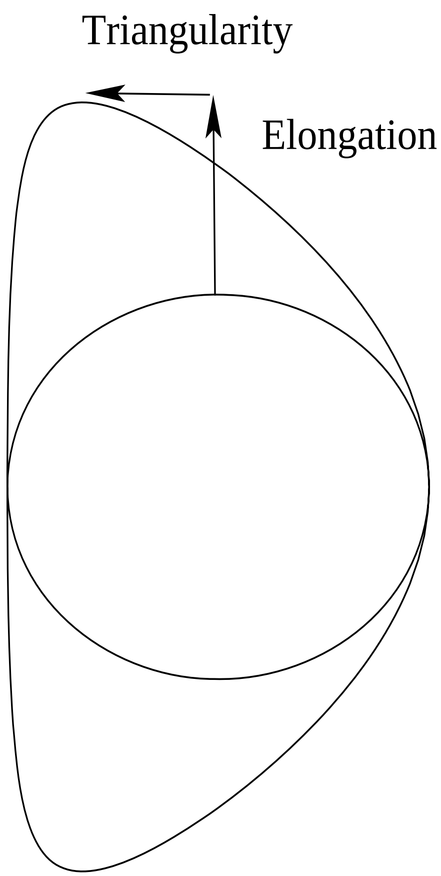
Figure 1.2.1-2 ITER Tokamak Cutaway

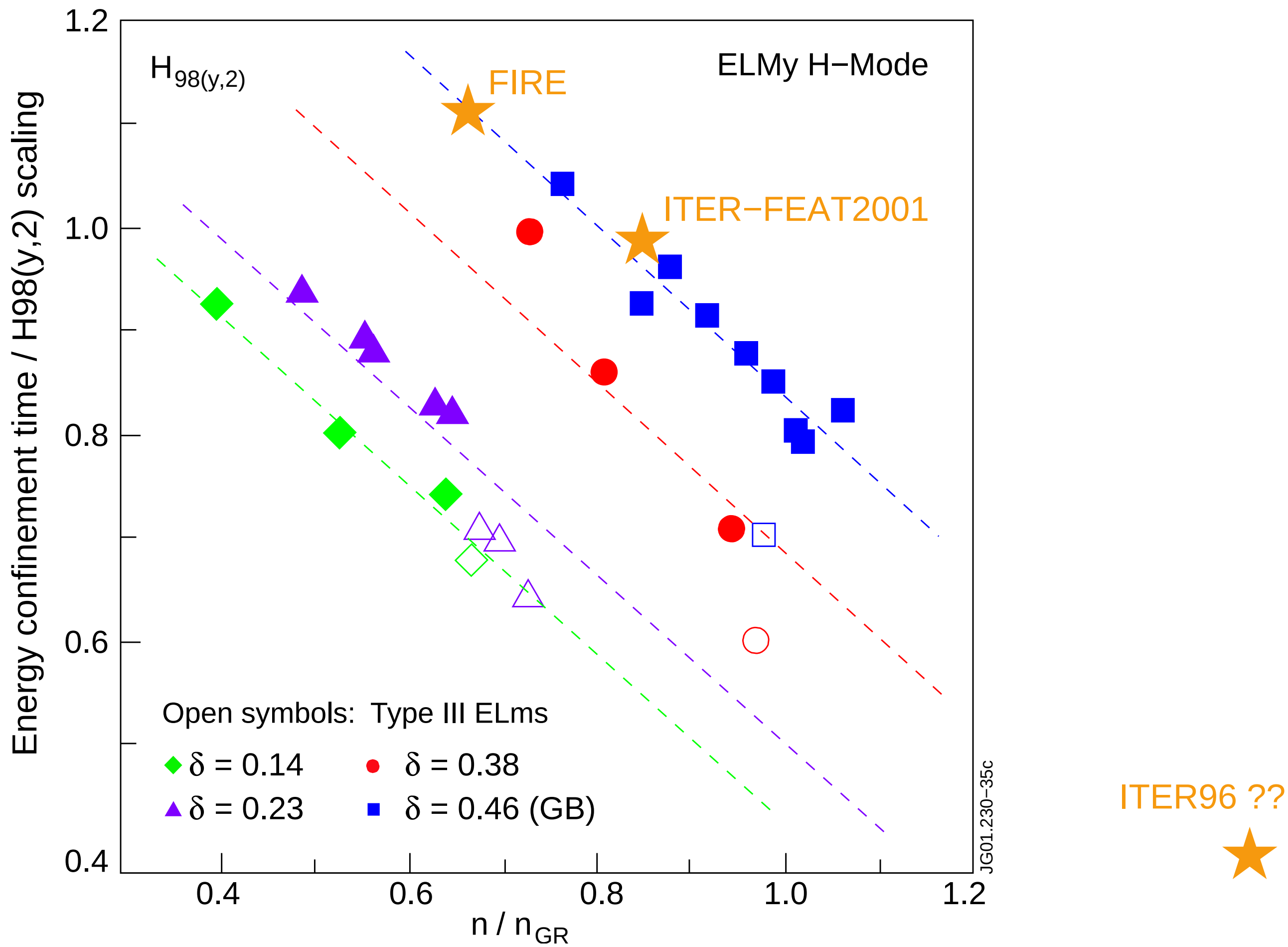
Parameter	400 MW	500 MW
R/a (m/m)	6.2/2.0	6.2/2.0
Volume (m^3)	831	831
Surface (m^2)	683	683
Sep.length (m)	18.2	18.2
$S_{cross\text{-}sect.}$ (m^2)	21.9	21.9
B_T (T)	5.3	5.3
I_P (MA)	15.0	15.0
κ_X/δ_X	1.85/0.48	1.85/0.48
κ_{95}/δ_{95}	1.70/0.33	1.70/0.33
l_i (3)	0.84	0.84
V_{loop} (mV)	75	75
q_{95}	3	3
β_N	1.8	2.0
$\langle n_e \rangle$ (10^{19} m^{-3})	10.1	11.3
$\langle n_e \rangle / n_G$	0.85	0.94
$\langle T_e \rangle$ (keV)	8.8	8.9
$\langle T_i \rangle$ (keV)	8.0	8.1
$\langle \beta_T \rangle$ (%)	2.5	2.8
β_p	0.65	0.72

Parameter	400 MW	500 MW
$P_{RF} + P_{NB}$ (MW)	7 + 33	17 + 33
P_{OH} (MW)	1	1
P_{TOT} (MW)	121	151
P_{BRM} (MW)	21	26
P_{SYN} (MW)	8	8
P_{LINE} (MW)	18	27
P_{RAD} (MW)	47	61
P_{FUS} (MW)	400	500
$P_{LOSS}/P_{L\text{-}H}$	87/48	104/51
Q	10	10
τ_E (s)	3.7	3.4
W_{th} (MJ)	320	353
W_{fast} (MJ)	32	34
$H_{H98\,(y,2)}$	1.0	1.0
τ_{He}^*/τ_E	5	5
$Z_{eff,\,ave}$	1.66	1.72
$f_{He,axis\,/\,ave}$ (%)	4.3/3.2	4.4/3.2
$f_{Be,axis}$ (%)	2.0	2.0
$f_{Ar,axis}$ (%)	0.12	0.14

ITER Final Design Report 2001, http://www.iter.org/reports.htm

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 $$n_{Gr} = \frac{I_p}{\pi a^2} \propto \frac{B_T}{Rq_{95}}\left[1+\kappa^2\left(1+2\delta^2\right)\right]$$

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

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

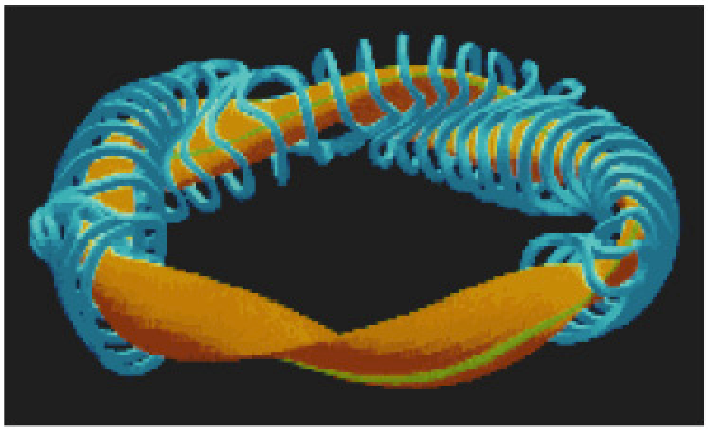
FIRE pushes to even stronger shaping (feedback coils closer) & reduced size with high field cryogenic CuBe (achievable someday with high-Tc superconductors?)

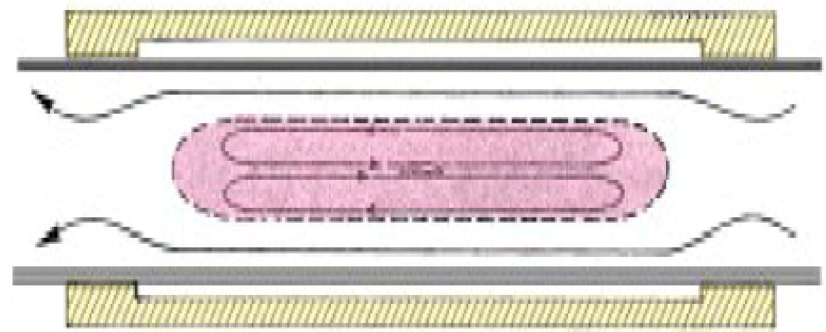
	R (m)	a (m)	B (T)	I_p (MA)	n_{Gr} $10^{20}/m^3$	$\langle n_e \rangle / n_{Gr}$	κ_x	δ_x	P_{fusion} MW	$P_\alpha / 2\pi R$	τ_E / τ_{98H}	β_{norm}
ITER-96	8.14	2.80	5.68	21.0	0.85	1.50	1.75	0.35	1500	5.9		
ITER-FEAT	6.20	2.00	5.30	15.1	1.19	0.85	1.85	0.48	400	2.0	1.0	1.8
FIRE	2.14	0.60	10.0	7.7	6.92	0.66	2.00	0.70	150	2.2	1.0	1.8
Aries-AT	5.20	1.30	5.86	12.8	2.41	1.00	2.18	0.84	1760	9.0	1.4	5.4

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.

MFE CONFIGURATIONS IN THE PORTFOLIO

Externally Controlled ⟷ **Self Organized**





Example: Stellarator
Coils link plasma
Magnetic fields from external currents
Toroidal field >> poloidal field
Large R/a
More stable, better confinement

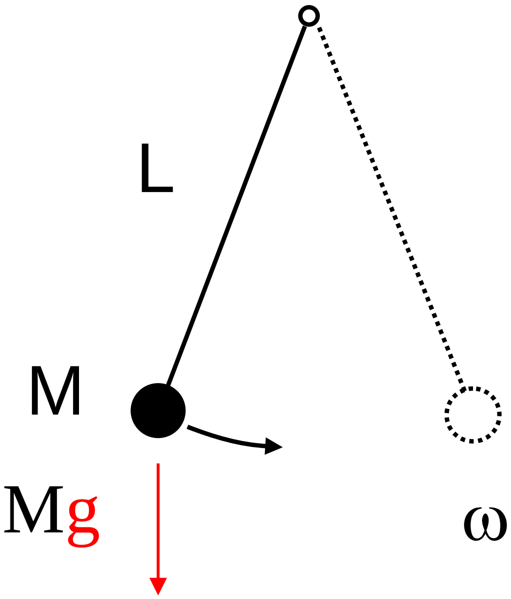
Example: FRC
Coils do not link plasma
B from internal currents
Poloidal B >> Toroidal B
R/a $\rightarrow$ 1.0
Higher power density

From R.J. Goldston, 1999, SEAB_RJG.pdf

Next few slides: Intuitive picture of the toroidal plasma instabilities, and how to stabilize them

