Spitzer's Pioneering Fusion Work and the Search for Improved Confinement

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100th Birthday Celebration for Lyman Spitzer
Peyton Hall, October 19-20, 2013

Thanks for slides: Dale Meade, Rob Goldston, Eleanor Starkman and PPPL photo archives, ...

(revised Oct. 22, 2013)

Spitzer's Pioneering Fusion Work and the Search for Improved Confinement

Outline:

- Pictorial tour from Spitzer's early days to TFTR's achievement of 10 MW of fusion power.
- Key physics of magnetic confinement of particles
- Physical picture of microinstabilities that drive small-scale turbulence in tokamaks
- Interesting ideas being pursued to improve confinement & reduce the cost of fusion reactors

- I never officially met Prof. Spitzer, though I saw him at a few colloquia. Heard many stories from Tom Stix, Russell Kulsrud, & others, learned from the insights in his book and his ideas in other books.

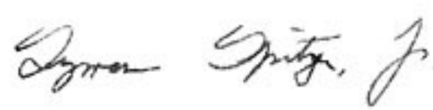


Photo by Orren Jack Turner, from Biographical Memoirs V. 90 (2009), National Academies Press, by Jeremiah P. Ostriker. http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/spitzer-lyman.pdf

- 1960, director of PPPL (1951-1961, and simultaneously, chair of Dept. of Astrophysical Sciences, 1947-1979.)

Spitzer's First Exploration of Fusion

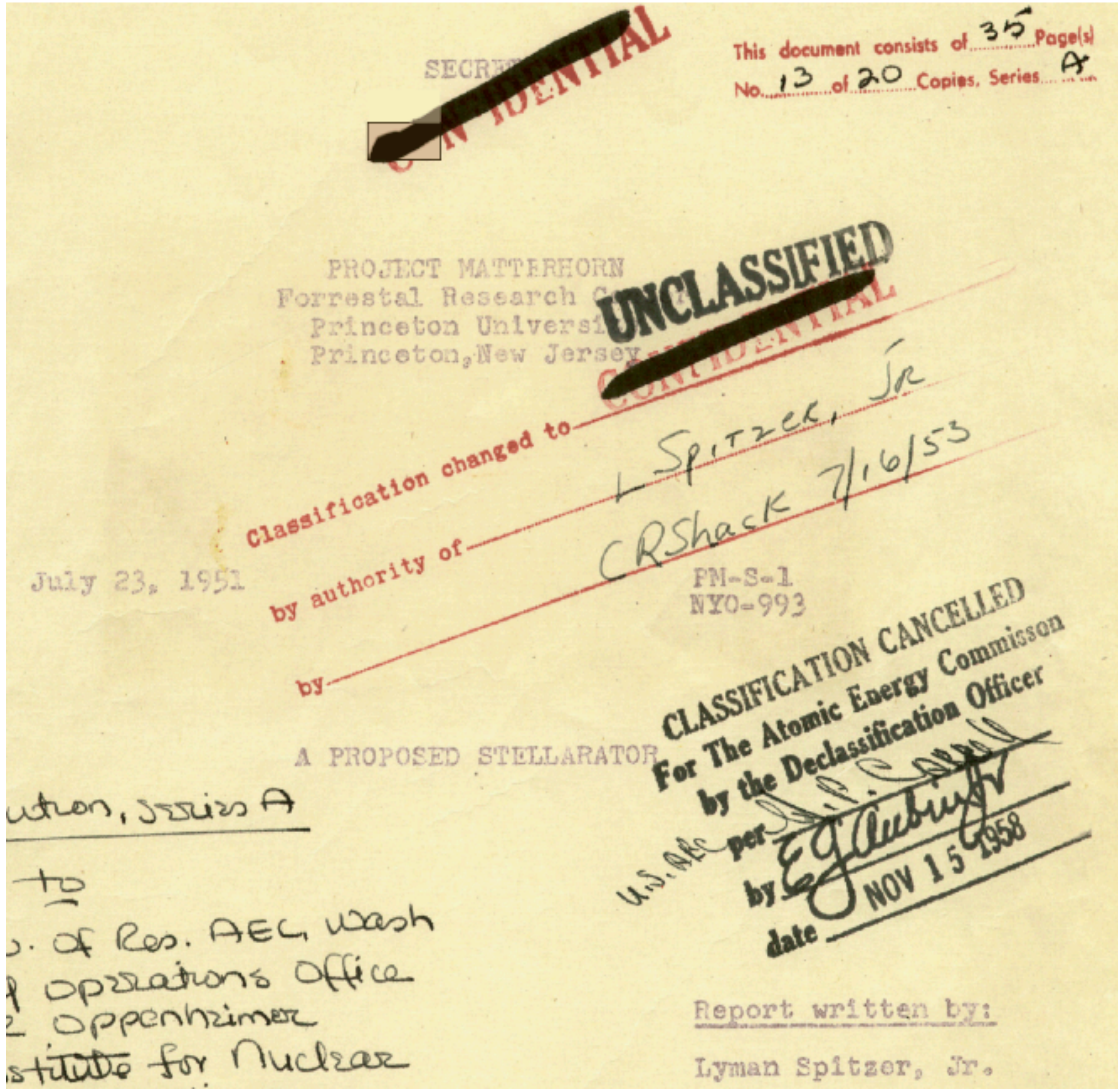
- 25 June, 1950, Korean war started.
- Lyman Spitzer and John Wheeler think about starting a theoretical program at Princeton studying thermonuclear explosions.
- March 24, 1951, President Peron of Argentina claimed his scientist, Ronald Richter, had produced controlled fusion energy in the lab. Quickly dismissed by many (later shown to be bogus), but got Spitzer thinking on the Aspen ski slopes.
- Spitzer had been studying hot interstallar gas for several years and had recently heard a series of lectures by Hans Alfven on plasmas (according to John Johnson).
- Spitzer knew a simple toroidal magnetic field couldn't confine a plasma. The story is that on the chair lift rides in March 1951, he invented the tokamak (later invented in Russia by Igor Tamm and Andrei Sakharov), which uses a current induced in a toroidal plasma to generate a twist in the magnetic field, but dismissed it because it wasn't steady state. Somehow came up with the idea of twisting a torus into a figure-8. Called it a stellarator, a star generator.

- May 11, 1951, meeting at AEC to describe figure-8 and other aproaches to fusion.
- May 12, Spitzer submits proposal to AEC to build a figure-8 stellarator.
- July 1, gets $50k (=$440k in 2013) from AEC for 1 year (Bromberg, p. 21, http://en.wikipedia.org/wiki/Perhapsatron)

CPI = 26.0 in 1951, 230. in 2013.

Spitzer’s Original May 12, 1951 Proposal

- July 23 reprint of original May 12, 1951 proposal
- All early PM-S reports available online:
- http://findingaids.princeton.edu/collections/PPL001/c0001
- http://diglib.princeton.edu/pdfs/PPL001/c0002.pdf
- http://library.pppl.gov/
- (large PDFs > 100MB)



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This document consists of 35 Page(s)
No. 13 of 20 Copies, Series A

PROJECT MATTERHORN
Forrestal Research Center
Princeton University
Princeton, New Jersey

UNCLASSIFIED
[redacted]

Classification changed to
by authority of L Spitzer, Jr
by CRShack 7/16/53

July 23, 1951

PM-S-1
NYO-993

CLASSIFICATION CANCELLED
For The Atomic Energy Commisson
by the Declassification Officer
per U.S.AEC
by EG Aubin
date NOV 15 1958

A PROPOSED STELLARATOR

ution, Series A
to
. of Res. AEC Wash
operations Office
Oppenheimer
stitute for Nuclear

Report written by:

Lyman Spitzer, Jr.

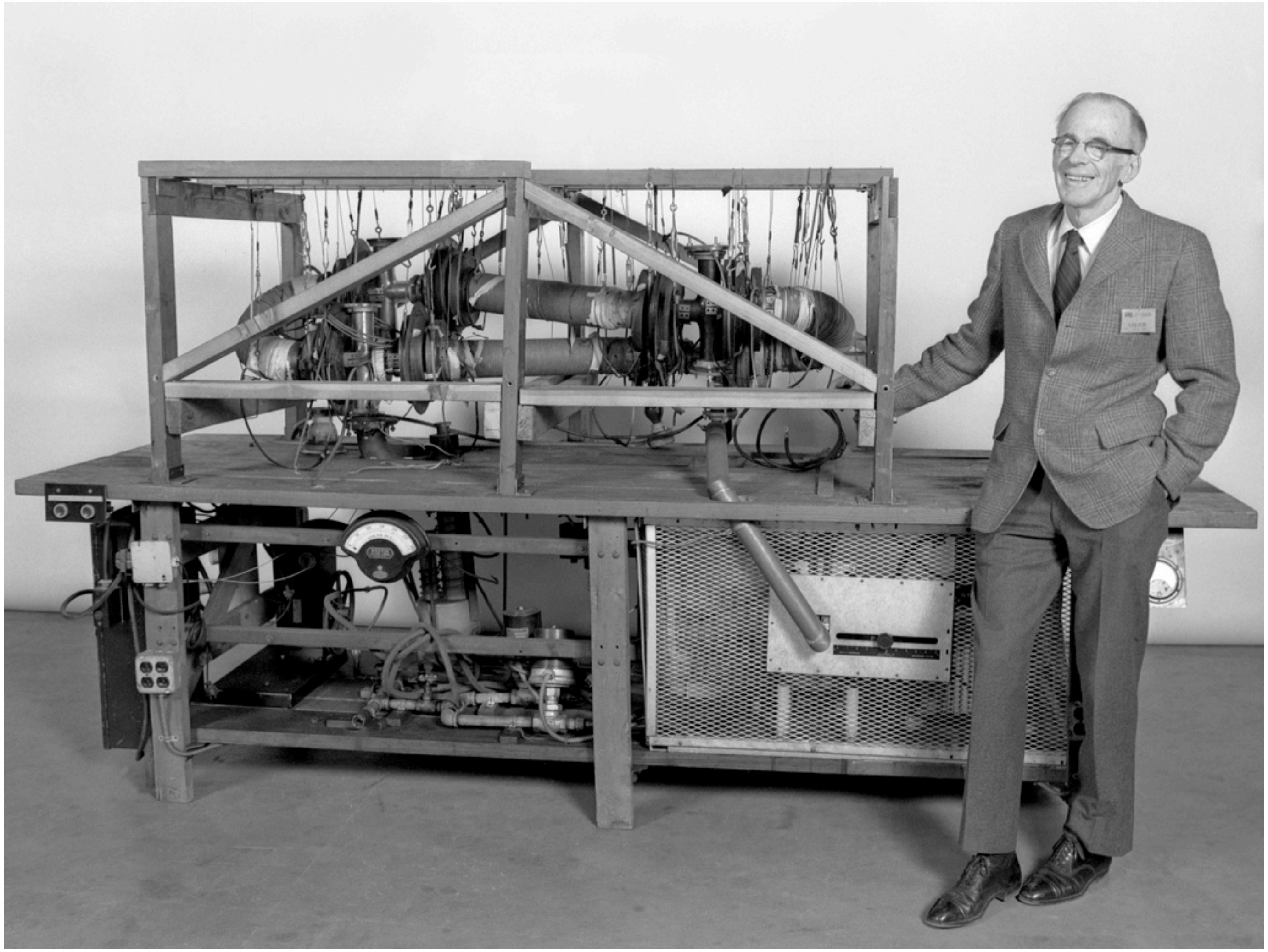
July 1, 1951 Project Matterhorn Begins

- Two sections:
  - S: headed by Spitzer, studying the stellarator concept
  - B: headed by John Wheeler

- “Project Matterhorn” name recommended by Spitzer, because “The work at hand seemed difficult, like the ascent of a mountain”*, and Spitzer was an avid mountain climber with pleasant memories of Switzerland.

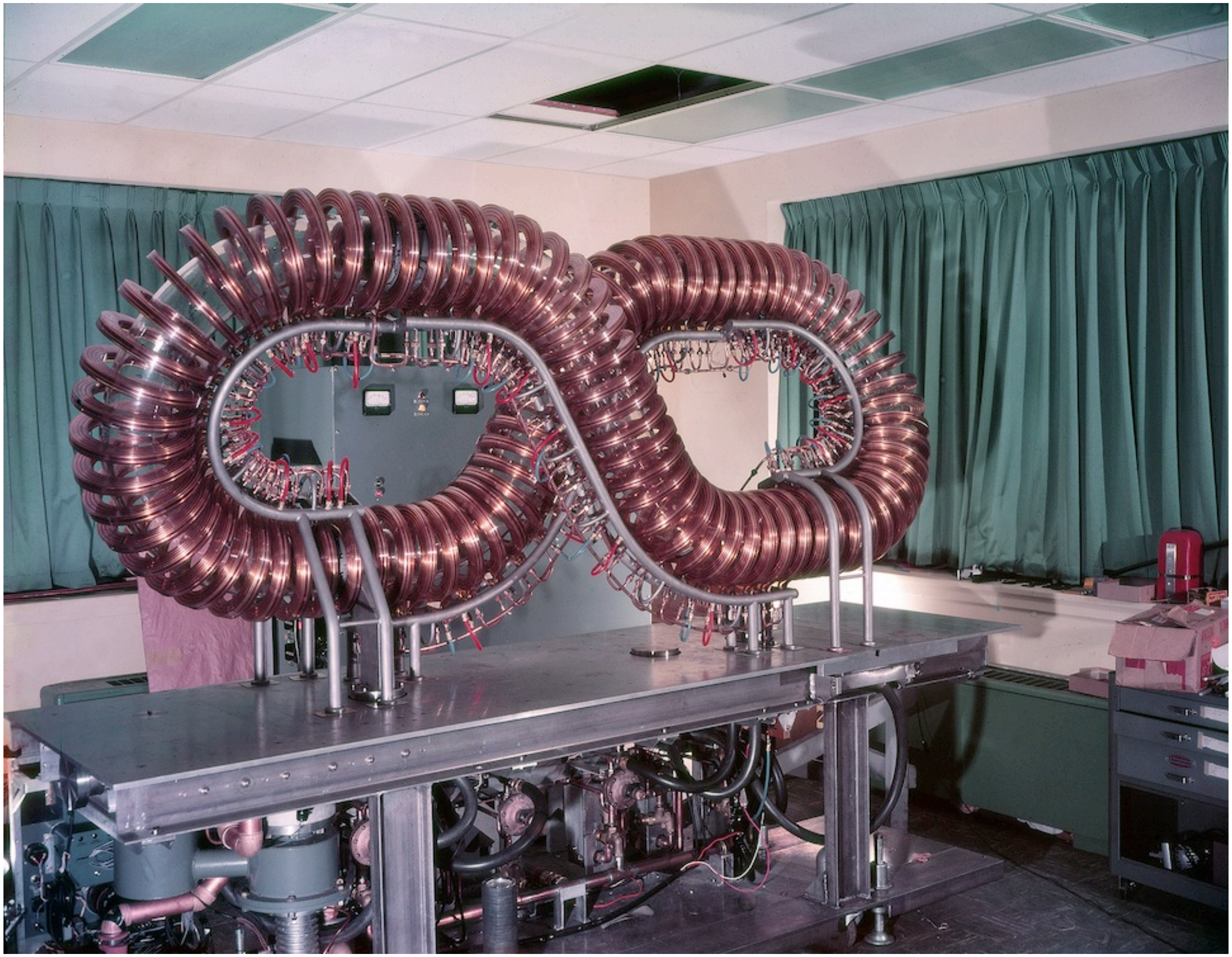
*Tanner, Project Matterhorn

Spitzer’s Model-A Stellarator



- Operated in early 1953, as figure-8 or racetrack. Showed that figure 8 could make plasmas much more easily (at lower voltage & field).
- Spitzer and his friend Prof. Martin Schwarzchild (both theorists) wound copper coils by hand, while sitting on the floor of “rabbit hutch” on Forrestal campus (formerly Rockefeller Inst. for Medical Research). Tanner, “Project Matterhorn”: Model-A fabricated under direction of Profs. C.H. Willis (chief engineer for Model-A & B) and N. Mather.
- Hired Prof. James Van Allen to run experimental program, 1953-1954. Mel Gotlieb came in 1954
- This picture in 1983, just before donated to the Smithsonian.