-- based on analogy with Inverted pendulum / Rayleigh-Taylor instability

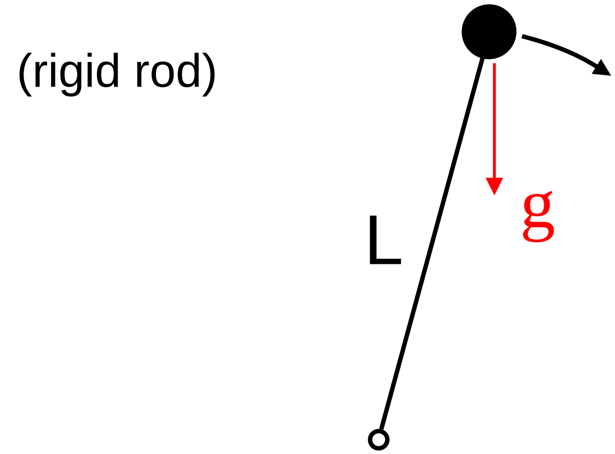
Stable Pendulum



F=Mg

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

Unstable Inverted Pendulum

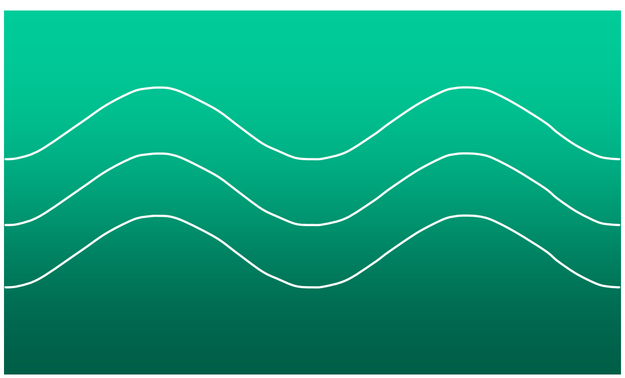


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

↑ Instability

Density-stratified Fluid

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

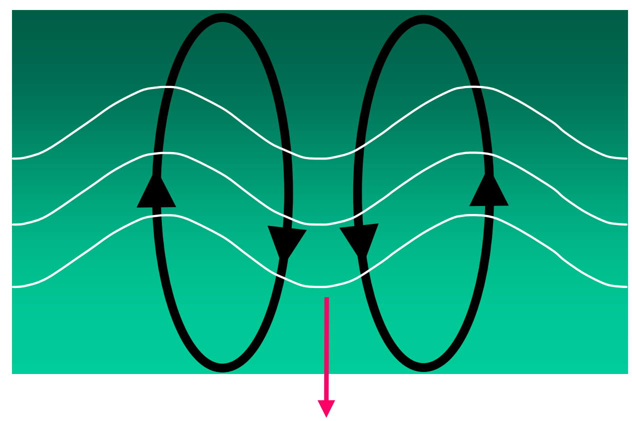


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

$\Rightarrow$Rayleigh-Taylor Instability

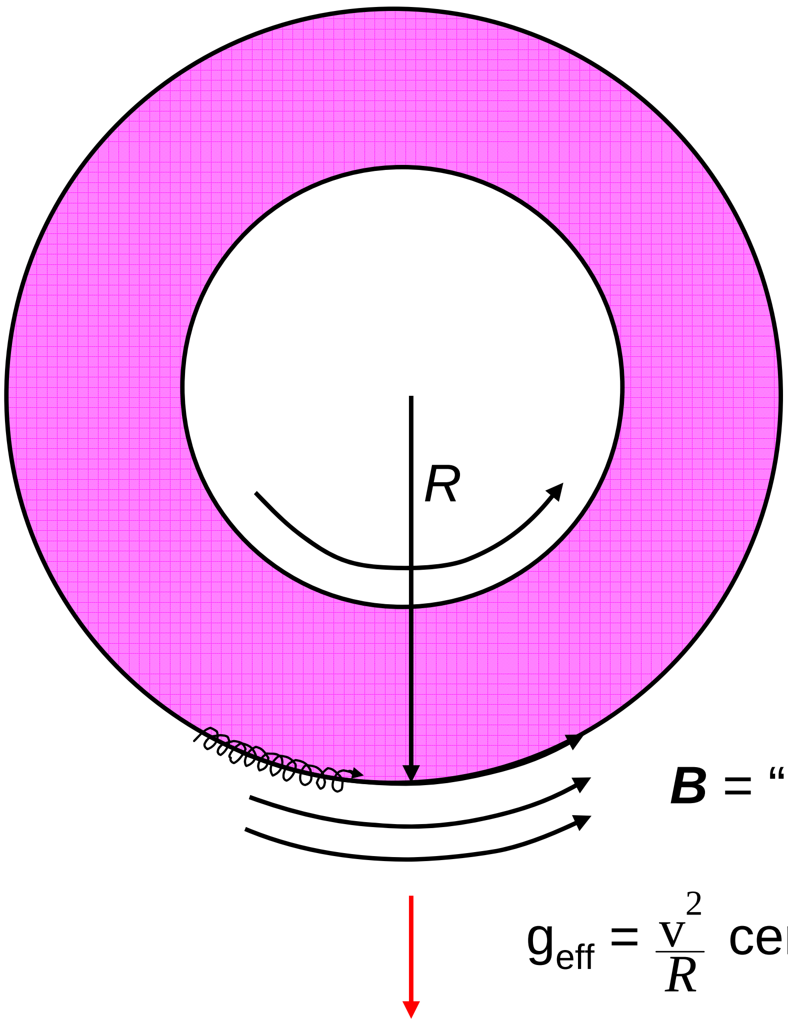
$\rho=\exp(y/L)$



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:

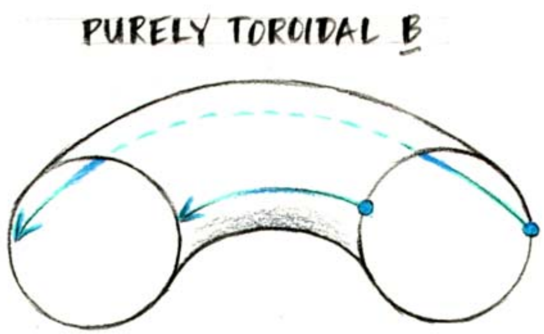
$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{V_t^2}{RL}} = \frac{V_t}{\sqrt{RL}}$$

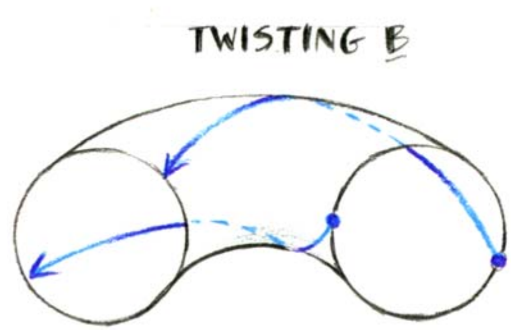
Similar instability mechanism
in MHD & drift/microinstabilities

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

The Secret for Stabilizing Bad-Curvature Instabilities

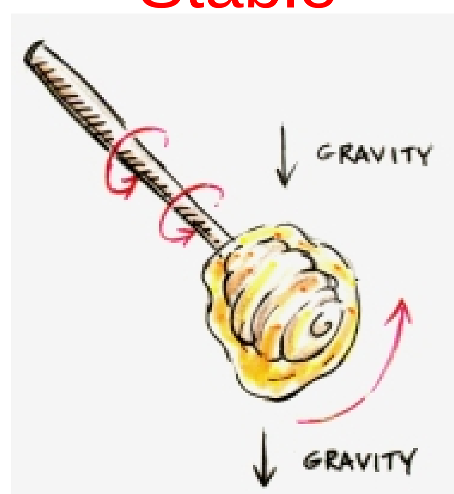
Twist in ***B*** carries plasma from bad curvature region to good curvature region:





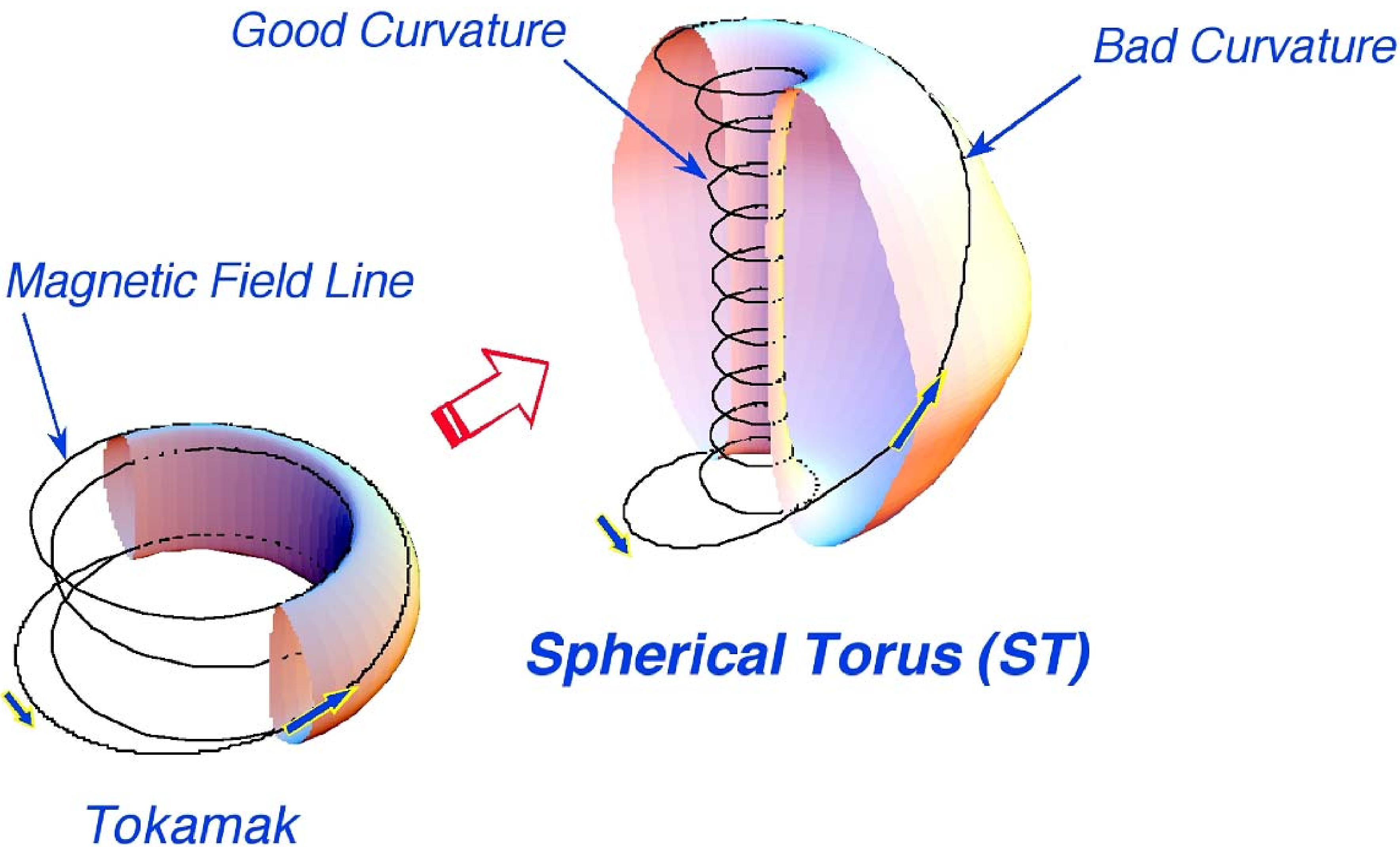
Unstable

Stable



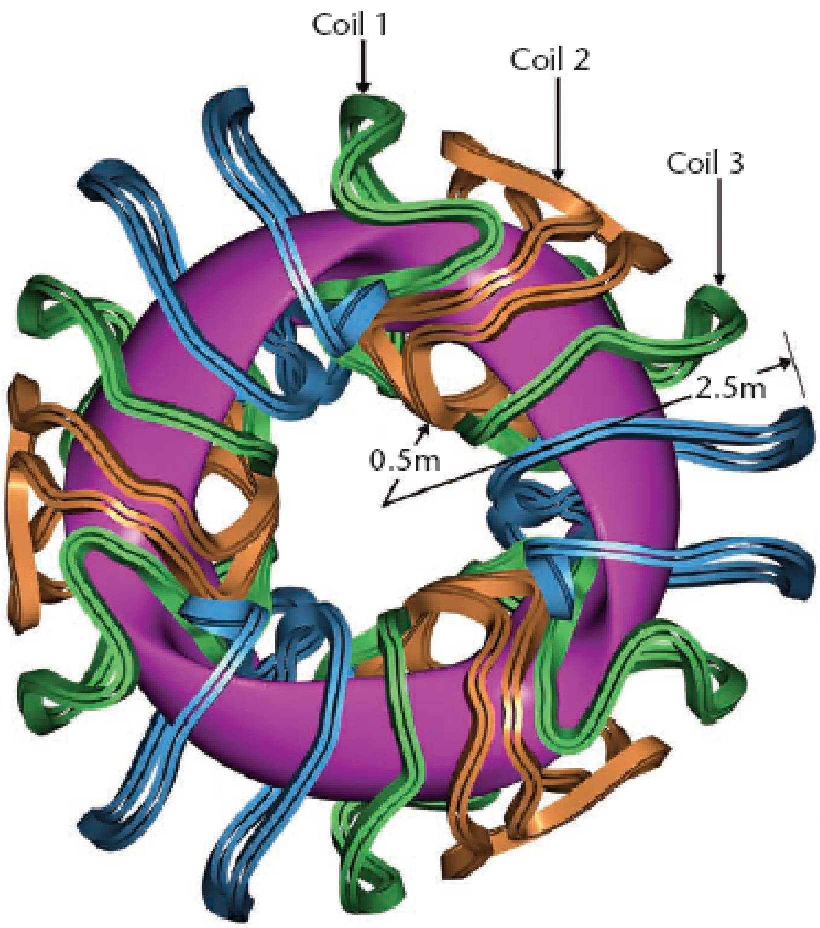
Similar to how twirling a honey dipper can prevent honey from dripping.

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

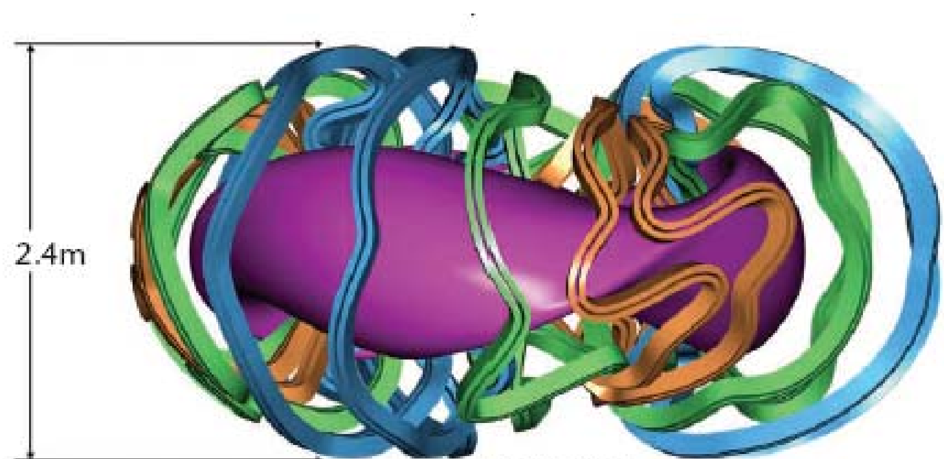


Improved Stellarators Being Built

- 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?

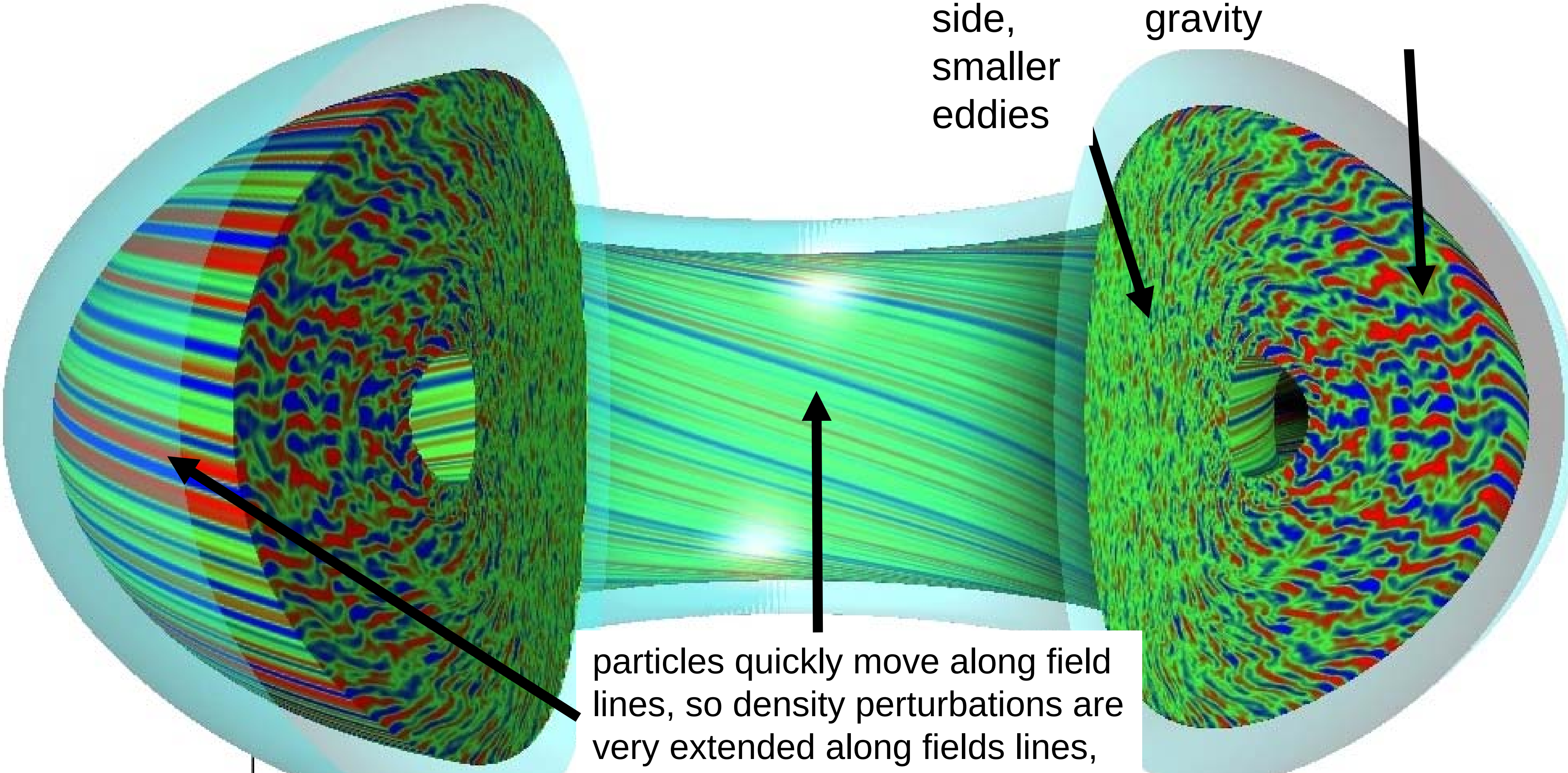


Top view

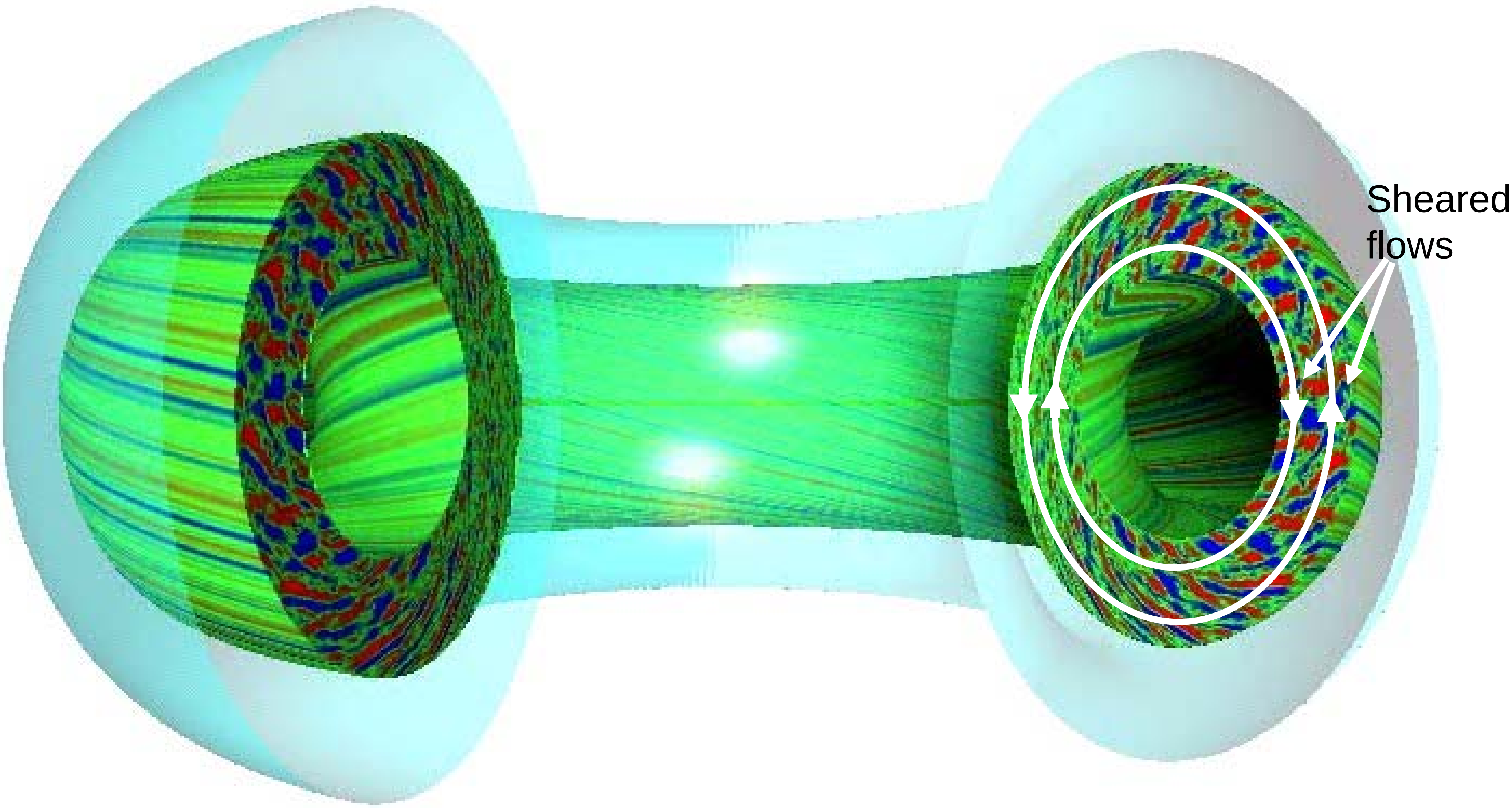


Front view

These physical mechanisms can be seen in gyrokinetic simulations and movies



Movie http://fusion.gat.com/THEORY/images/3/35/D3d.n16.2x_0.6_fly.mpg from http://fusion.gat.com/theory/Gyromovies shows contour plots of density fluctuations in a cut-away view of a GYRO simulation (Candy & Waltz, GA). This movie illustrates the physical mechanisms described in the last few slides. It also illustrates the important effect of sheared flows in breaking up and limiting the turbulent eddies. Long-wavelength equilibrium sheared flows in this case are driven primarily by external toroidal beam injection. (The movie is made in the frame of reference rotating with the plasma in the middle of the simulation. Barber pole effect makes the dominantly-toroidal rotation appear poloidal..) Short-wavelength, turbulent-driven flows also play important role in nonlinear saturation.



The electrostatic Gyrokinetic equation, in a Drift-Kinetic-like form for the full, gyro-averaged, guiding center density $\bar{f}(\vec{R}, v_{\|}, \mu, t)$:

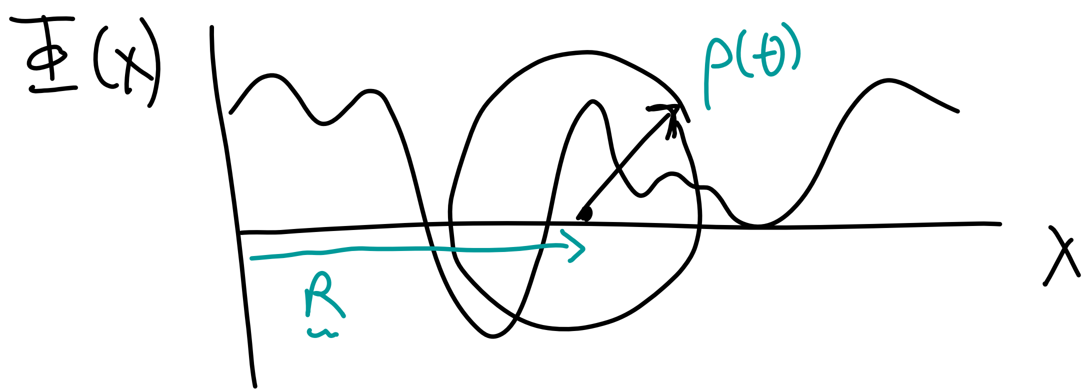
$$\frac{\partial \bar{f}}{\partial t} + (v_{\|}\hat{\mathbf{b}} + \mathbf{v}_E + \mathbf{v}_d)\cdot\nabla\bar{f} + \left(\frac{q}{m}E_{\|} - \mu\nabla_{\|}B + v_{\|}(\hat{\mathbf{b}}\cdot\nabla\hat{\mathbf{b}})\cdot\mathbf{v}_E\right)\frac{\partial \bar{f}}{\partial v_{\|}} = 0$$

$$\underset{\sim}{V}_E = -\frac{c}{B}\nabla\langle\Phi\rangle\times\hat{b} \qquad E_{\|} = -\hat{b}\cdot\nabla\langle\Phi\rangle \qquad \mu = \frac{1}{2}\frac{v_\perp^2}{B}$$

using gyroaveraged potential $\langle\Phi\rangle(\vec{R}) = \frac{1}{2\pi}\int d\theta\, \Phi(\underset{\sim}{R} + \rho(\theta))$

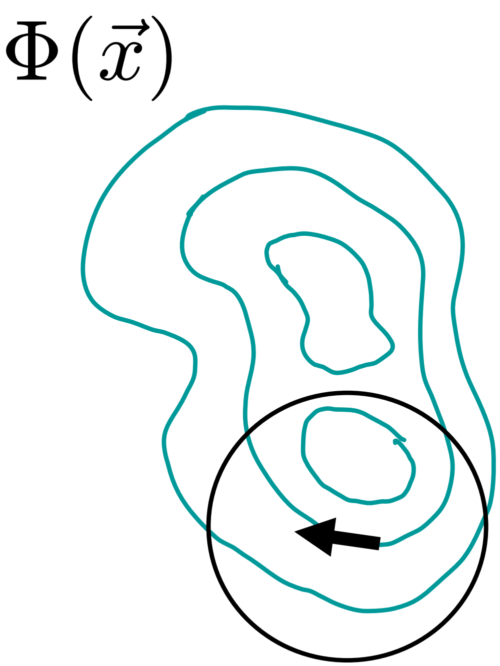
$$= \sum_{\underset{\sim}{k}} J_0(k_\perp\rho)\,\Phi_k\, e^{i\underset{\sim}{k}\cdot\underset{\sim}{R}}$$