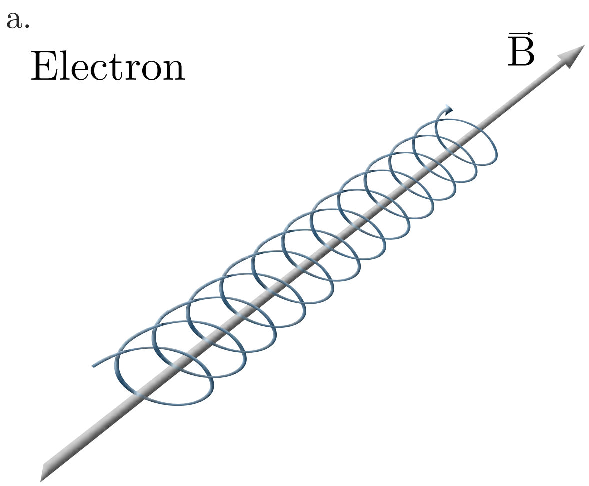
2cd UN Atoms For Peace Conference, Geneva 1958.

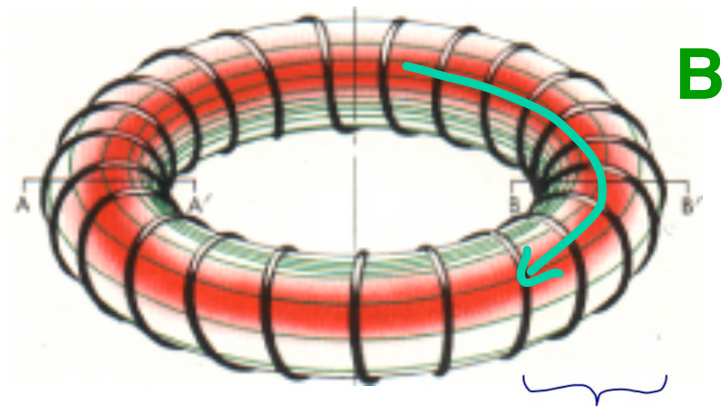


Perhaps SIM-8, one of the simulator stellarators (w/ e-beam) used in demonstrations at the 2cd Atoms-For-Peace Conference, Geneva (1958)

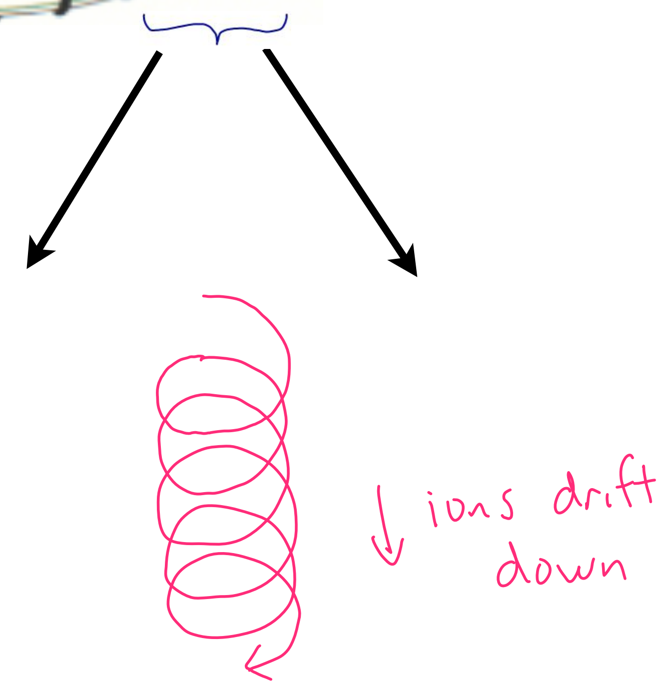
A Crash Course in Magnetic Confinement (in 3 slides)

Particles have helical orbits in B field, not confined along B. Try to fix by wrapping B into a torus.





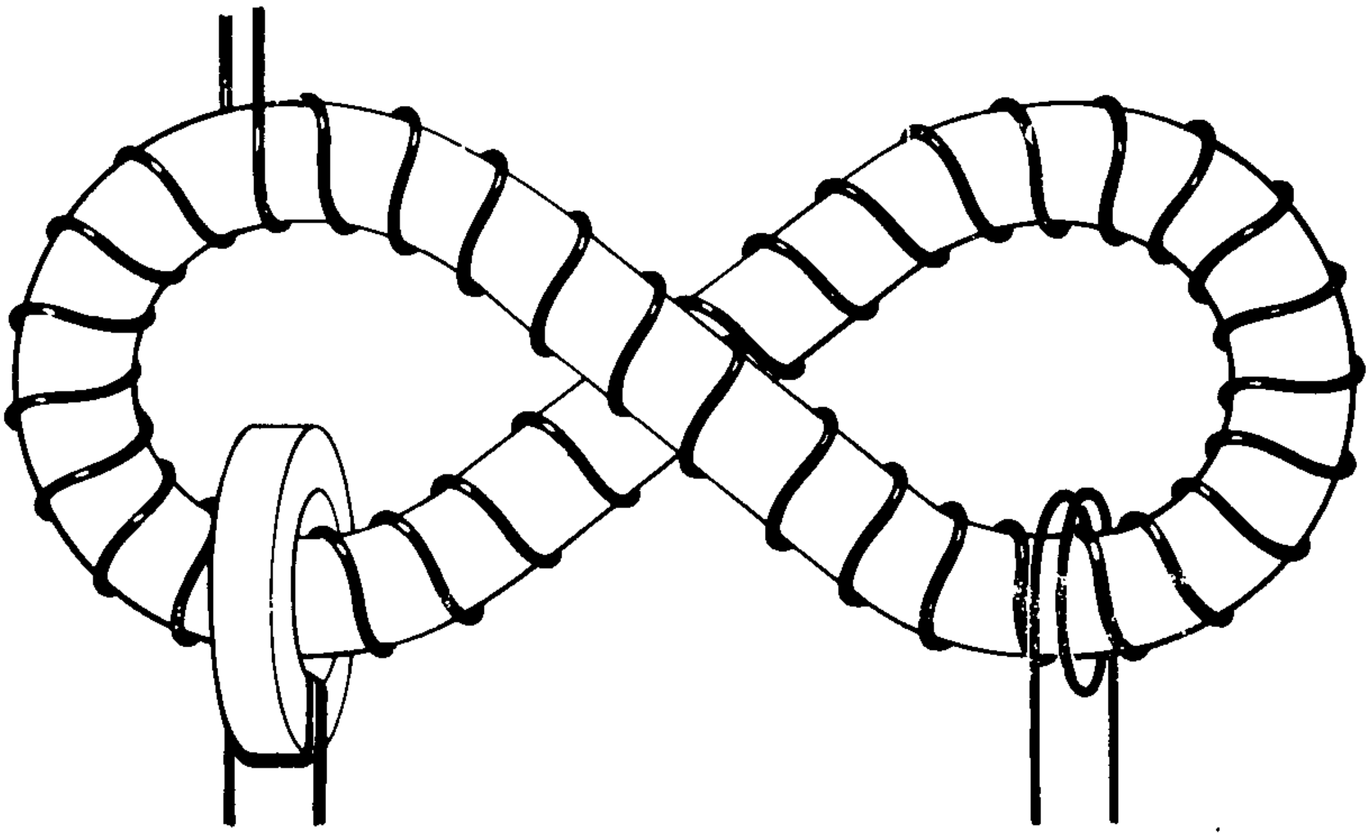
$$m\frac{d\mathbf{v}}{dt} = q\mathbf{v} \times \mathbf{B}$$



but now B ~ 1/R, so
particles will drift out:

worse than this: ions drift down & electrons drift up -->
ExB drift drives particles outward before 1 transit around torus

Spitzer's stellarator solution: twist torus into figure-8 to cancel drifts and confine particles.



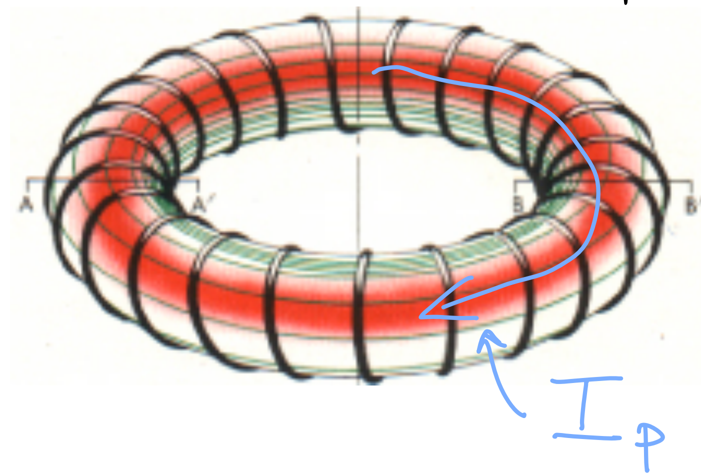
ions drift down on one side of figure 8, but drift up on other side.

(Also, electrons can flow along field lines to shield charge buildup.)

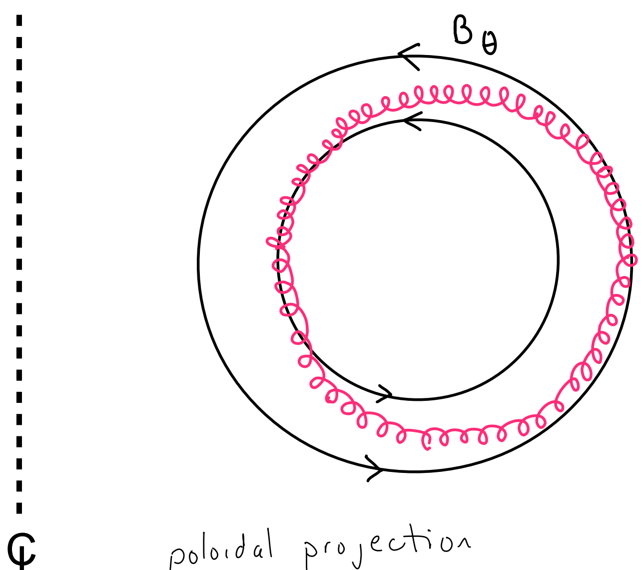
R. A. Ellis, Jr,, Princeton Alumni Weekly, Sept. 19, 1958

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

Induce a current in plasma:

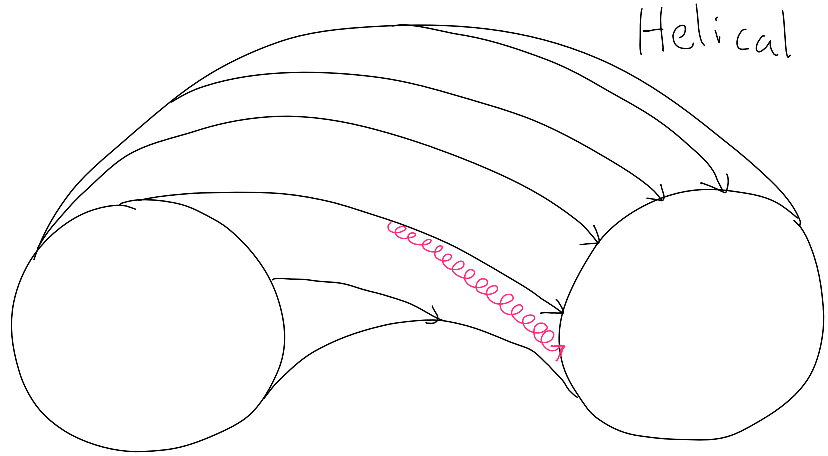


Ion motion along twisting $\underset{\sim}{B}$ field + downward drift:



poloidal projection

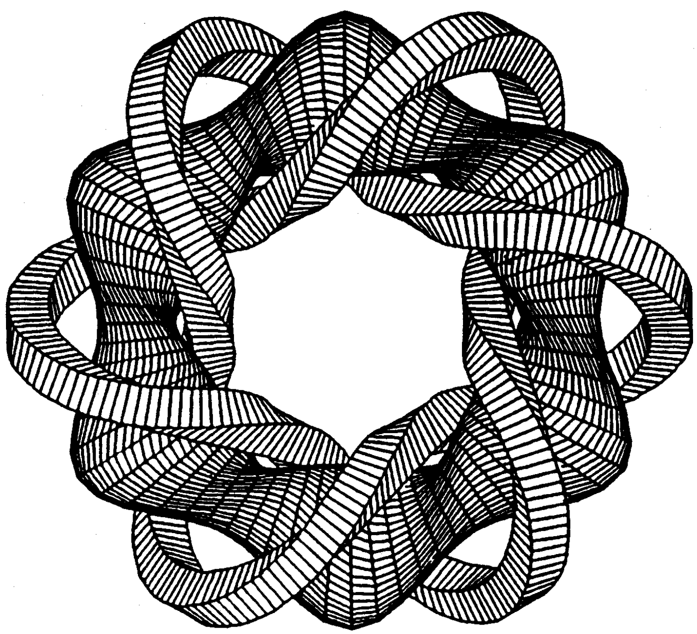
Helical twist in $\vec{B}$



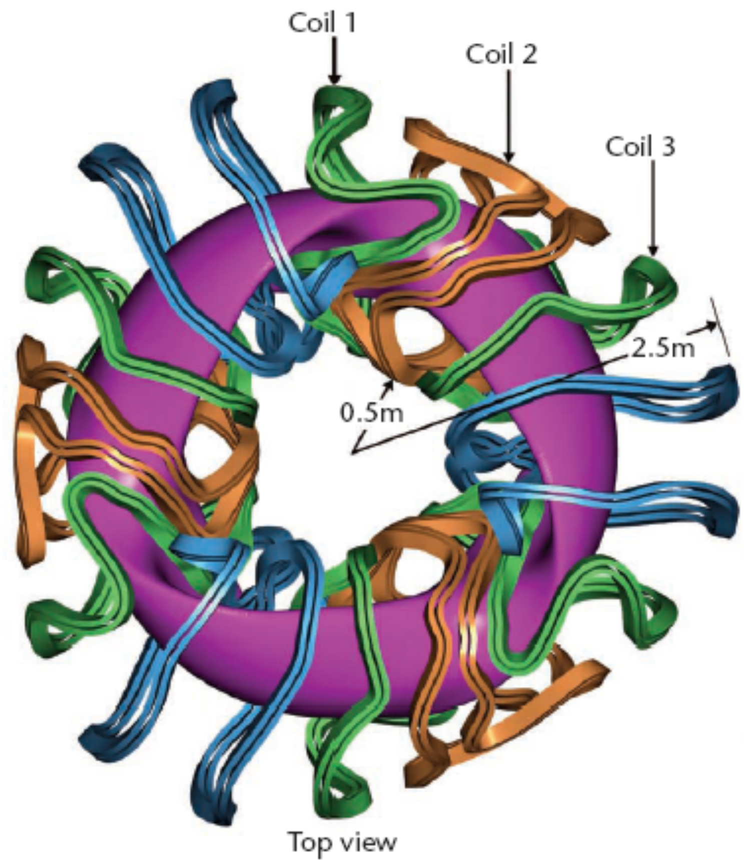
Perspective view

Modern stellarators

Spitzer et al. later realized that particles can be confined by a net poloidal twist in the magnetic field produced by helical coils. Eventually evolved into modern stellarator designs with modular, unlinked coils.



JF Lyon et al., 1997 http://aries.ucsd.edu/LIB/REPORT/SPPS/FINAL/chap2.pdf



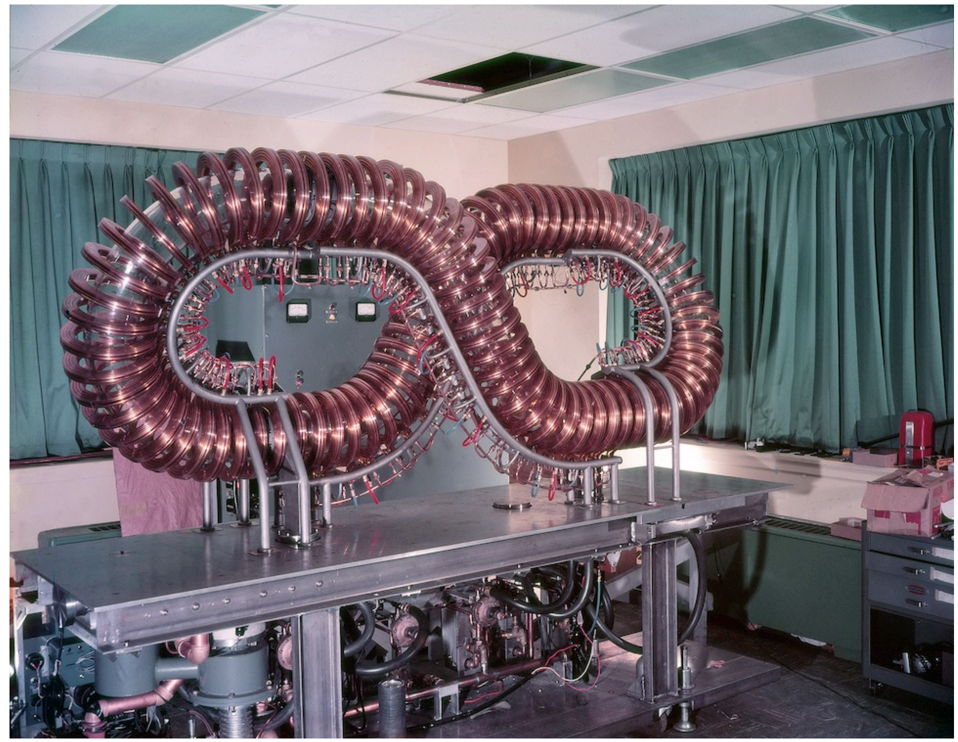
Princeton Quasar (Quasi-axisymmetric Stellarator)

2cd Atoms-For-Peace Conference, Geneva 1958.

Controlled fusion energy declassified worldwide in 1958. Roald Sagdeev, then a young physicist, said that going from Soviet Union to meet western scientists was like meeting martians.

Both sides invented pinches, mirror machines, symmetric toroidal devices. But the one unique idea invented only by one side was the stellarator.

Rosenbluth went to the meeting, surprised to see Russians had a stellarator:
"... the Stellarator always seemed to me like something ... I never quite understood how Spitzer was ever able to envision it. His geometrical intuition was better than mine. Sure enough, the Russians showed up with a Stellarator. And Sagdeev later told me that that was just a fake. Artsimovich had heard about our Stellarator and told them we couldn't claim that we had something they hadn't thought of, so they just added it on."

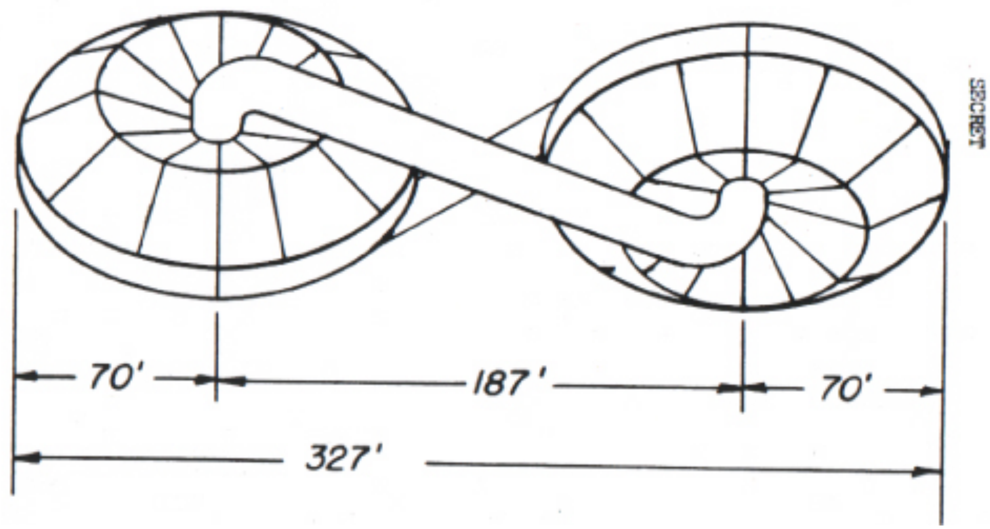


Perhaps SIM-8, one of the simulator stellarators (w/ e-beam) used in demonstrations at the 2cd Atoms-For-Peace Conference, Geneva (1958)

"... That's one of the few examples I know that that sort of chicanery was going on in this business." AIP oral history, Marshall Rosenbluth, 2003, http://www.aip.org/history/ohilist/28636_1.html

The First Stellarator Reactor Design ~ 1955

- In 1954, Spitzer et al (incl. industry) carried out a study of a commercial-scale stellarator: Model D. The design was a large figure 8 with a divertor in each U-bend. H_2O Cu coils



- Parameters of Model D (D-T reactor):
  - confinement assumed to be OK, T~10 keV, $n \approx 10^{21}$ m^{-3}
  - $\beta = 0.24$, B = 7.5 T, $a_p = 0.45$ m, circularized $R_0 = 24$ m
  - $P_{fusion} = 17$ GW (90 MWm^{-3}), $P_n = 6$ MWm^{-2}, $P_{elec} = 4.7$ GW

Comparison: ITER, $R_0 = 6.2$ m, $a_p = 2$ m, B = 5 T, Pfusion = 0.4 GW
ARIES-AT $R_0 = 5.2$ m, $a_p = 1.3$ m, B = 5.9 T, $P_{elec} = 1.0$ GW
ARIES-CS Compact stellarator: $R_0 = 7.75$ m, $a_p = 1.7$ m, B = 5.7 T, $P_{elec} = 1.0$ GW

$$\tau_E \sim \frac{a_p^2}{D}$$

(based on D. Meade)

B-3 Stellarator Group

Original Plan: Models A, B, C, and D (industrial scale)

Model A showed basic advantage of figure 8 over racetrack.

But started to find difficulties with Model B. Series of expts. built in 1950's: Model B, B-2, B-3, B-64/65/66.

B-3 was first with ℓ=3 helical coils, provides magnetic shear in response to Teller's concerns.

Spitzer built a team of excellent scientists. Here are members of the B-3 Group in 1960, including physicists Wolfgang Stodiek and Bob Ellis (2cd and 3rd from left on bottom), who led the experimental program for decades.

Model-C Stellarator, 1961-1969

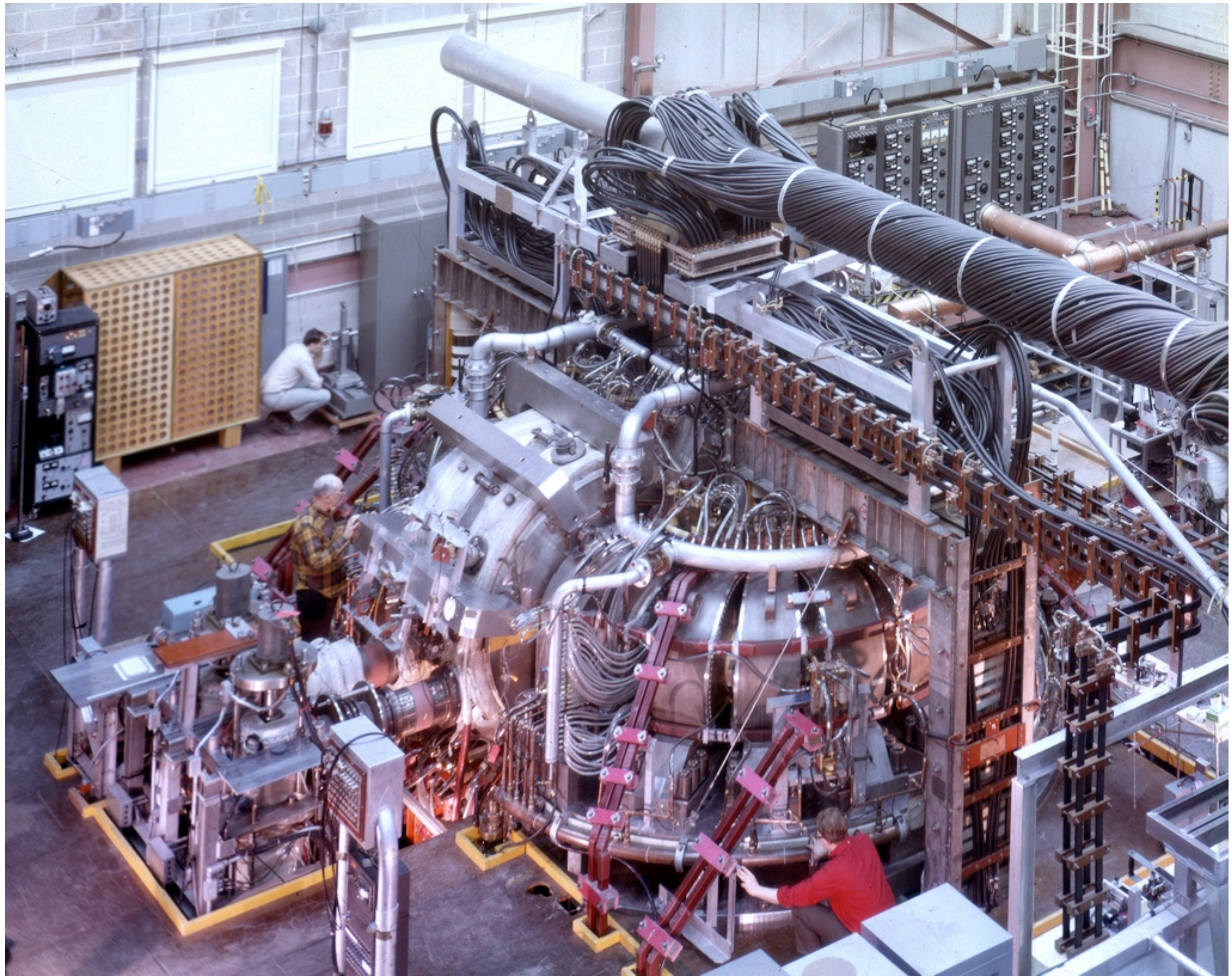
R ~ 1.9 m
a = 5 - 7.5 cm

Principal finding, strong turbulent diffusion limited performance:

$D \sim D_{Bohm}$
$\sim T_e/(eB)$

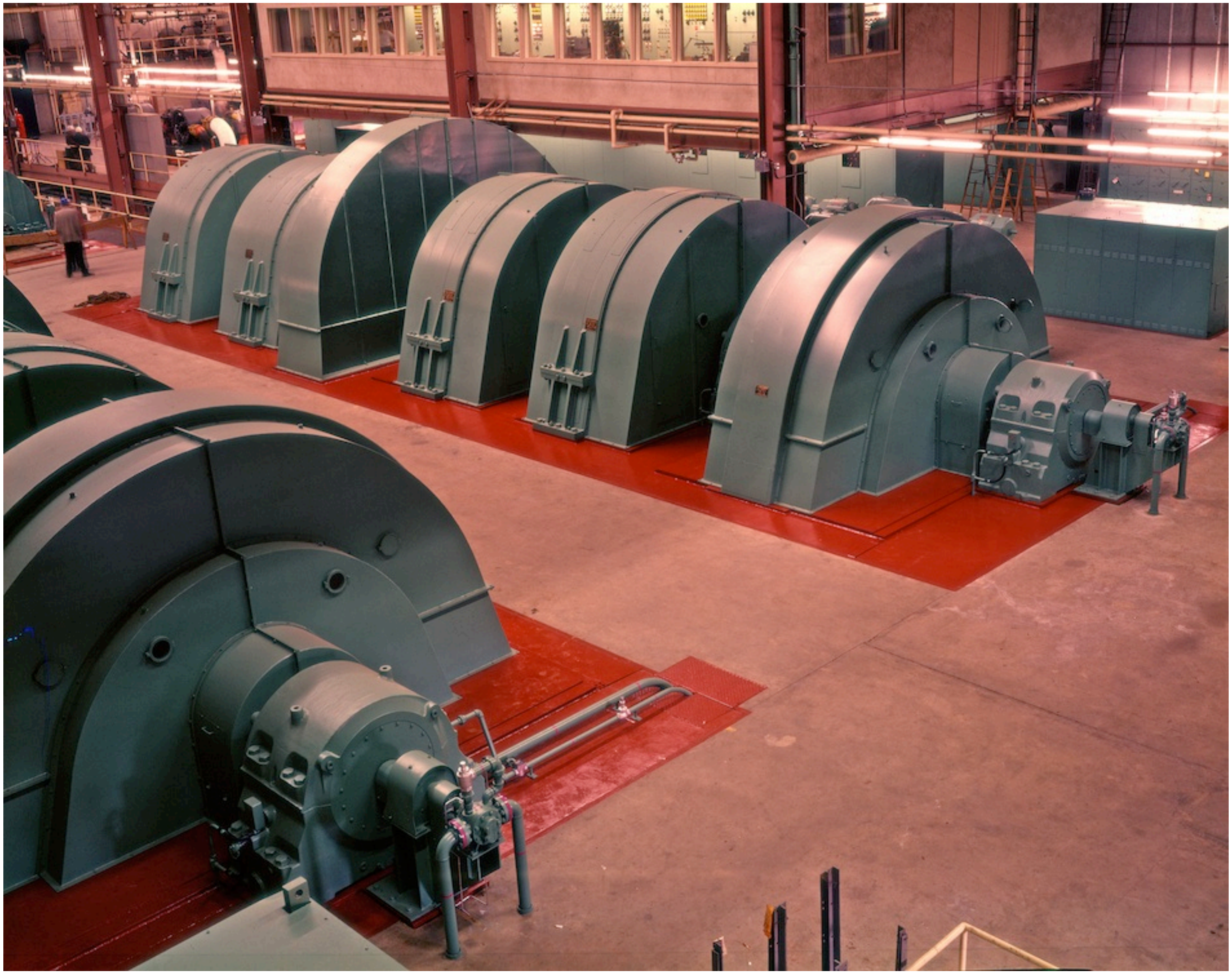
But with 4MW ICRF heating, got mirror trapped
$T_i \sim 8$ keV,
avg $T_i \sim 400$ eV

Stix, 1998



(1967). Converted to ST Symmetric Tokamak in 1970, after breakthrough results reported by Russian tokamak at 1968 IAEA meeting, much better than Bohm diffusion. British laser scattering team went to Russia, confirmed $T_e \sim 1$ keV with just ohmic heating (Nature, Nov. 1969).