$\underset{\sim}{V}_d = \nabla B$ + curvature drift



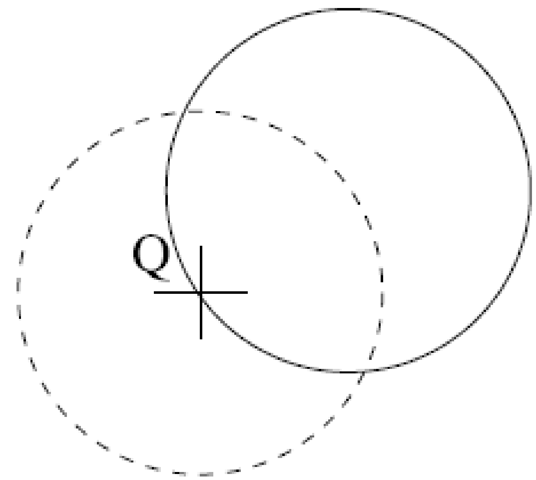
2. Development of & physics in gyrokinetic equations

if low frequencies ω << cyclotron frequency (Ω_c),
→ average over particle gyration, treat particles as rings of charge in spatially varying fields



$$E \times B \to -\nabla\langle\Phi\rangle \times \vec{B}$$

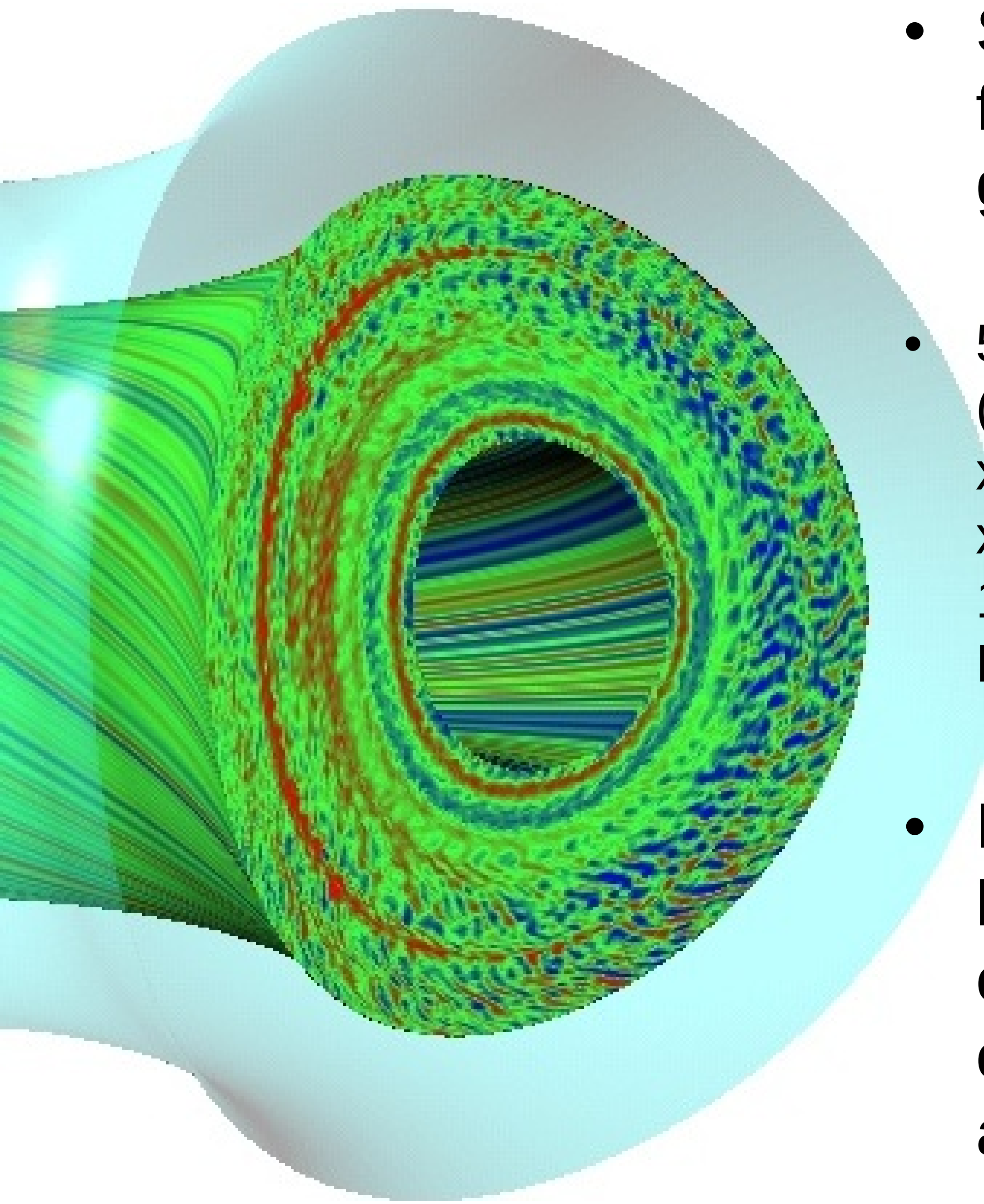
potential averaged around particle orbit, even if $k_\perp \rho_i$ large



When calculating charge at point Q, have to sum over all particles whose guiding centers are on the dashed line, & have to include small variation of particle density around gyro-orbit (→ polarization shielding)

Development of nonlinear gyrokinetics was a major breakthrough

3. Fairly Comprehensive 5-D Gyrokinetic Turbulence Codes Have Been Developed

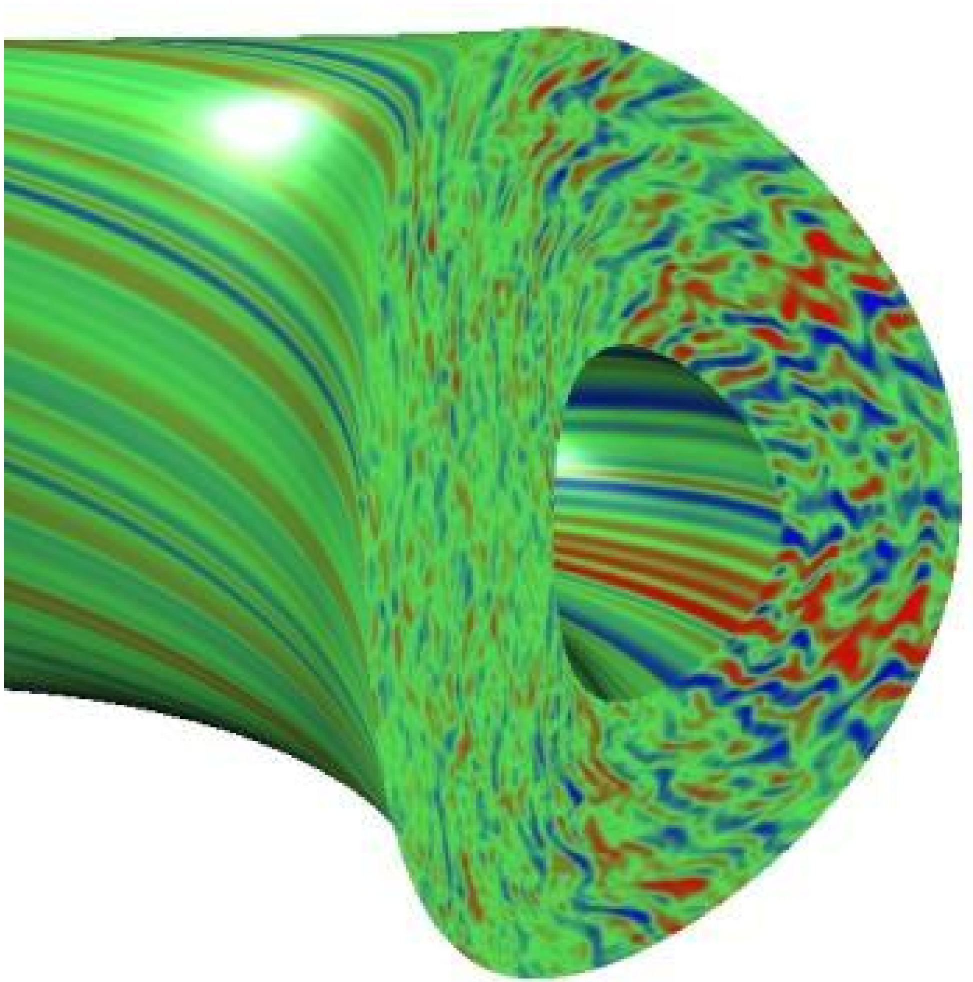


- Solve for the particle distribution function $f(r,\alpha,\theta,E,\mu,t)$ (avg. over gyration: 6D → 5D)

- 500 radii x 32 complex toroidal modes (96 binormal grid points)
  x 10 parallel points along half-orbits
  x 8 energies x 16 $v_{||}/v$
  12 hours on ORNL Cray X1E with 256 MSPs

- Realistic toroidal geometry, kinetic ions & electrons, finite-β electro-magnetic fluctuations, collisions. Sophisticated algorithms.

Understanding Turbulence That Affects the Performance of Fusion Device



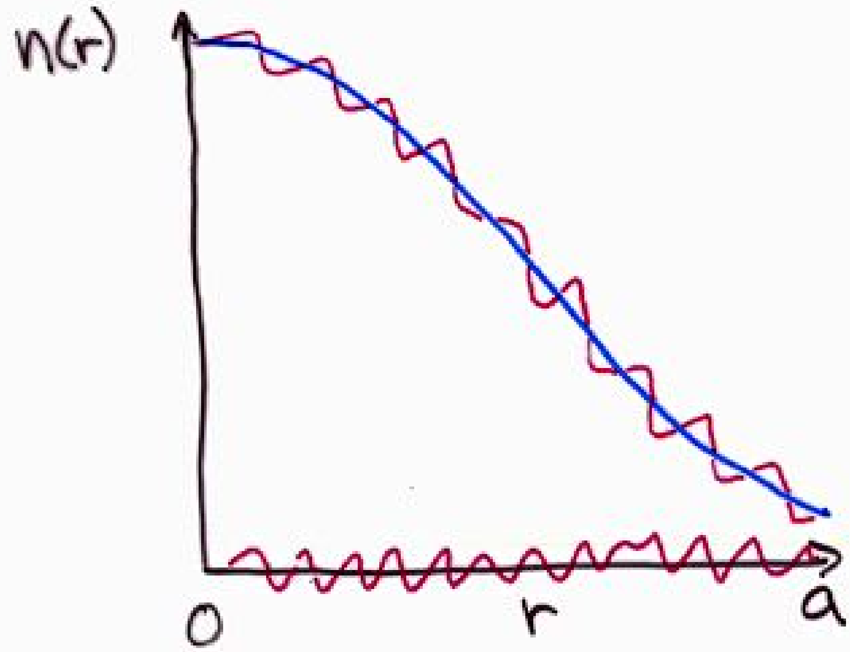
(Candy & Waltz, GA 2003)

Central temp ~ 10 keV ~ 10^8 K

Large temperature gradient
→ turbulent eddies
→ cools plasmas
→ 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

Microinstabilities are small-amplitude but still nonlinear



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

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

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

↑ 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 $\sim \frac{a}{v_t} \sim 1\ \mu\text{sec}$

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

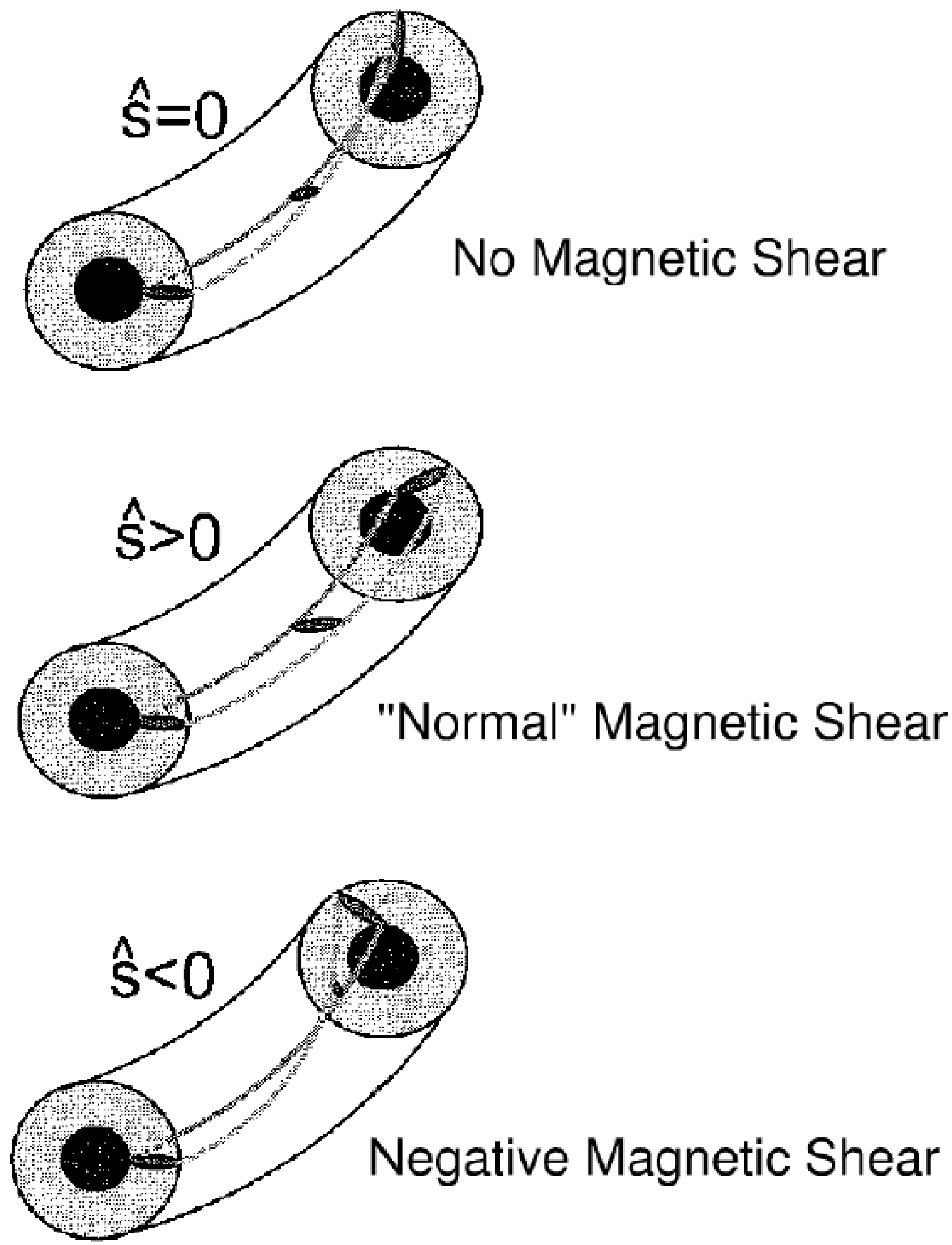
Simple picture of reducing turbulence by negative magnetic shear

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".