Motor-Generators used to power Model-C Stellarator



(1961) Motor generators used through the 1990's to power tokamaks including PLT (my thesis), PDX, ...

December 9-10,1993: Momentous Days for Two of Spitzer's Biggest Ideas: Fusion Energy & Space Telescopes

- Sequence of larger Princeton tokamaks built starting in 1970: ST, ATC, PLT, PDX ... (and others elsewhere). Arab Oil Embargo & 1st Energy Crisis led to large funding of alternative energy. Combined with good performance of tokamaks, motivated a large tokamak expt. to actually use tritium. 1974: Design of TFTR began, 1976: construction authorized, 1982: first plasma (construction ~$1.4B in 2012$), 1993: DT experiments.

- December 9, 1993, TFTR (Tokamak Fusion Test Reactor) does first DT shots, eventually making 10 MW of fusion power.
  "Increased the fusion power gain by a factor of 1 million over the value when it was designed in 1975 to Q = 0.3 in 1995"

- December 10, 1993: Space Shuttle fixed Hubble Space Telescope optics.

- http://www.nytimes.com/1993/12/10/us/scientists-at-princeton-produce-world-s-largest-fusion-reaction.html
- http://www.nytimes.com/1993/12/11/us/shuttle-releases-hubble-telescope.html

GAO: construction cost ~$0.5B as spent, 2012/1981 CPI = 229.6/82.4

TFTR First DT Shot, Dec. 9, 1993

- December 9, 1993. TFTR does first DT shots, eventually making 10 MW of fusion power.
- http://www.nytimes.com/1993/12/10/us/scientists-at-princeton-produce-world-s-largest-fusion-reaction.html
-

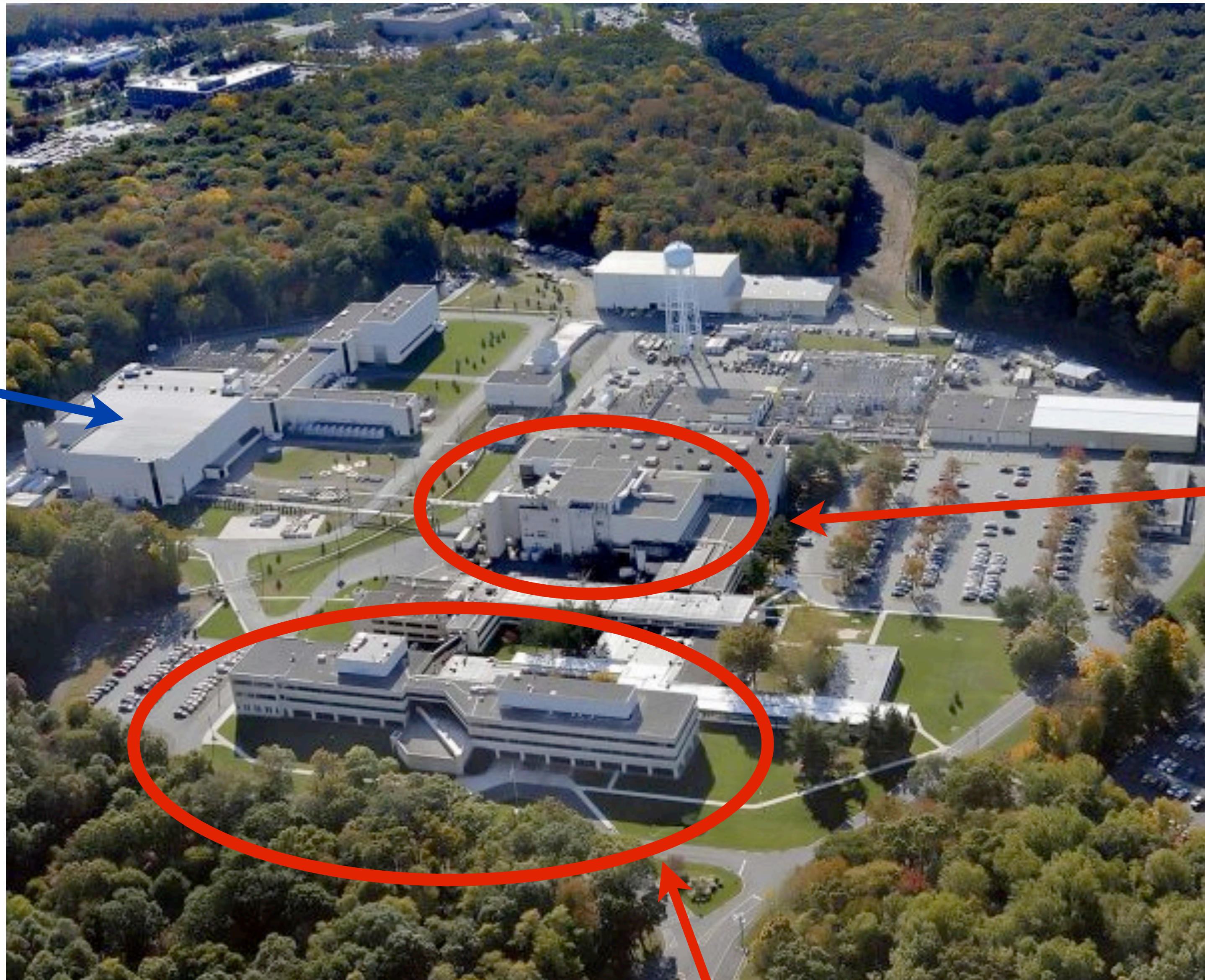

The New York Times
NEW YORK, FRIDAY, DECEMBER 10, 1993
Scientists at Princeton Produce World's Largest Fusion Reaction
Chicago Tribune
circulation 740,713
2nd fusion test again 'replicates the sun'
The Dallas Morning News
Sunday, December 19, 1993
STAR POWER
Do we have the vision to harness it?
The Star-Ledger
SATURDAY, DEC. 11, 1993
FUSION EUPHORIA
Princeton team again shatters its record producing energy in huge reactor
The Orlando Sentinel
Fusion record set at Princeton
Nuclear breakthrough
THE NEWS-JOURNAL
Serving Volusia And Flagler Counties
SATURDAY
The Oregonian
Circulation 332,250
Keep fusion dream alive
Nuclear fusion promises cheap, unlimited energy supply; with research support, it could take over when oil runs out
The Washington Post
Princeton Scientists Set Fusion Record
3 Million Watts of Power Produced in a Single Nuclear Burst
HOW IT WORKS
Chicago Tribune
Making progress toward fusion
San Francisco Chronicle
THE VOICE OF THE WEST
EDITORIALS
Nuclear Fusion's Hopeful Promise
Fusion lab clones power of sun
Princeton Plasma Physics lab engineer Doug Loesser kneels in Tokamak Fusion Test Reactor.
THE SUN
Circulation 494,867
Fusion reactor generates record energy in tests
THE DAILY OKLAHOMAN
Will fusion turn out to be 1993's big story?
GEORGE WILL
The top science stories of 1993
The Nobel Prize
living
The Philadelphia Inquirer
A milestone for nuclear fusion
Key experiments on the potential energy source begin in Princeton
Key nuclear fusion experiments begin
THE TORONTO STAR Sunday, December 19, 1993
SCIENCE
Fusion power: The fire finally lights
Princeton team's success seen as a major step but aim now is to turn
A promise for the future

TFTR First Plasma, 3:06 am, Dec. 24, 1982

- December 10, 1993: Space Shuttfle fixed Hubble Space Telescope optics.
- http://www.nytimes.com/1993/12/11/us/shuttle-releases-hubble-telescope.html

Princeton Plasma Physics Laboratory (PPPL) today

TFTR,
NSTX



Model-C stellarator, PLT, PDX, PBX-M.

Ready for new Quasar stellarator someday?

Lyman Spitzer Building (offices)

My Perspective on Fusion Energy

- Need to pursue many energy sources. All have tradeoffs & uncertainties. Challenging to supply all energy needed in the long term. Energy demand expected to triple throughout this century as poor countries continue to develop.

- Fusion energy is hard, but it's an important problem, we've been making progress, and there are interesting ideas to pursue that could make it more competitive.

Good confinement needed for fusion

- Simple power balance: $P_{fusion,\alpha} > P_{losses} \sim 3n_eT\,V/\tau_E$ leads to Lawson criterion:

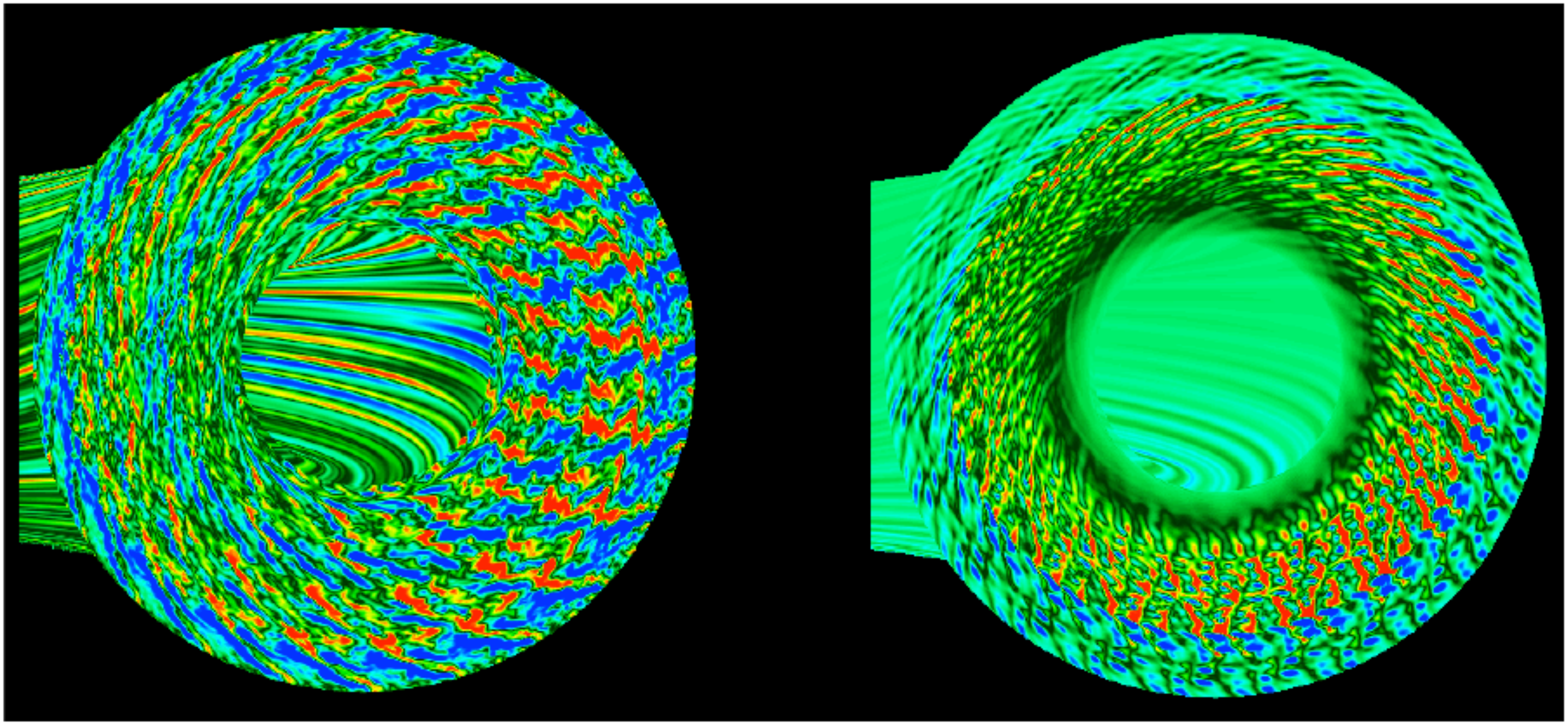
$$n_e\,T\,\tau_E \quad \sim 10^{20}\ \mathrm{m}^{-3}\ \ 15\ \mathrm{keV}\ \ 3\ \mathrm{sec}$$

$P_{fusion,\alpha} \sim n^2 \langle\sigma v\rangle\, V,$
and $\langle\sigma v\rangle \sim T^2$

- In 3 sec, a 15 keV ion will go $\sim 10^5$ times around the torus.

- Modern fusion designs are MHD stable (usually), but are subject to small scale turbulence from drift wave instabilities (FLR corrections to MHD). This turbulence causes particles to leak out a bit faster than we would like. Would like to improve relative τ_E by another 20% to x4.

Sheared ExB Flows can reduce turbulence

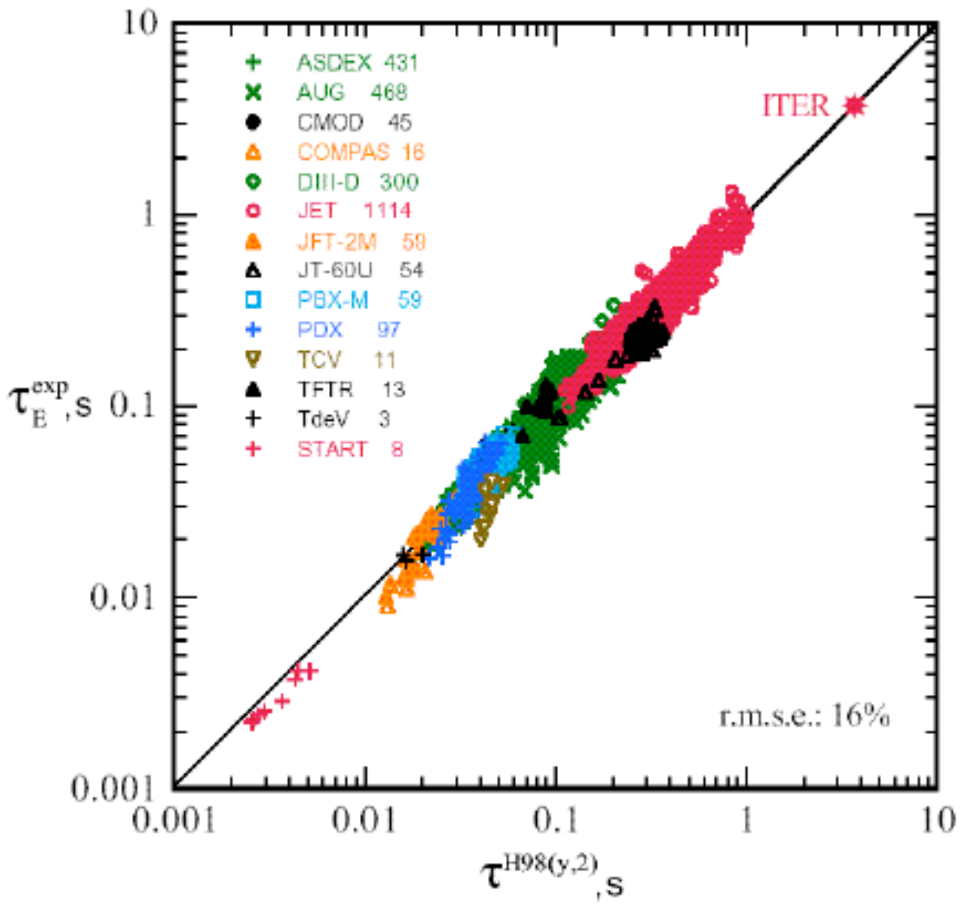


Snapshot of density fluctuations driven by small-scale drift-wave turbulence
(small amplitude fluctuations, $\delta n/n_0$ ~ 1%)

Various methods to reduce this turbulence, such as background sheared flow.

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

Empirical H-mode scaling for confinement time fit to experiments



This is for standard "H-mode" operational scenario. There are other operating scenarios (reversed magnetic shear, strong flows, impurity seeding, etc.) that have done better in experiments, but we aren't as confident in how they will extrapolate to a reactor.

$$\tau_{E,th}^{\mathrm{IPB98(y,2)}} = 0.0562\, H\, I_p^{0.93} B_T^{0.15} \bar{n}_e^{0.41} P^{-0.69} R^{1.97} M^{0.19} \kappa_a^{0.78} \varepsilon^{0.58}$$

$$\propto H B_T^{1.49} R^{2.49} P^{-0.69}$$

At fixed Greenwald fraction & fixed geometry (q, ε, κ)

In steady-state, heating power $P = 3n_eT\, V/\tau_E$. Solving for τ_E makes it a sensitive function: $\tau_E \sim H^{3.2}$ at fixed n_eT.

Improving Confinement Can Significantly Lower Cost of a Fusion Reactor

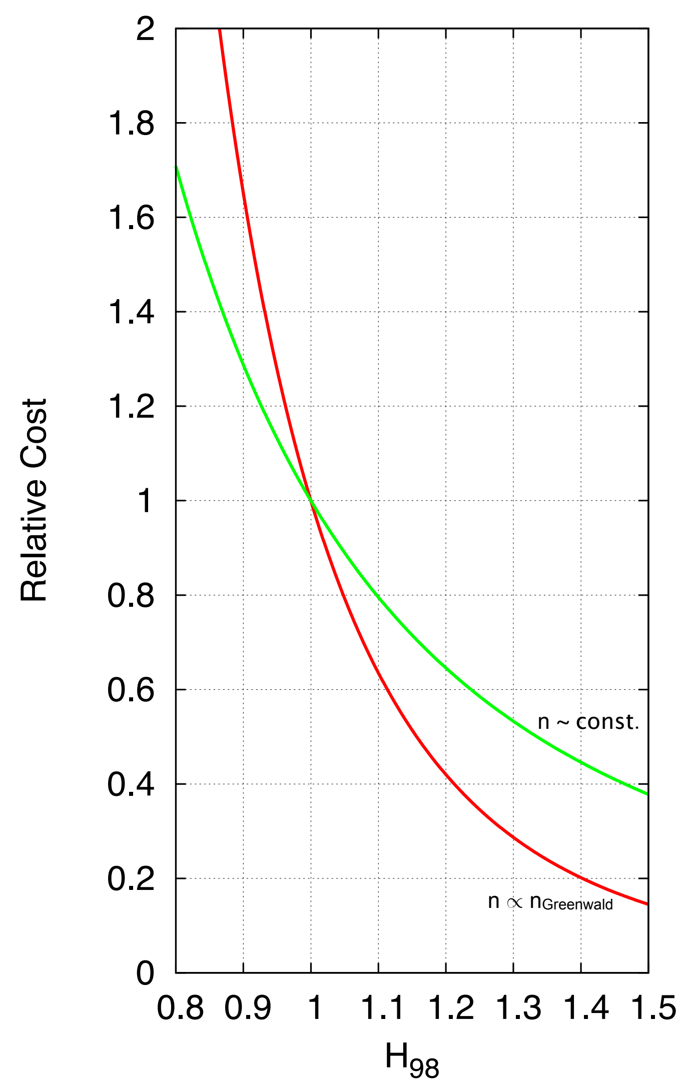
Well known that improving confinement factor H & beta limit can significantly lower cost of electricity at fixed power output.

H has even stronger impact on construction cost at fixed fusion gain Q, because higher H allows a smaller machine to achieve same Q.

Even with a conservative estimate: cost $\propto R^2$,
get cost $\propto 1/H^{4.76}$ (if $n \propto n_{Greenwald} \propto 1/R$).

If H can be improved just 25%, can reduce cost by x3.
(Lower bounds on device size set by blanket & coil thickness, $\langle\sigma v\rangle \sim T^2$ assumption, but can go smaller than present.)

ITER conservatively designed with H=1. Experiments have achieved better confinement via various mechanisms that are understood qualitatively. Working to develop better computer simulations, particularly near plasma edge, to predict extrapolation to reactors.



Interesting Ideas To Improve Fusion

* Liquid metal (lithium, tin) coatings on walls: (1) protects solid wall (2) absorbs incident hydrogen ions, reduces recycling of cold neutrals back to plasma, raises edge temperature & improves global performance. TFTR found: ~2 keV edge temperature. NSTX, LTX: more lithium is better, where is the limit?

* Spherical Tokamaks (STs) appear to be able to suppress much of the ion turbulence: PPPL & Culham upgrading 1 --> 2 MA to test scaling

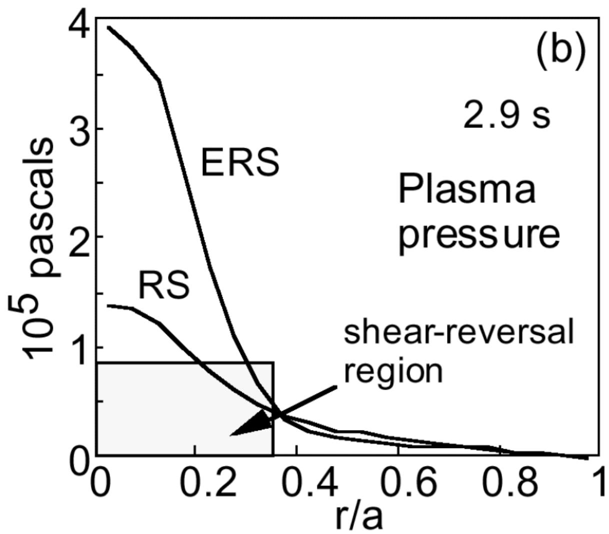
* Advanced tokamaks, alternative operating regimes (reverse magnetic shear or “hybrid”), methods to control Edge Localized Modes, higher plasma shaping. Will beam-driven rotation be more important than previously thought?

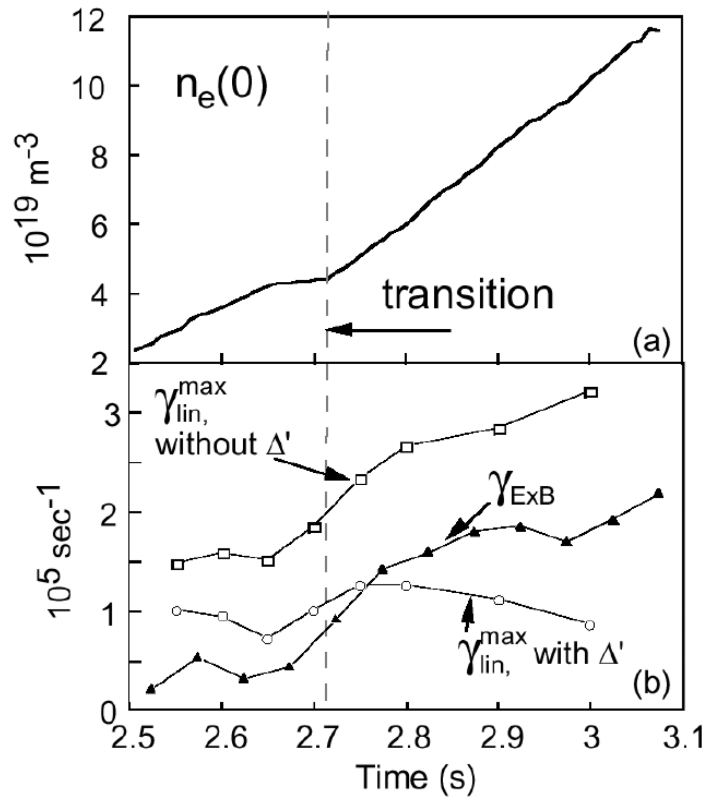
* Tokamaks spontaneously spin: can reduce turbulence and improve MHD stability. Can we enhance this with up-down-asymmetric tokamaks or non-stellarator-symmetric stellarators with quasi-toroidal symmetry?

* Many possible stellarator designs, room for further optimization: Quasi-symmetry / quasi-omnigenity improvements discovered relatively recently, after 40 years of fusion research. Stellarators fix disruptions, steady-state, density limit.

* Robotic manufacturing advances: reduce cost of complex, precision, specialty items

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





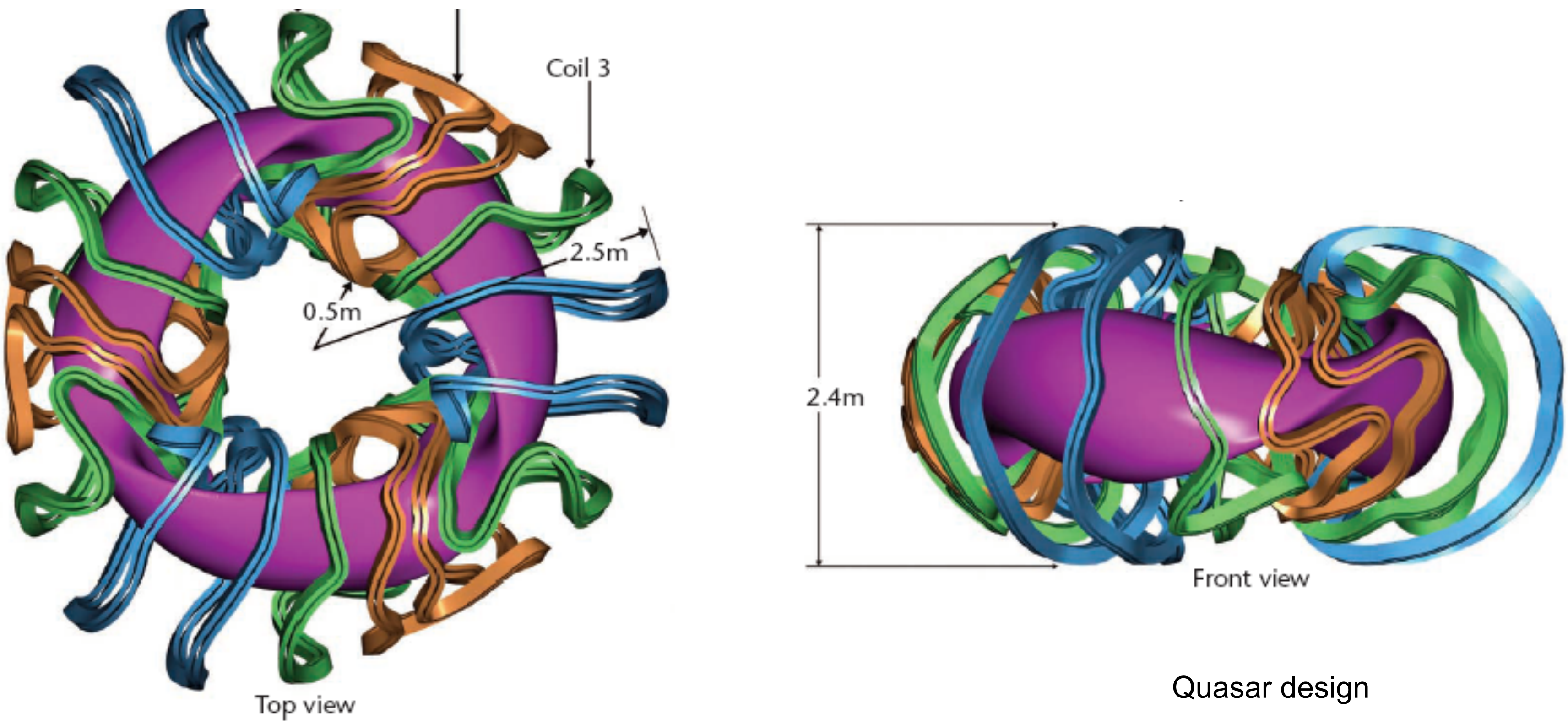
Synakowski, Batha, Beer, et.al. Phys. Plasmas 1997

$P_{fusion} \propto$ pressure^2

Stellarators can naturally have reversed magnetic shear, short distance between stable and unstable regions.

Improved Stellarators Being Studied

- Originally invented by Spitzer ('51). Mostly abandoned for tokamaks in '69. But computer optimized designs now much better than slide rules.
- Quasi-symmetry discovered in late 90's: don't need vector ***B*** exactly symmetric toroidally, |***B***| symmetric in field-aligned coordinates sufficient to be as good as tokamak. (Zarnstorff's talk)
- Magnetic field twist & shear provided by external coils, not plasma currents, inherently steady-state. Stellarator expts. don't have hard beta limit & don't disrupt.
- Robotic advances could bring down manufacturing cost.