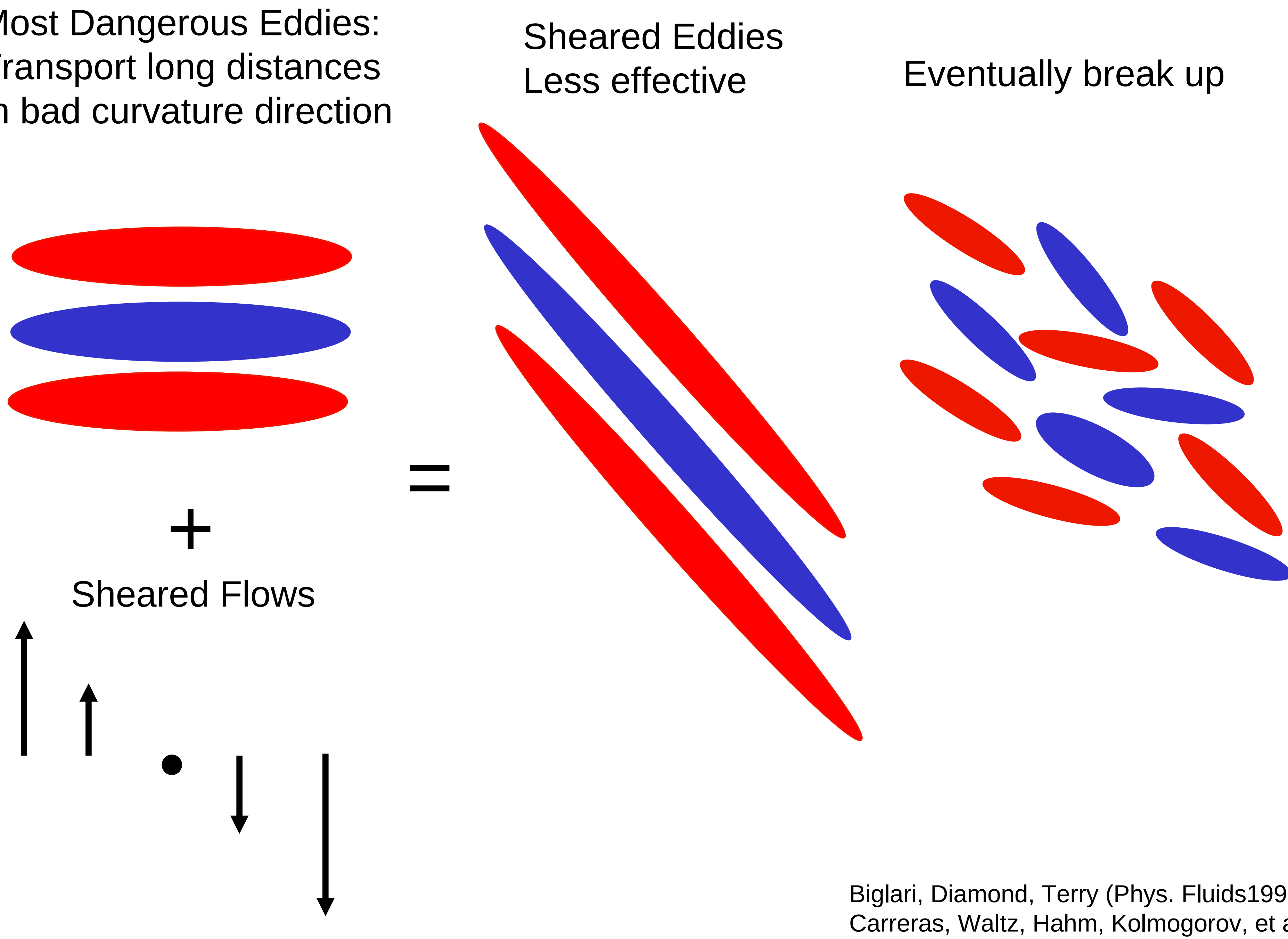
Locally reversed magnetic shear naturally produced by squeezing magnetic fields at high plasma pressure: ``Second stability" Advanced Tokamak or Spherical Torus.

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



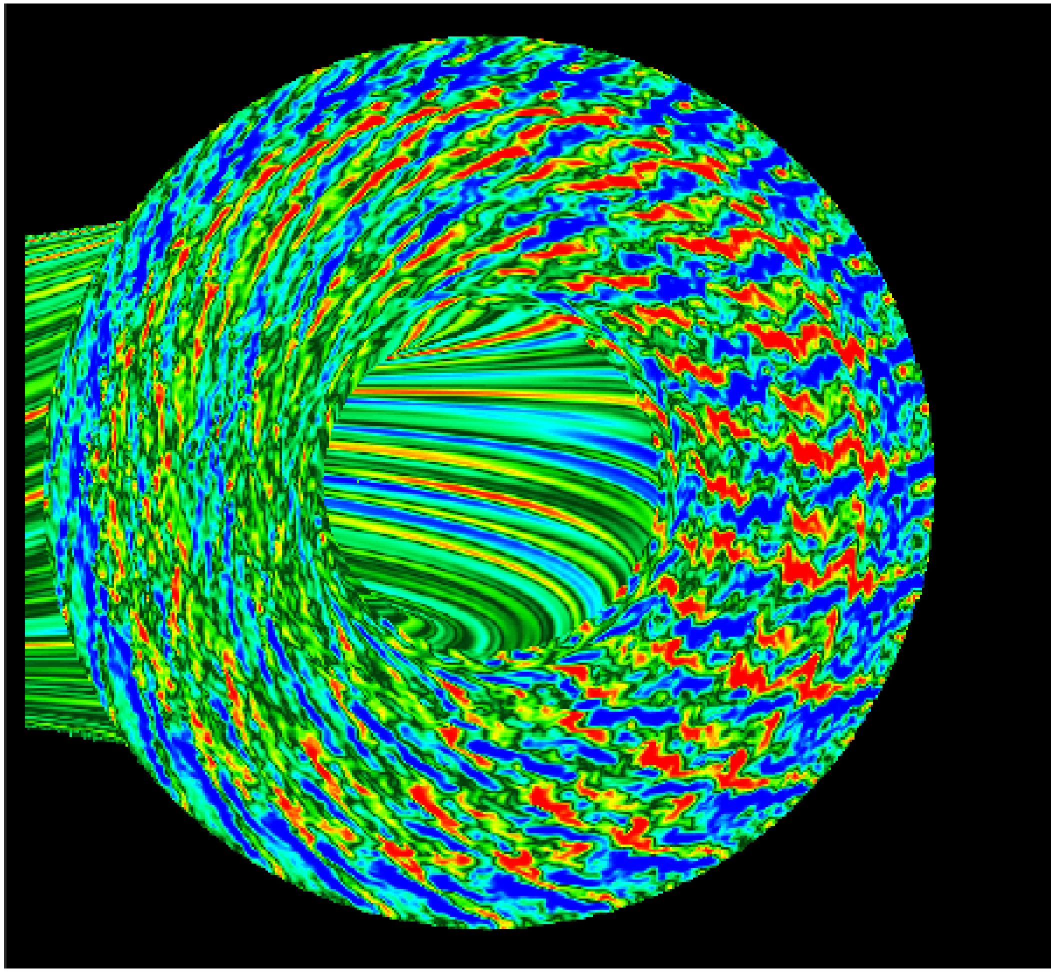
Antonsen, Drake, Guzdar et al. Phys. Plasmas 96
Kessel, Manickam, Rewoldt, Tang Phys. Rev. Lett. 94

Sheared flows can suppress or reduce turbulence

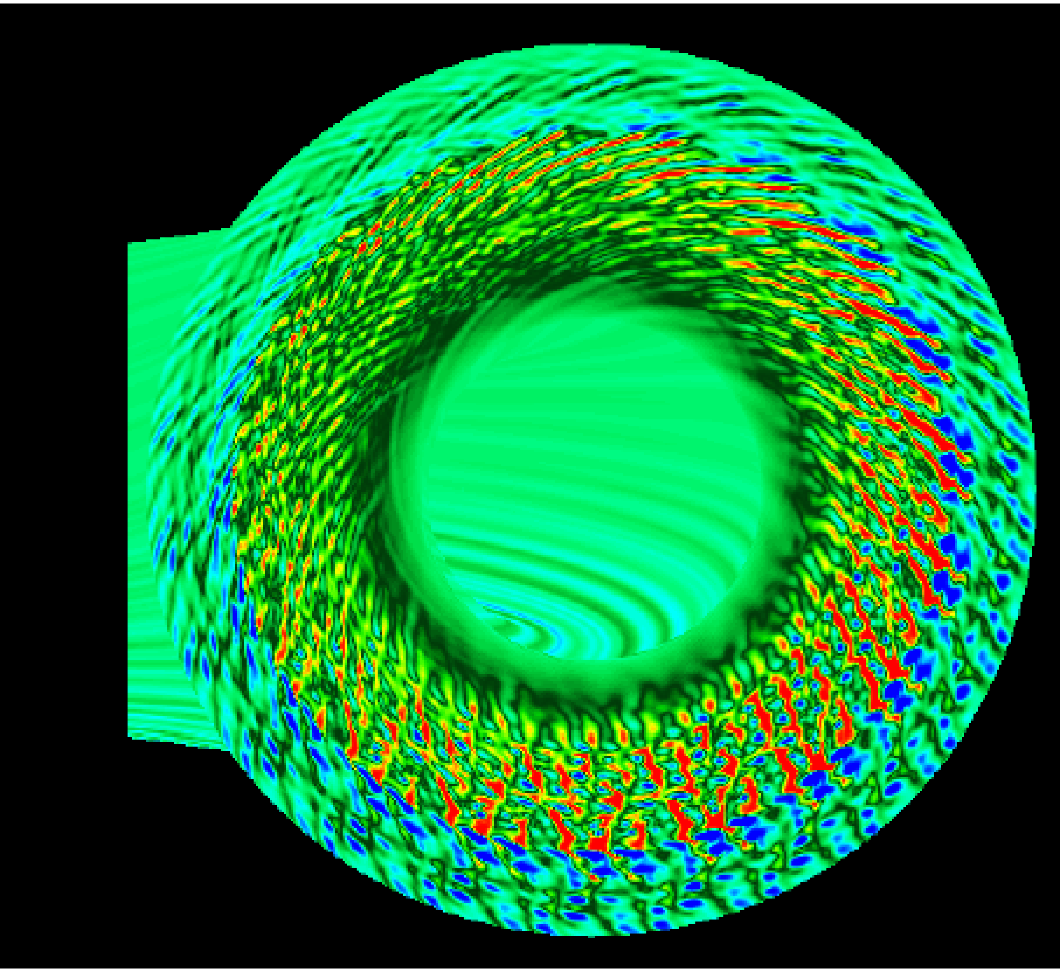


Biglari, Diamond, Terry (Phys. Fluids1990),
Carreras, Waltz, Hahm, Kolmogorov, et al.

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



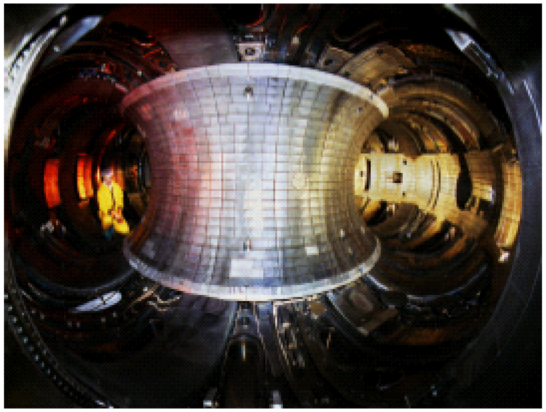
Dominant nonlinear interaction between turbulent eddies and ±θ-directed zonal flows.