Quasar design

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- Interesting ideas being pursued to improve confinement & reduce the cost of fusion reactors

References

- Earl C. Tanner, *Project Matterhorn,* 1977 (revised 1982).
- Amasa S. Bishop, *Project Sherwood: The U.S. Program in Controlled Fusion*, 1958.
- "Lyman Spitzer Jr., 1914-1997", A Biographical memor by J. P. Ostriker, Biographical Memoirs, V.90 (2009), (biographies of members of the National Academy of Sciences) http://www.nap.edu/openbook.php?record_id=12562&page=354, National Academies Press. http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/spitzer-lyman.pdf
- Thomas H. Stix, personal communications (c. 1980-1998), from stories Stix told in classes and elsewhere.
- Thomas H. Stix, "Highlights in Early Stellarator Research at Princeton", J. Plasma Fusion Res. Series, V. 1, 3 (1998).
- http://fire.pppl.gov , http://fire.pppl.gov/fusion_library.htm
- Dale Meade, 50 years of fusion research, Nuclear Fusion and IAEA meetings, http://fire.pppl.gov/IAEA08_Geneva_Meade.ppt, http://fire.pppl.gov/nf_50th_6_Meade.pdf
- Dale Meade, "A Brief History of Fusion and Fusion Basics" and other talks at the 2005 Spring Princeton Graduate Seminars, http://fire.pppl.gov/ast558_2005.html
- Bromberg, Joan Lisa (1982) *Fusion: Science, Politics, and the Invention of a New Energy Source* MIT Press, Cambridge, Massachusetts, p. 44, ISBN 0-262-02180-3
- http://en.wikipedia.org/wiki/Project_Sherwood
- Robin Herman, "Fusion: the search for endless energy", Cambridge University Press, 1990
- James Phillips, "Magnetic Fusion", Los Alamos Science, Winter/Spring 1983
- http://en.wikipedia.org/wiki/Perhapsatron
- AIP oral history interviews:
  - Lyman Spitzer (1978) http://www.aip.org/history/ohilist/4900.html,
  - Marshall Rosenbluth (2003) http://www.aip.org/history/ohilist/28636_1.html
- ...

EXTRAS

EXTRAS

Other Historical Tidbits

- Right after WWII, there were discussions at LANL of what to do next, including discussions of the possibility of fusion for peaceful energy source. In those discussions, Fermi gave a proof that one can't use a simple torus. (One record of this is in classified British reports summarizing those discussions. Also mentioned in James Phillips, "Magnetic Fusion", Los Alamos Science, Winter/Spring 1983
- However, in Spitzer's oral history, he says he wasn't aware of Fermi's work on this, but he apparently knew it independently in 1951 when he started thinking about fusion. His 1958 paper "The Stellarator Concept" in Physics of Fluids says this was first pointed out by J. J. Thompson in 1906.
- Hired Martin Kruskal in 1951, one of the first things he worked out was working out favorable confinement properties of magnetic fields with rotational transform. So it wasn't just how the figure-8 cancelled the drifts. At a fairly early time he understood the twist in the field was also important (though I don't know if this was actually mentioned in the original May 12, 1951 proposal). (As pointed out by Amitava Bhattacharjee, the stellarator was the first realization of the phenomenon that later became known as the Berry phase.)
- Bryan Taylor told me stories about his first learning about the stellarator from a talk Spitzer gave at Harwell. He initially couldn't understand how the stellarator could work, how could the magnetic field twist without a current in the plasma. Later thought it was brilliant, seemed intuitively better to rely on magnetic field from coils that are bolted the floor and won't move, unlike tokamaks that rely on currents flowing in a plasma that can move, and is thus subject to instabilities...
- One of the hallmarks of Spitzer's work was deep intuition in looking at problems from both single particle and collective fluid perspectives (or from the microscopic viewpoint and the macroscopic viewpoint) and showing how to harmonize them. In particular, he pointed out how to reconcile what is known as "Spitzer's paradox": in equilibrium grad(p) ~ j x B, so there is a fluid drift associated with this j proportional to grad(p). But in single particle drifts, the drifts only involve gradients of magnetic fields, not grad(p). He pointed out that one must include the magnetization current, i.e. a diamagnetic current, to harmonize the microscopic and macroscopic view points. I.e., a fluid flow is not the same as a particle drift. (There is a picture illustrating this in his textbook.)

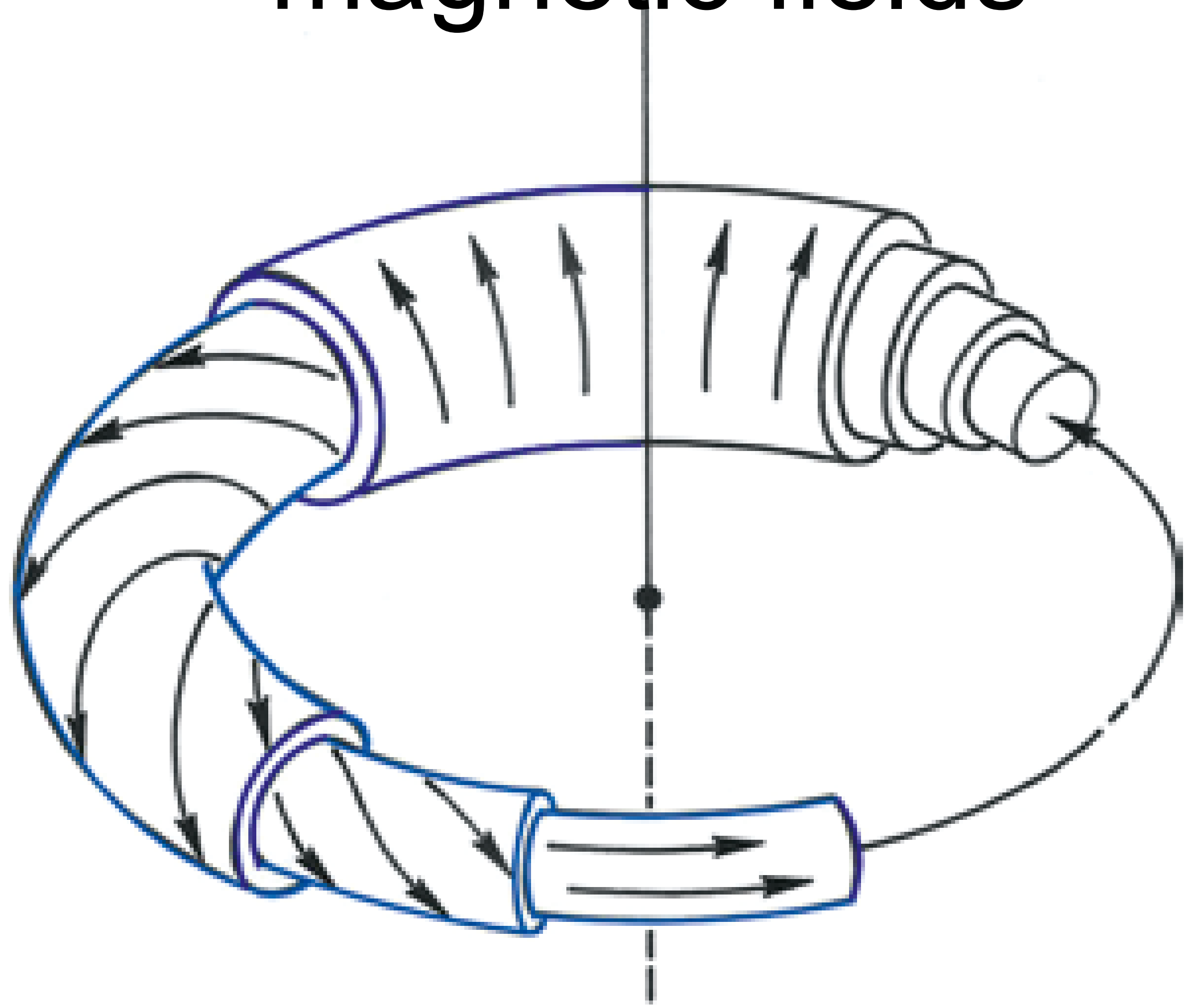
Refs. for Model D stellarator

- By June, 1954 a preliminary study had been completed for a full scale "Model D" stellarator that would be over 500 feet long and produce 5,000 MW of electricity at a capital cost of $209 per kilowatt. according to:
- Bromberg, Joan Lisa (1982) *Fusion: Science, Politics, and the Invention of a New Energy Source* MIT Press, Cambridge, Massachusetts, p. 44, ISBN 0-262-02180-3
- and http://en.wikipedia.org/wiki/Project_Sherwood

- Copper coils. 75% beta

- Key refs:
- Joan Lisa Bromberg, "Fusion: science, politics, and the invention of a new energy source", MIT Press, 1982
- Robin Herman, "Fusion: the search for endless energy", Cambridge University Press, 1990
- James Phillips, "Magnetic Fusion", Los Alamos Science, Winter/Spring 1983
- http://en.wikipedia.org/wiki/Perhapsatron
-

Torus with sheared helical magnetic fields



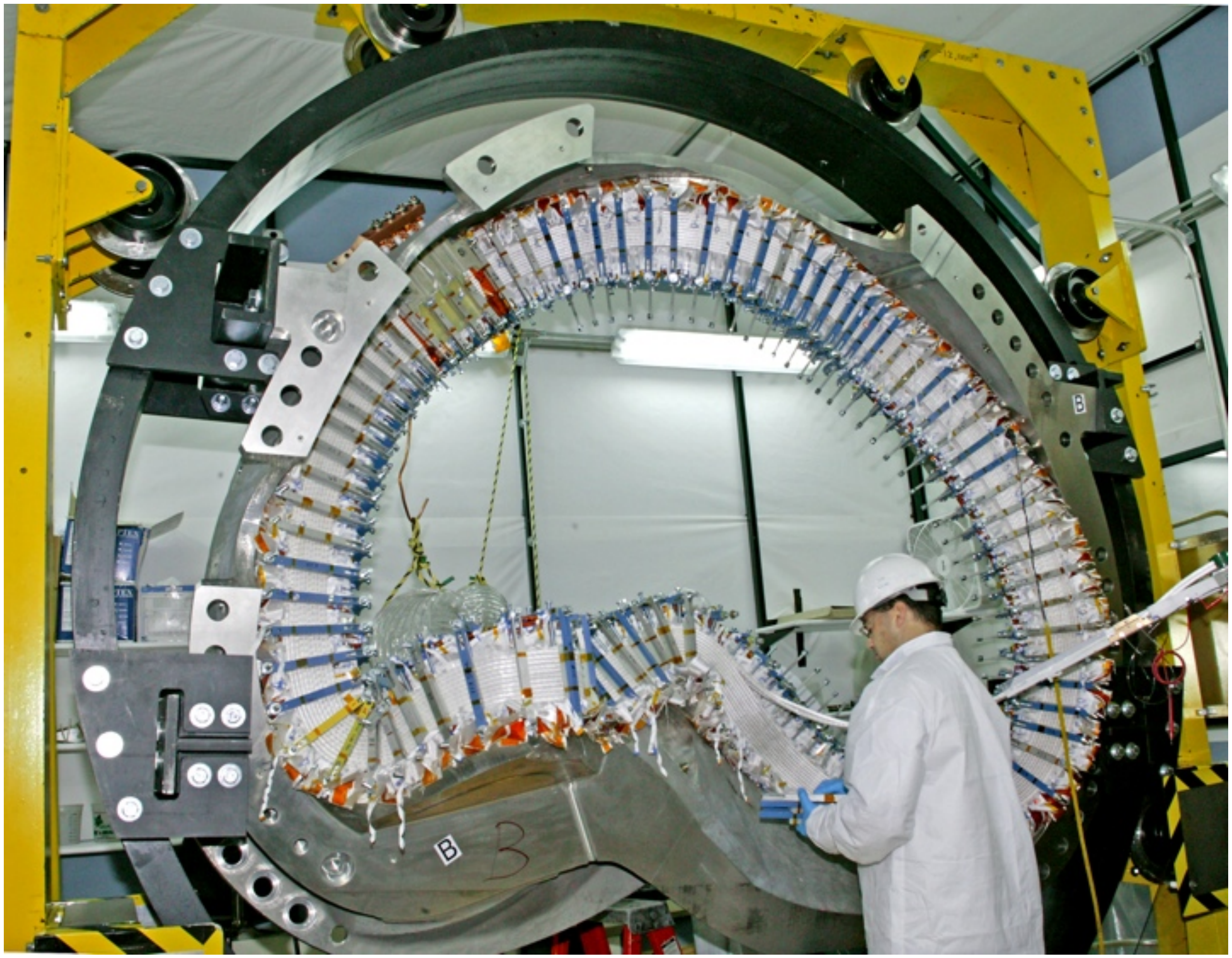
Extreme example, magnetic field is mostly in toroidal direction in standard tokamak.

magnetic shear can help stabilize instabilities
(negative & zero average shear can be better, average ≠ local shear)

From F.F. Chen, “An Indispensable Truth”, 2011

Figure of technician hand winding stellarator coils on large rotating metal forms

contact: Chryzanowski (Hutch Neilsen rec.)



Winding the coils on this large rotating frame required about 1 month per coil, because of the complexity and high accuracy required. The project was able to achieve the required tolerance of ± 0.020" by careful winding, many in-process measurements, use of clamps to re-position turns as required, and lacing to hold turn positions. Chryzanowski, et al., (Fus. Eng. 2007, IEEE)

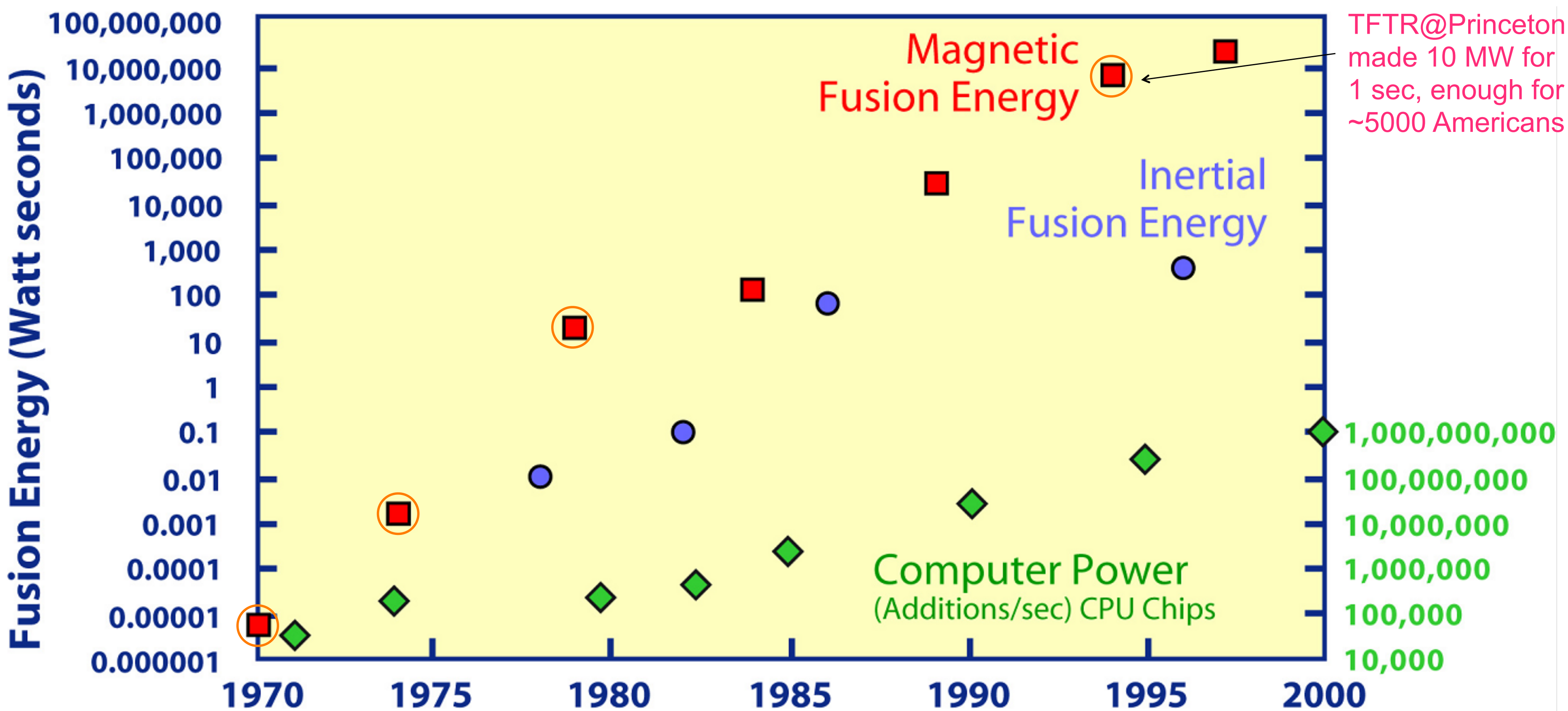
Wide Field Planetary Camera 1

Wide Field Planetary Camera 2

- Galaxy M100, before and after fix of Hubble optics,
- December 10, 1993: Space Shuttfle fixed Hubble Space Telescope optics.
- http://www.nytimes.com/1993/12/11/us/shuttle-releases-hubble-telescope.html
- http://commons.wikimedia.org/wiki/File:Hubble_Images_of_M100_Before_and_After_Mirror_Repair_-_GPN-2002-000064.jpg

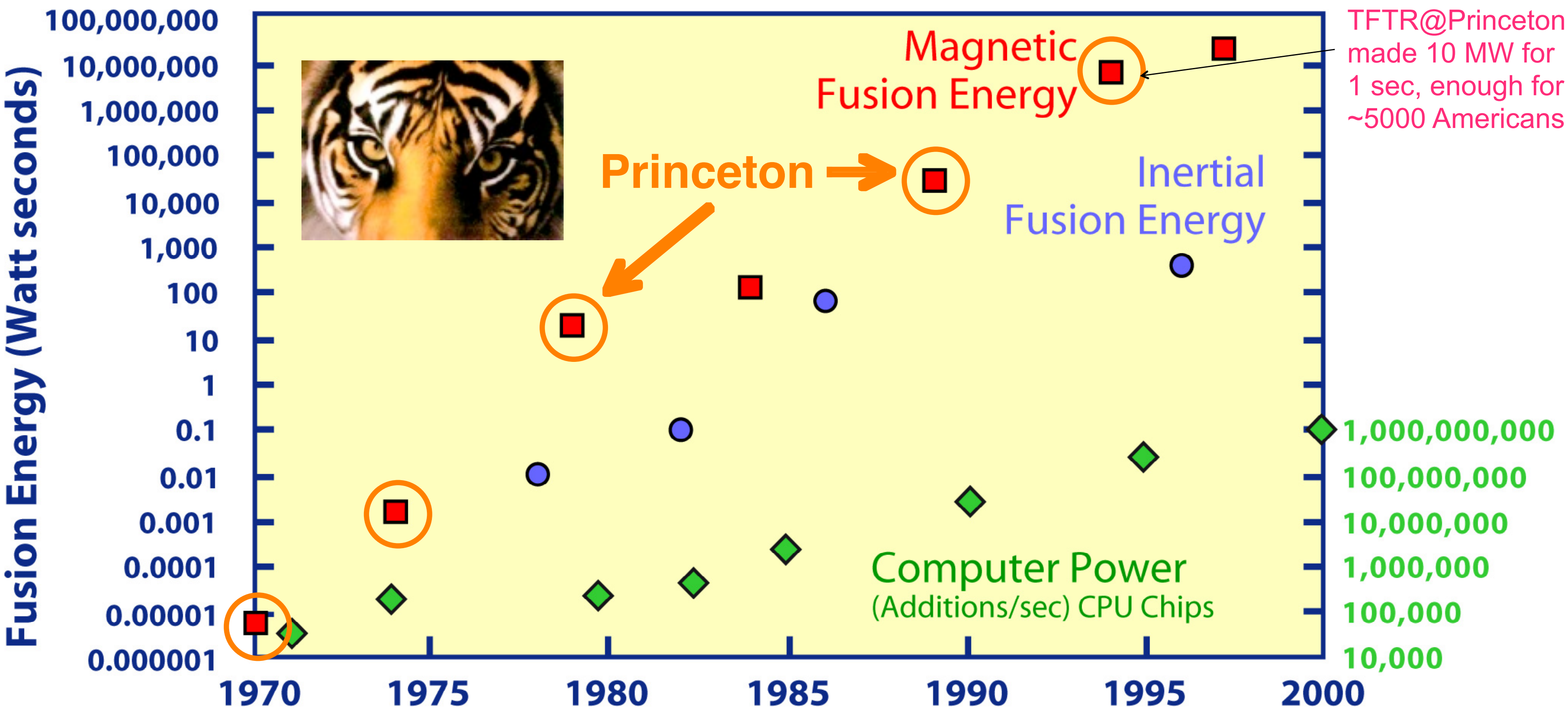
NASA photo

Progress in Fusion Energy has Outpaced Computer Speed



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

Progress in Fusion Energy has Outpaced Computer Speed



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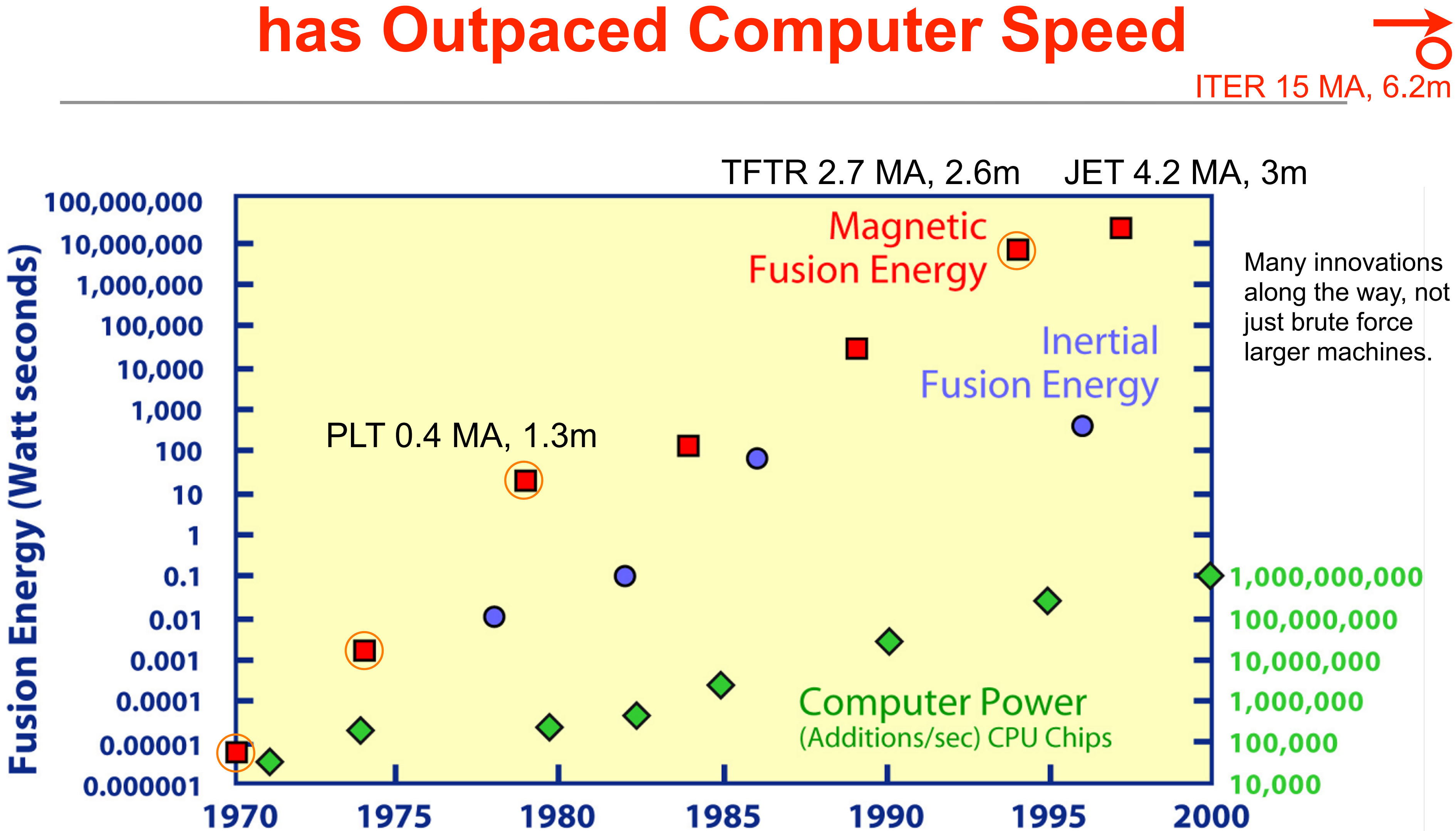
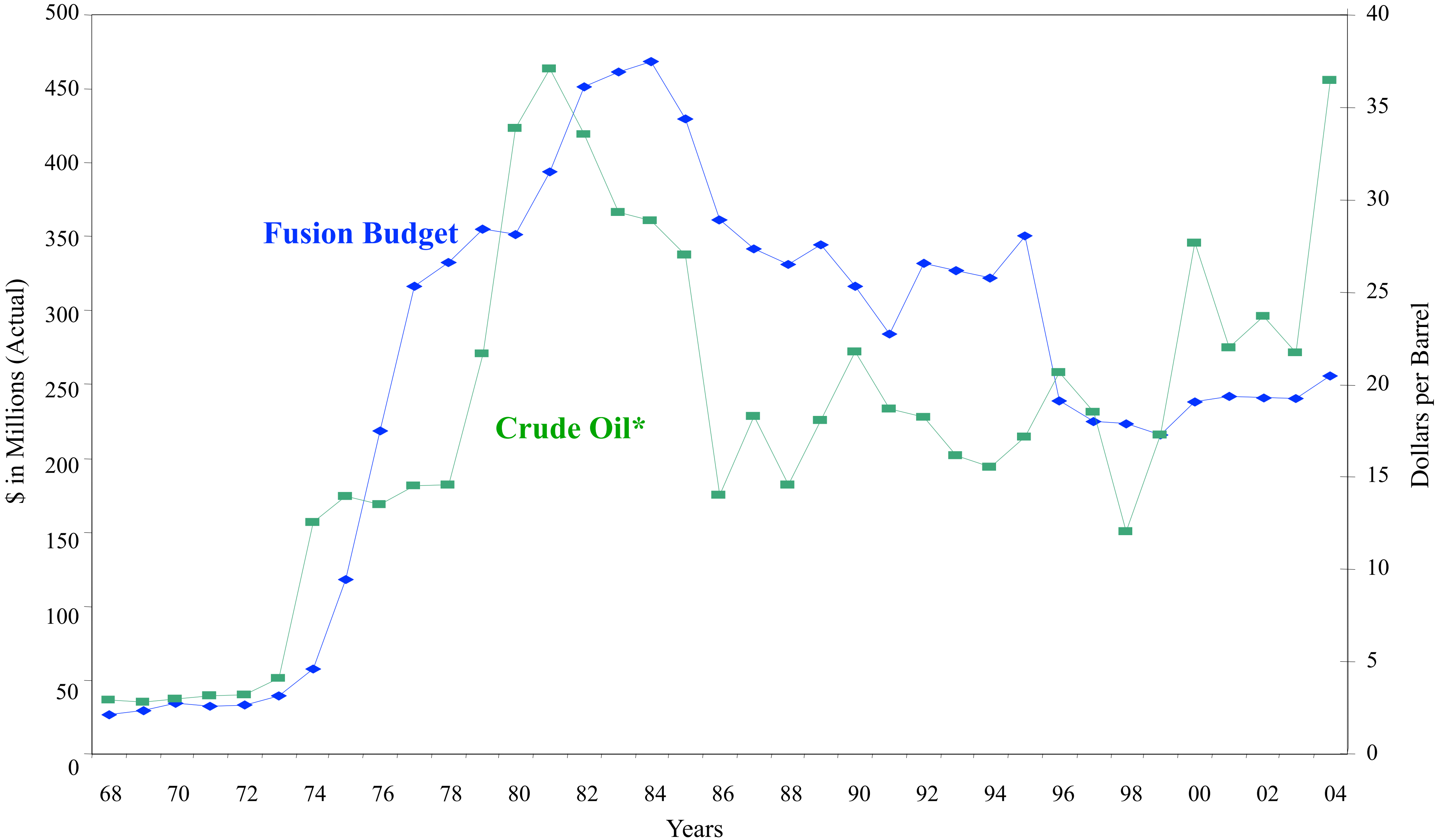


Many innovations along the way, not just brute force larger machines.