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

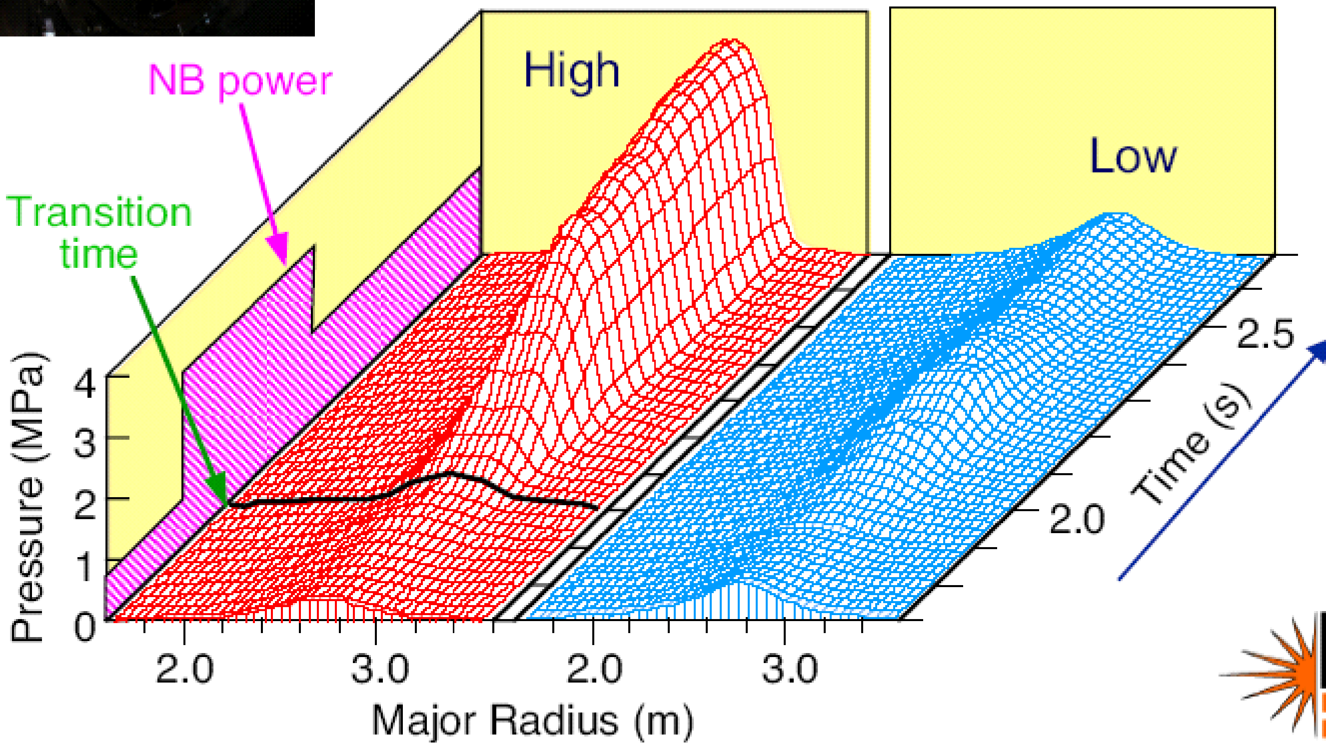
Waltz, Kerbel, Phys. Plasmas 1994 w/ Hammett, Beer, Dorland, Waltz Gyrofluid Eqs., Numerical Tokamak Project, DoE Computational Grand Challenge

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



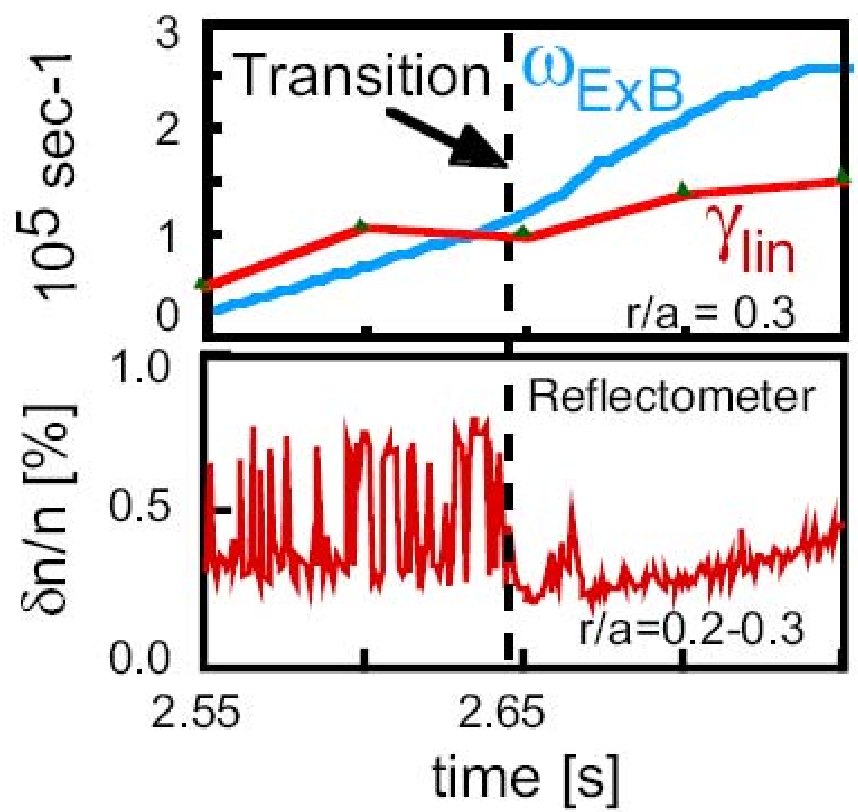
TFTR

- 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?

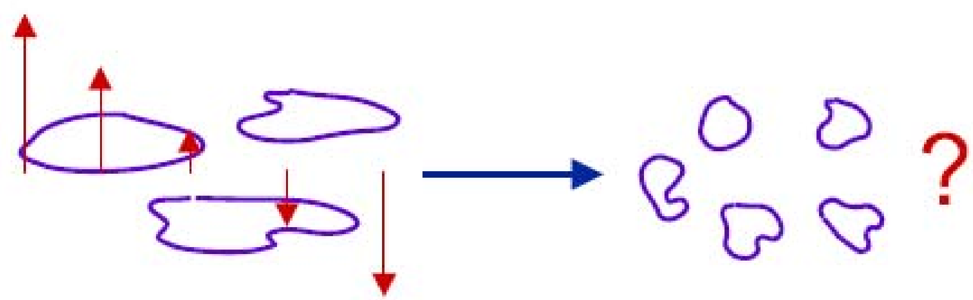


R. Nazikian et al.

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?

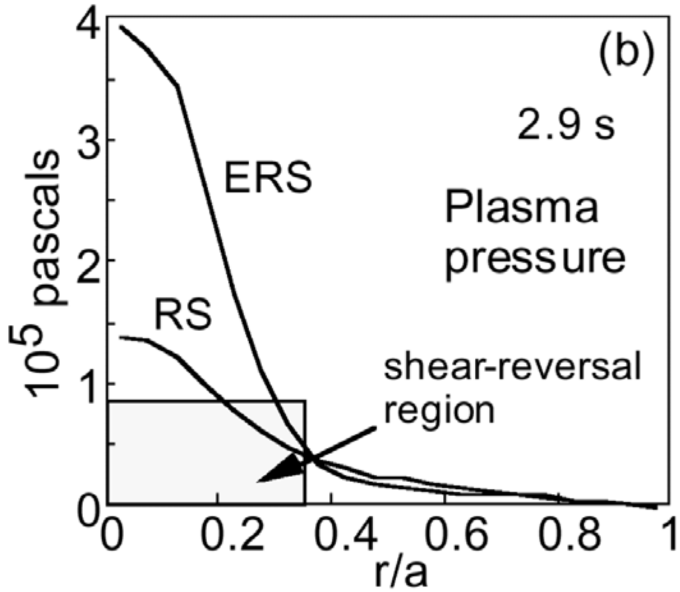


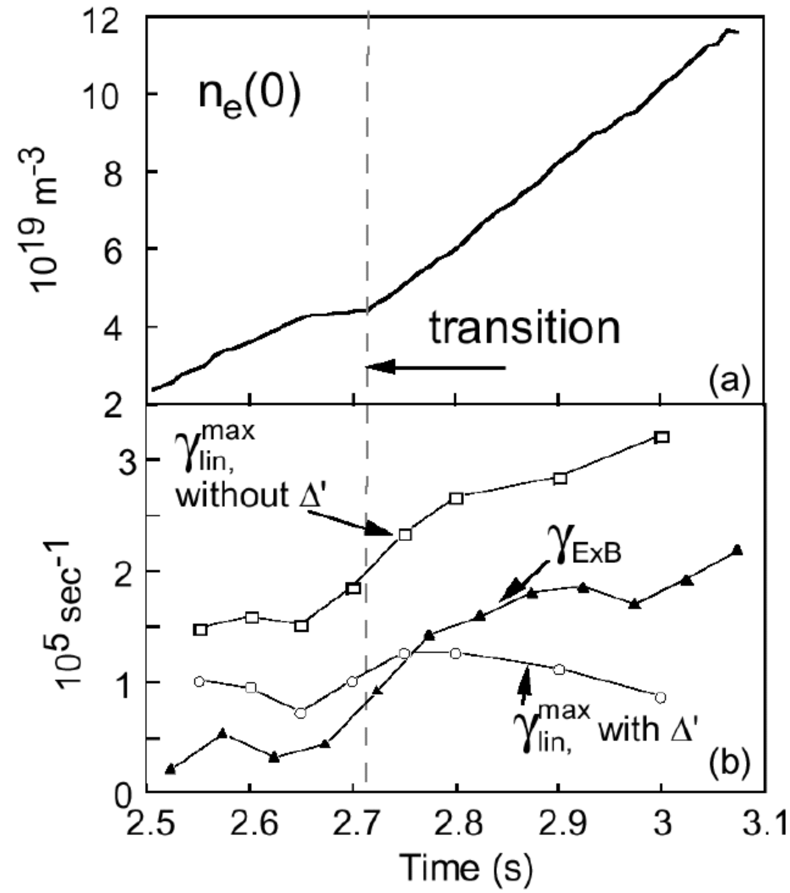
- Similar suppression observed on JET (X-mode reflectometer) and DIII-D (FIR Scattering)

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

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

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, $P_{fusion} \propto$ pressure^2 ~ x 4

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 would push 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.

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

Continuum/Eulerian Approach to Electromagnetic Gyrokinetic Turbulence

GS2 (Dorland & Kotschenreuther), GENE (Jenko), and GYRO (Candy & Waltz) have demonstrated that direct Eulerian simulations of microturbulence using the 5-D electromagnetic gyrokinetic equations can be effective, by

(1) Using modern massively parallel supercomputers and clusters, and

(2) Using modern advanced algorithms, including

- implicit / semi-implicit methods (or carefully designed explicit methods)

- pseudo-spectral and/or Arakawa treatment of nonlinearities (preserves all 3 conservation properties of Poisson bracket nonlinearities)

- pseudo-spectral and/or high-order upwind advection algorithms: very low dissipation at long wavelengths, effective sink at small scales.

- high-order velocity-space integration algorithms,

- efficient field-aligned coordinate systems, …

Continuum/Eulerian Approach to Electromagnetic Gyrokinetic Turbulence

GS2 (Dorland & Kotschenreuther) http://gs2.sourceforge.net
GENE (Jenko) http://www.ipp.mpg.de/~fsj/
GYRO (Candy & Waltz) http://fusion.gat.com/comp/parallel/

These codes widely used by many to study plasma turbulence in fusion devices. GYRO is currently the most comprehensive gyrokinetic code available:

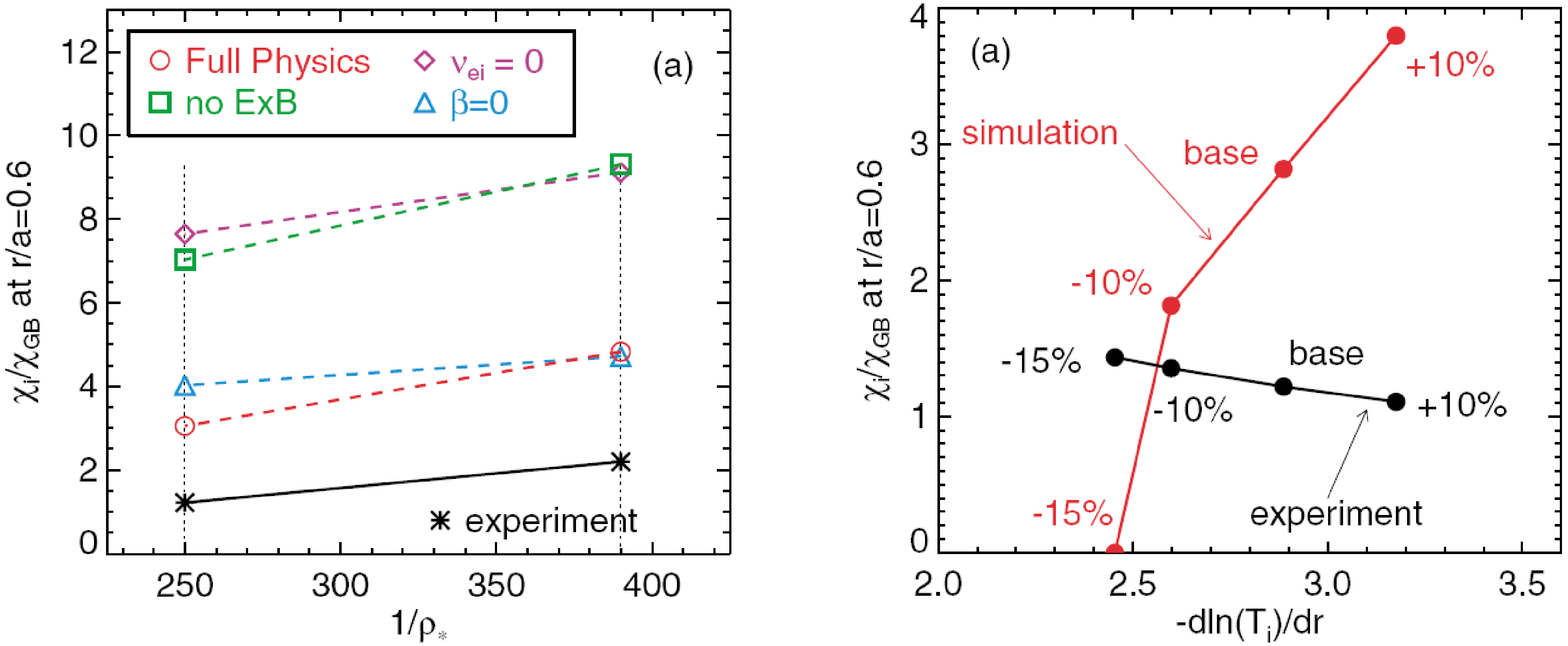
- Gyrokinetic ions (multiple species) & adiabatic/drift-kinetic/gyrokinetic electrons
- Trapped and passing electrons (and ions) for Trapped Electron Mode
- Pitch-angle scattering collision operator (TEM / neoclassical effects)
- Finite beta magnetic fluctuations as well as electrostatic fluctuations (important for kinetic-ballooning modes, magnetic flutter contribution to transport)
- General shaped tokamak geometry
- Equilibrium ExB and parallel velocity shear
- Finite-ρ_* effects (profile shear stabization, nonlocal transport)…

Nevertheless, a lot of interesting work remains to be done: more tests against experiments, particle transport, transport barrier formation, shaping effects, understand scalings, couple to transport codes for complete predictive ability, &:

edge simulations (new codes needed to do gyrokinetics in the edge, challenging…)

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.

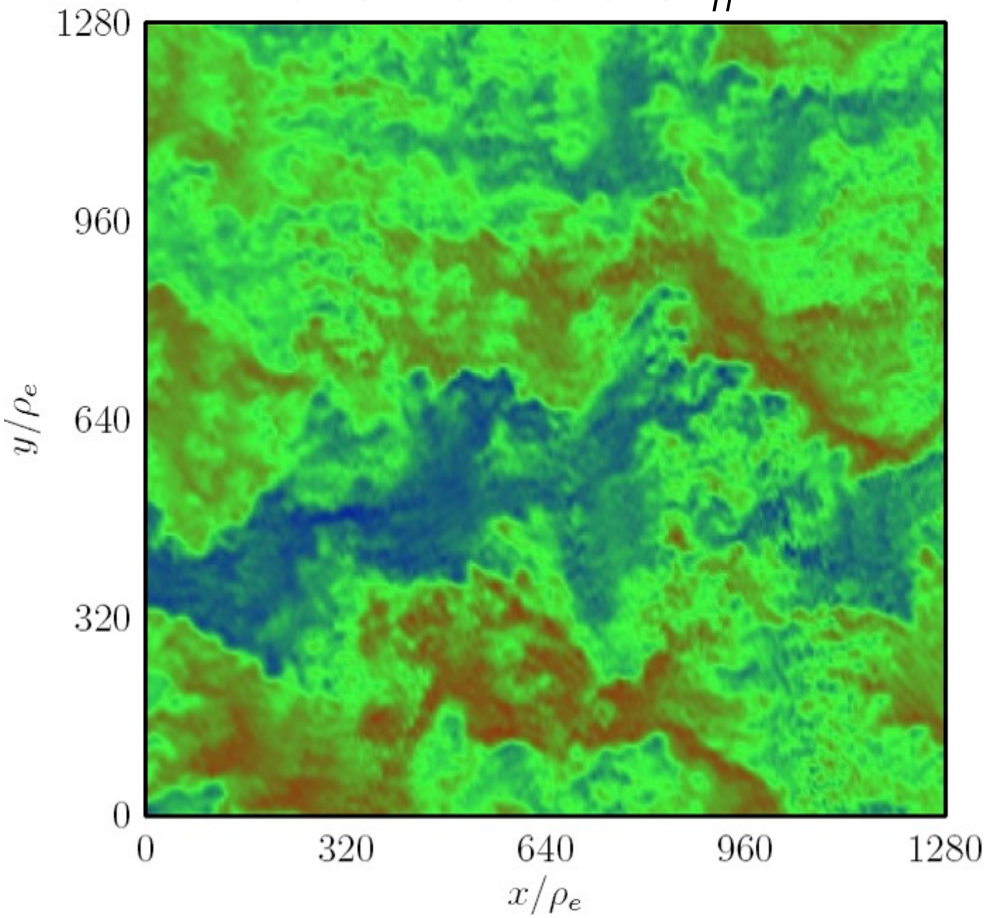
Now within experimental error on temperature gradient. Importance of critical gradient effects emphasized in 1995 gyrofluid-based IFS-PPPL transport model.

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

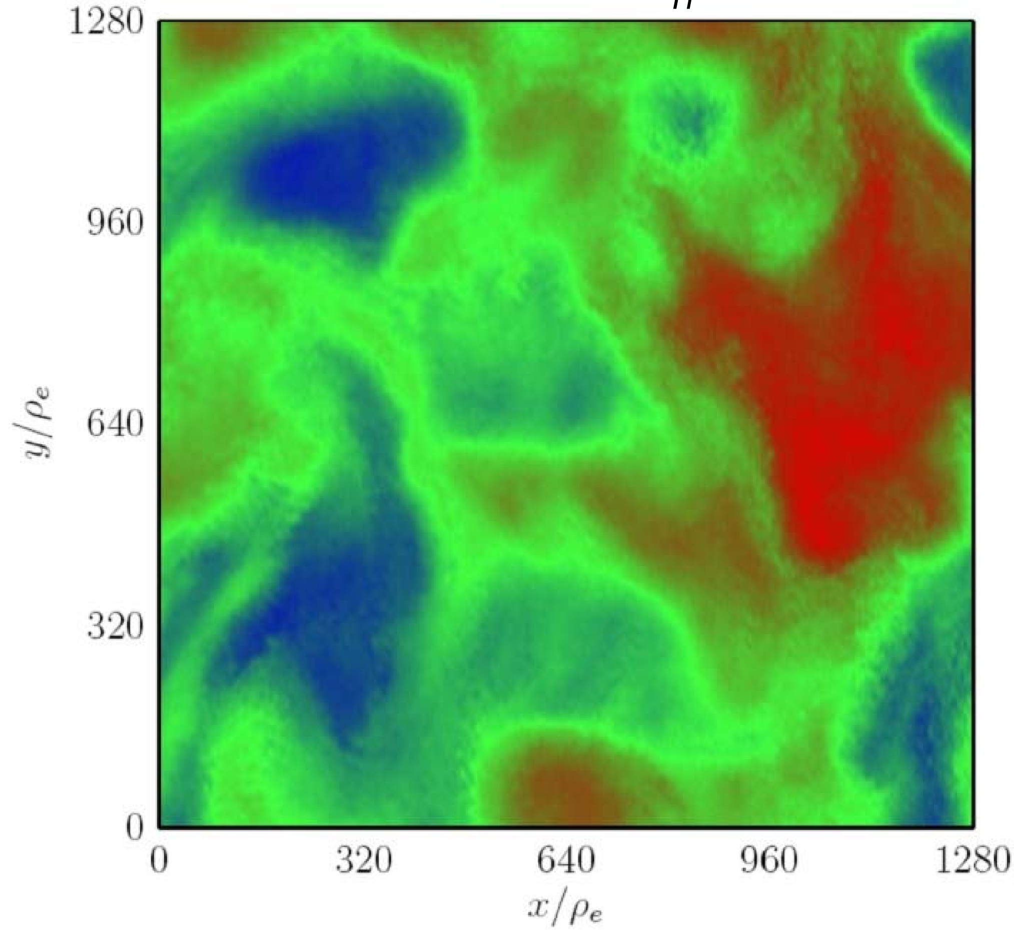
Largest GYRO simulations used to study interaction of ITG & ETG Turbulence

- 1280 ρ_e x 1280 ρ_e x 20 parallel pts/orbit x 8 energies x 16 $v_{||}/v$
- electrons + kinetic ions, $m_i/m_e = 20^2 - 30^2$
- 5 days on DOE/ORNL Cray X1E w/ 720 Multi-Streaming Processors

ETG w/ kinetic ions R/L_{Ti}=0



ETG+ITG R/L_{Ti}=6.9

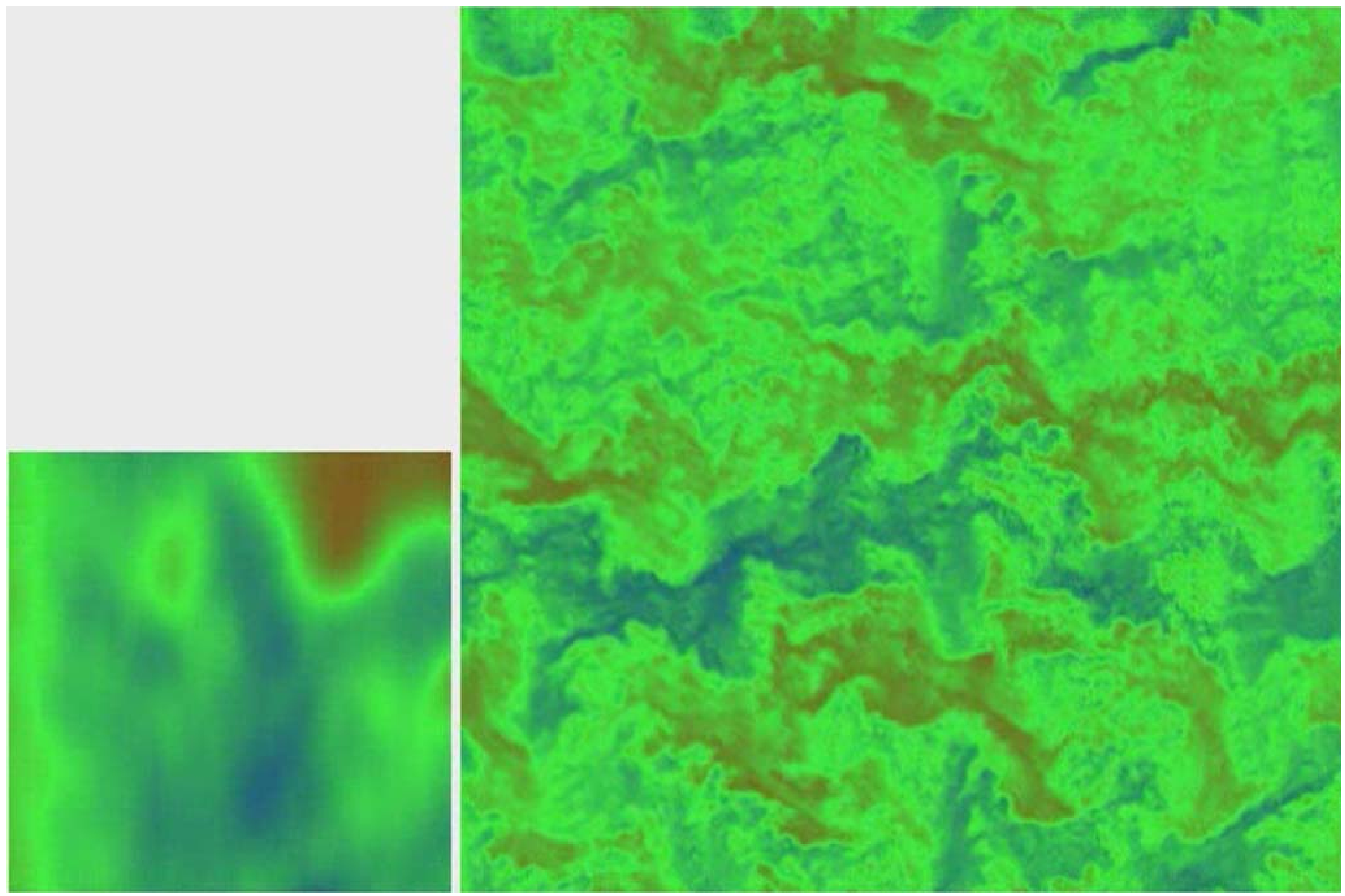


Candy, Waltz, et al. JPSC 2007

ETG + kinetic ion GYRO simulation movie

- large box on right: full simulation domain, 1280 ρ_e x 1280 ρ_e = 64 ρ_i x 64 ρ_i
- small box on lower left: zoom in on a 64 ρ_e x 64 ρ_e patch

http://fusion.gat.com/THEORY/images/1/1f/ETG-ki.mpg from http://fusion.gat.com/theory/Gyromovies



Candy & Waltz

ETG fluctuations ($k_\perp \rho_i > 1$) may account for significant fraction of transport in some plasmas

Simple scaling from ITG to ETG:

$$\chi_{itg} \sim C_{itg}\, \rho_i^2\, v_{ti}/L$$
$$\chi_{etg} \sim C_{itg}\, \rho_e^2\, v_{te}/L \sim \chi_{itg}/60$$

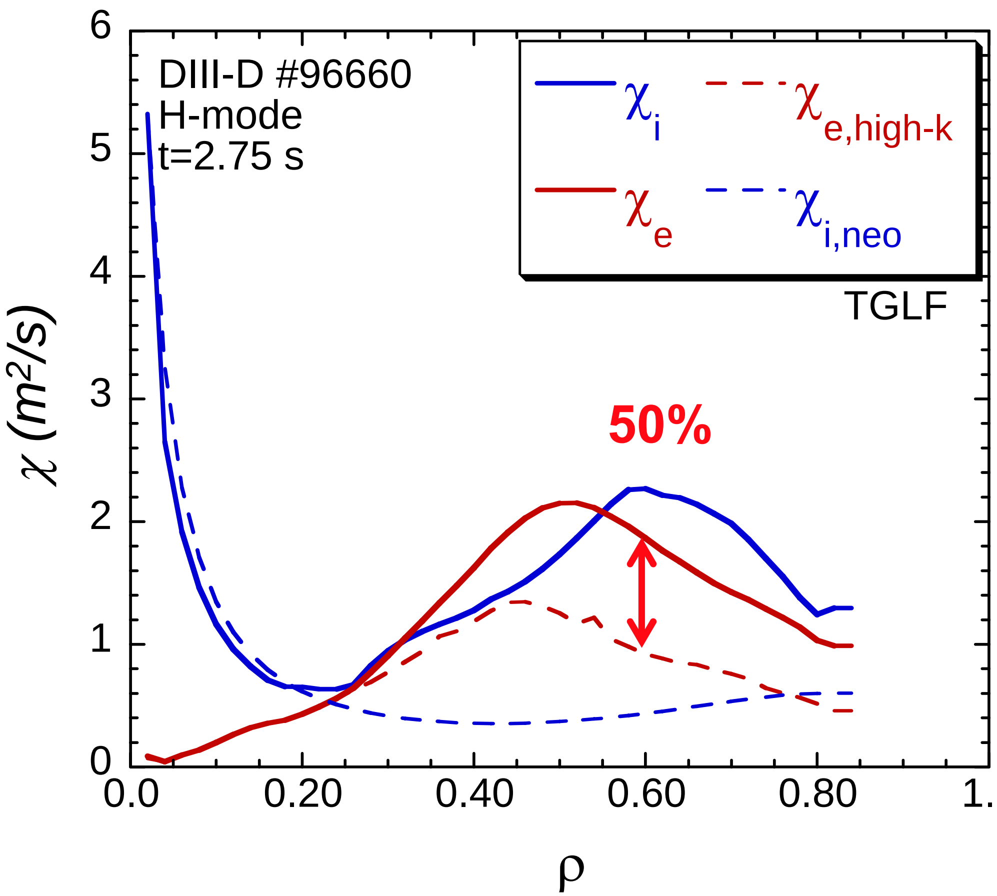
But Dorland & Jenko (2000) showed ETG turbulence larger because:

perpendicular adiabatic ions for ETG gives more shielding of zonal electric fields than does parallel adiabatic electrons for ITG.

Candy showed ETG will be reduced by kinetic ions, more so if strong ITG turbulence

ITG can be weak near marginal stability w/ ExB shear. TGLF transport model shows ETG / high-k TEM may still be important in some cases.

DIII-D H-mode

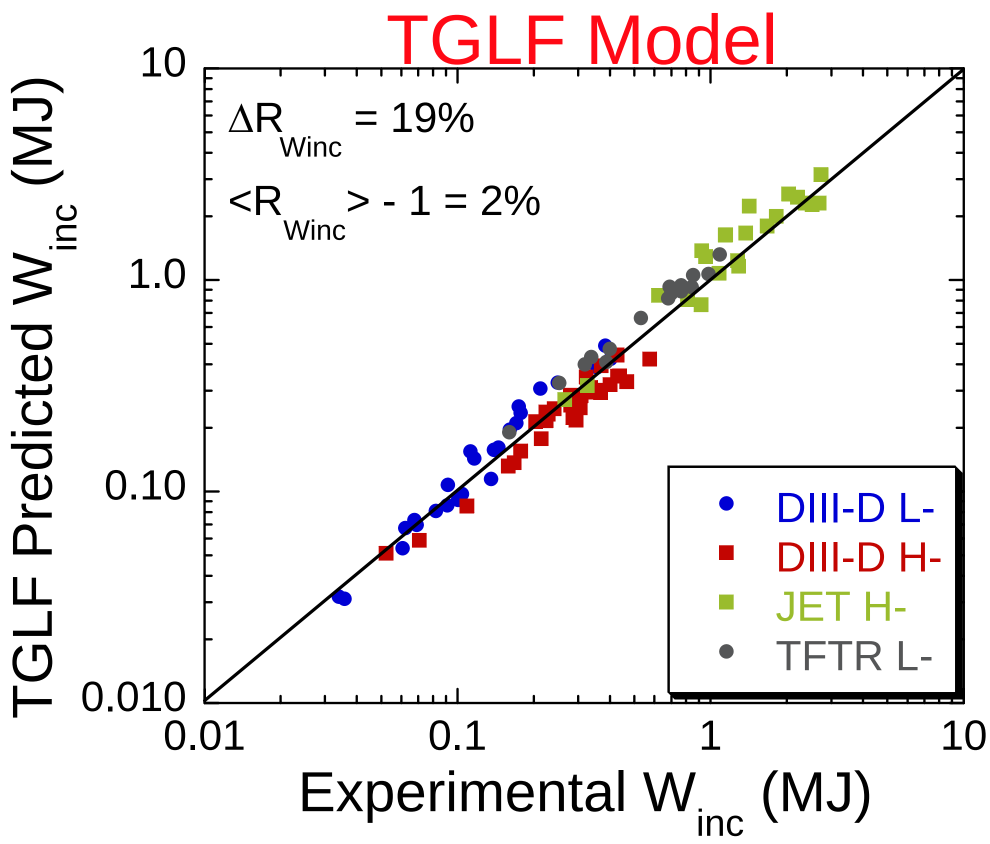


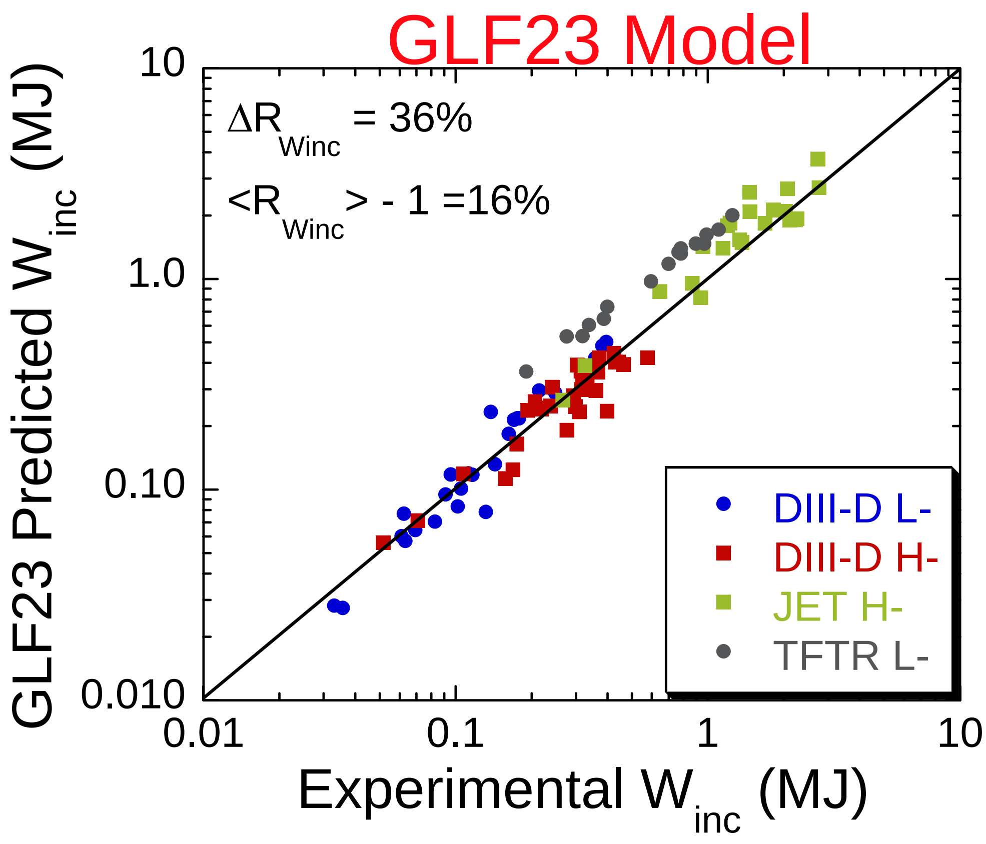
J. Kinsey BI2.6, Monday 12:00 Noon

TGLF exhibits lower average global errors than GLF23 for a large L- and H-mode profile database of 96 discharges

- **Database: 25 DIII-D L-,33 DIII-D H-, 22 JET H-, 16 TFTR L-mode discharges**
- **Avg RMS errors in W_{inc} is 19% for TGLF, 36% for GLF23**
- **Avg RMS error in W_{tot} is ΔR_{Wtot}=10% for TGLF, 20% for GLF23**

Wider range of conditions than earlier GLF23 comparisons





DIII-D NATIONAL FUSION FACILITY

J. Kinsey BI2.6, Monday 12:00 Noon

GENERAL ATOMICS

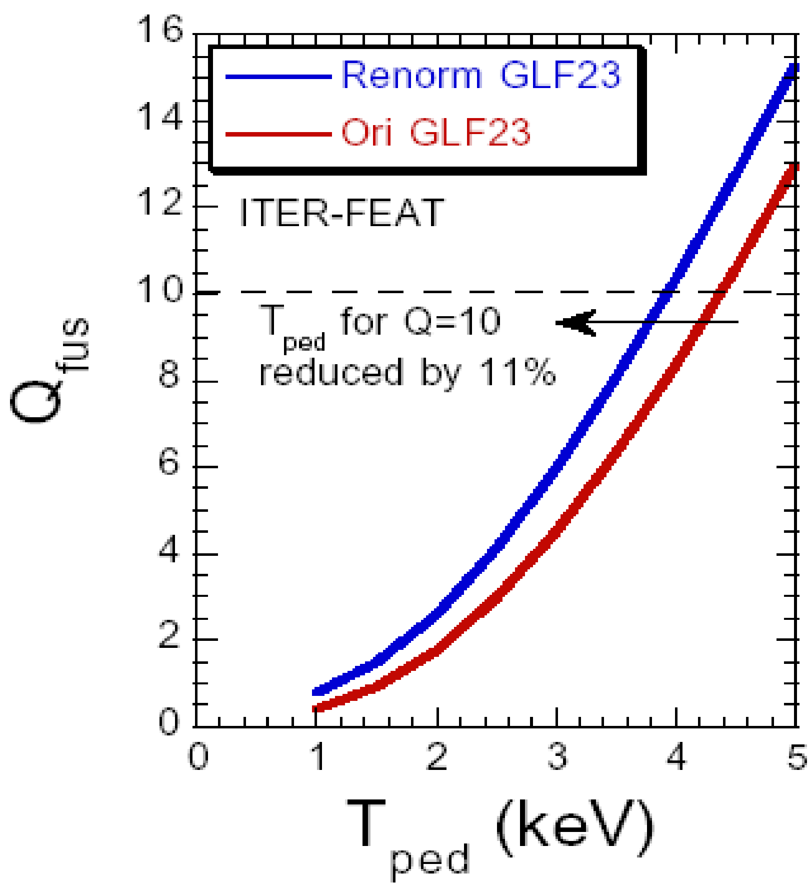
5. Future challenges & opportunities:

– more detailed comparisons w/ expts incl. synthetic fluctuation diagnostics

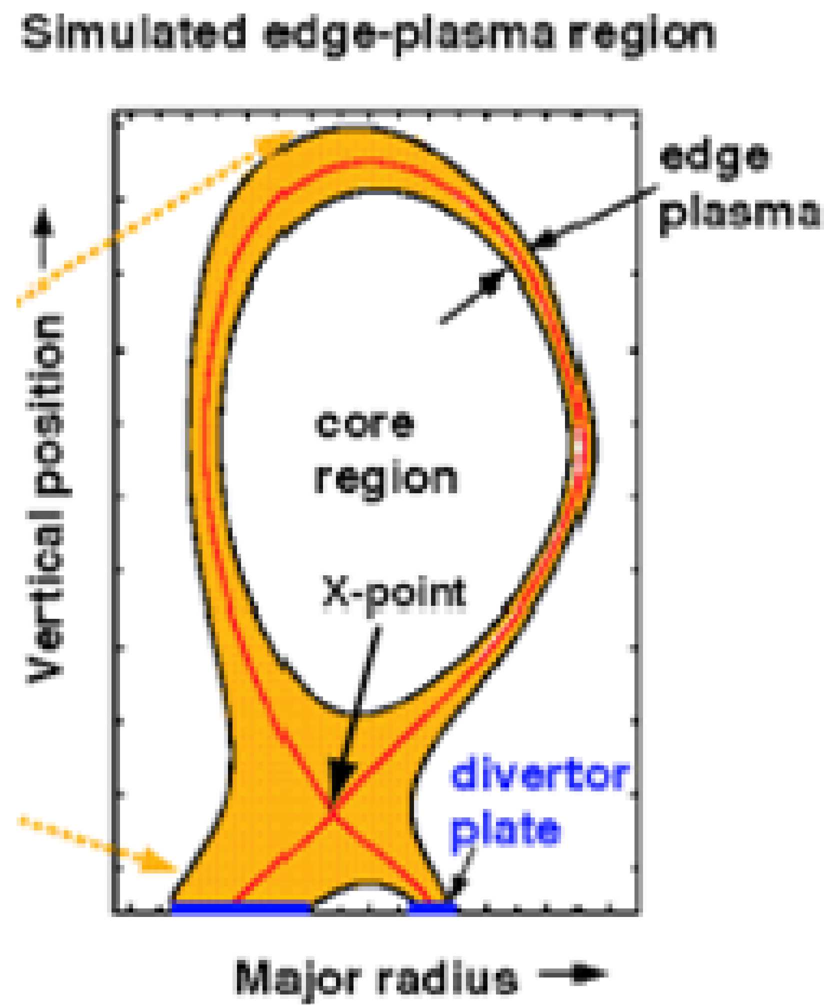
– coupling turbulence simulations directly in long-time transport codes

– Edge Turbulence, very challenging but critical problem

- Edge important: core depends on edge, ELMs, transport barriers
- present core codes don't handle edge, need X-point separatrix, open & closed field lines, strong recycling, wide range of collisionality, …



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



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

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/
- "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.

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?

- Lots of progress in understanding turbulence in tokamaks, understand many pieces of the puzzle, but comprehensive tools for predicting and optimizing tokamaks remains to be developed…

- Highest priorities include need for developing comprehensive simulations of edge turbulence, extending the progress made in core gyrokinetics to the edge region to predict the temperature at the top of the pedestal, ELM size, H-mode power threshold…
- 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, bootstrap 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.