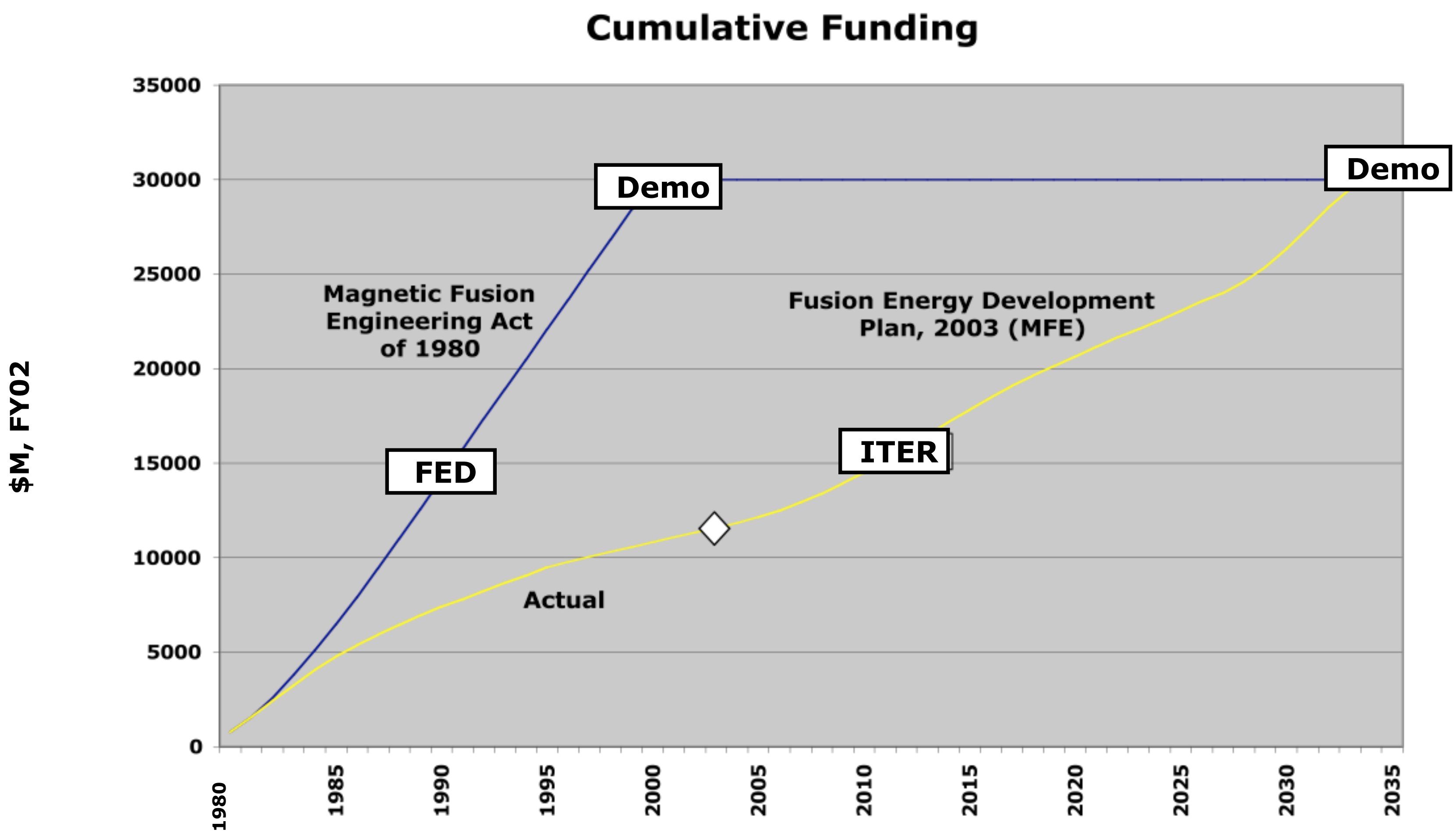
ITER goal: 200 GJ/pulse (500 MW = 30 x JET's power 16 MW, for 400x longer), 10^7 MJ/day of fusion heat).
NIF goal: 20 MJ/pulse (and /day) of fusion heat.

1973 Oil Embargo - Energy R&D Explodes



*In Actual $'s from Energy Information Administration/Annual Energy Review 2004 Table 9.1, Crude Oil Price Summary, Refiners Acquisition Costs, Imported, Nominal. Web Site: eia.doe.gov. Year 2004 is estimated based on 9 months record.

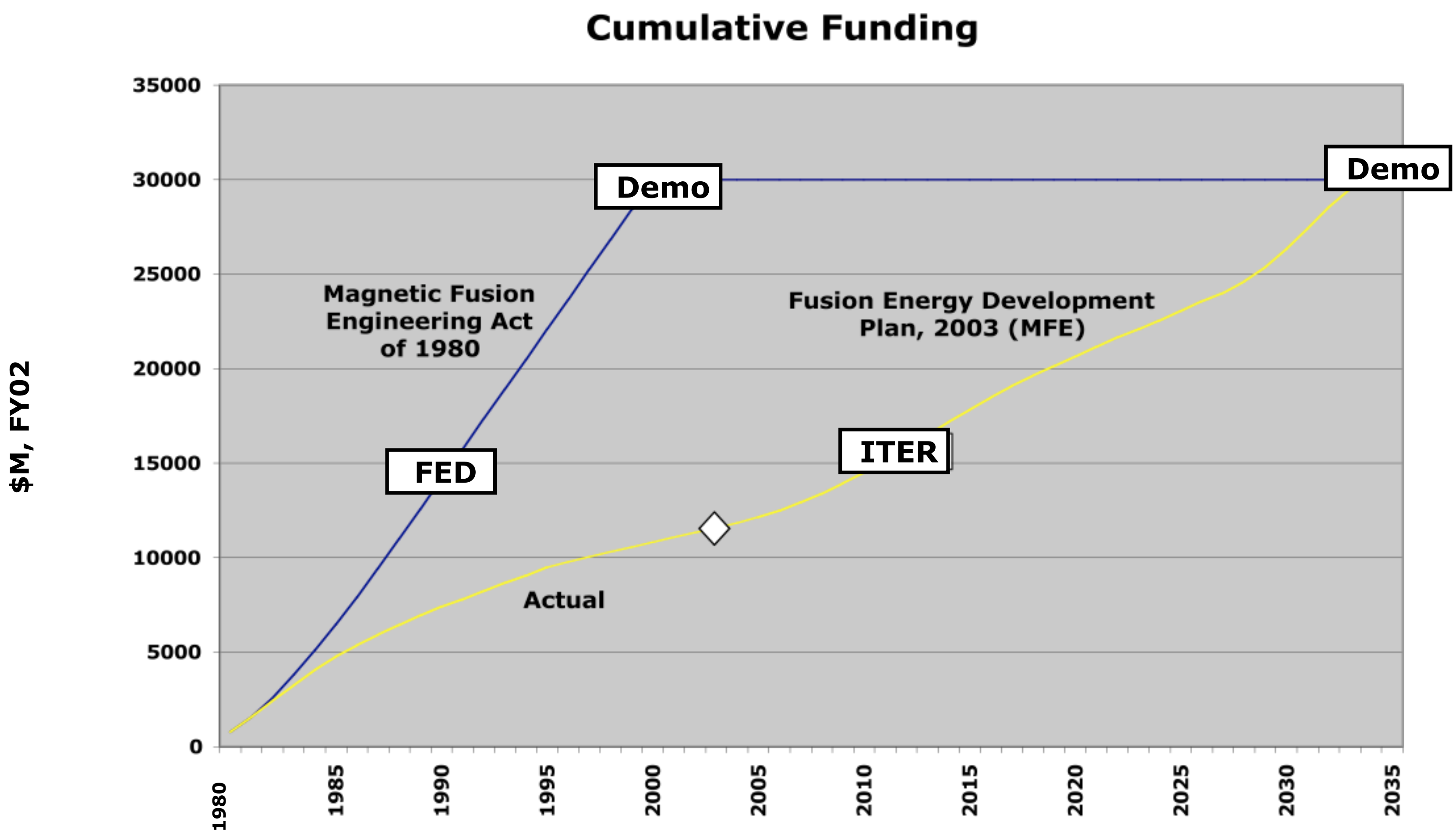
Fusion Could Be Done In A Shorter Time Scale If Sufficient Budget Eventually Provided



$30-$90B development cost is tiny compared to >$100 Trillion energy needs of 21st century & potential costs of global warming. (Apollo program ~ $100B.) Still 40:1 payoff after discounting 50+ years.

based on slide from R.J. Goldston

Fusion Could Be Done In A Shorter Time Scale If Sufficient Budget Eventually Provided



Einstein: Time is relative,

$30-$90B development cost is tiny compared to >$100 Trillion energy needs of 21st century & potential costs of global warming. (Apollo program ~ $100B.) Still 40:1 payoff after discounting 50+ years.

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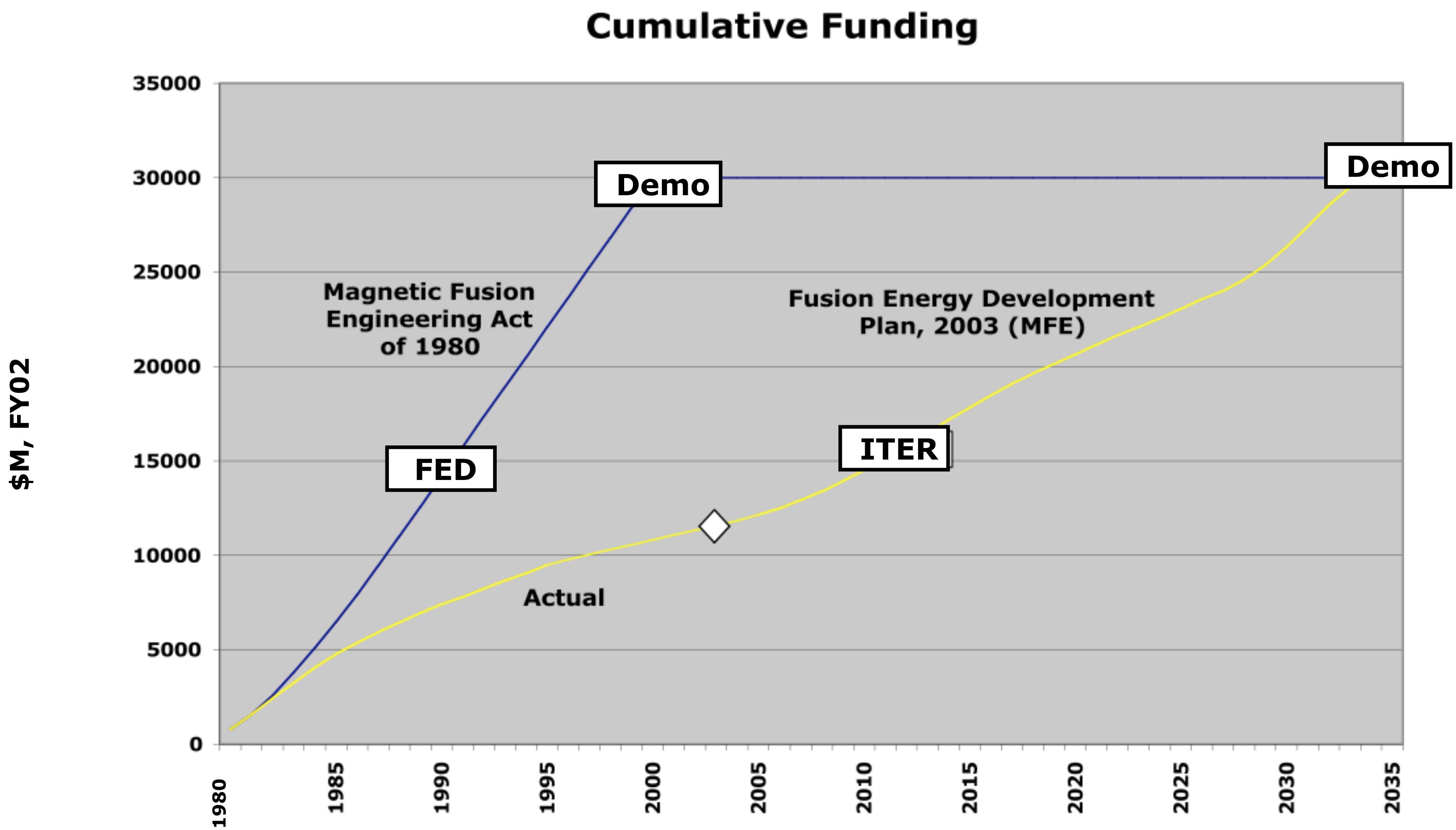
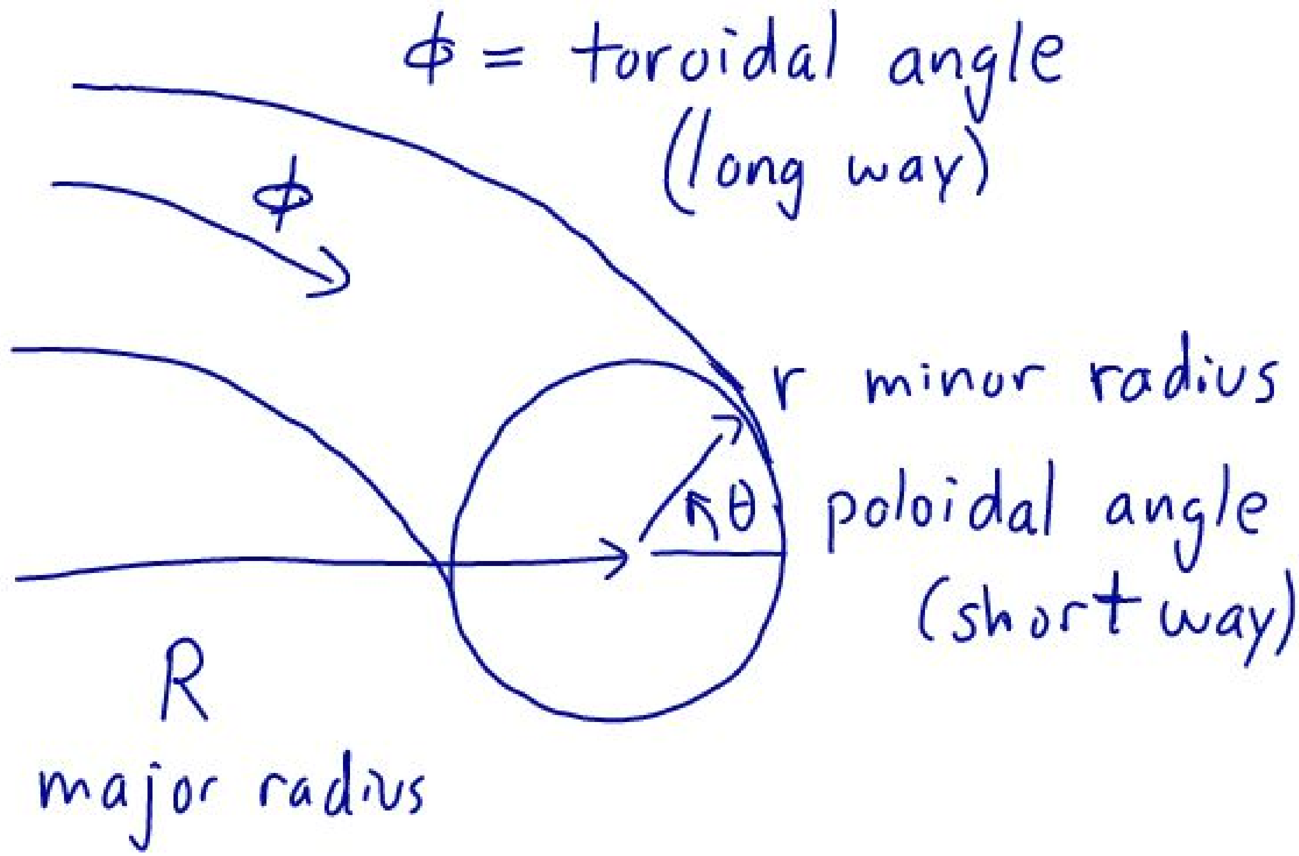


Einstein: Time is relative, Measure time in $$

$30-$90B development cost is tiny compared to >$100 Trillion energy needs of 21st century & potential costs of global warming. (Apollo program ~ $100B.) Still 40:1 payoff after discounting 50+ years.

based on slide from R.J. Goldston

Tokamak Geometry

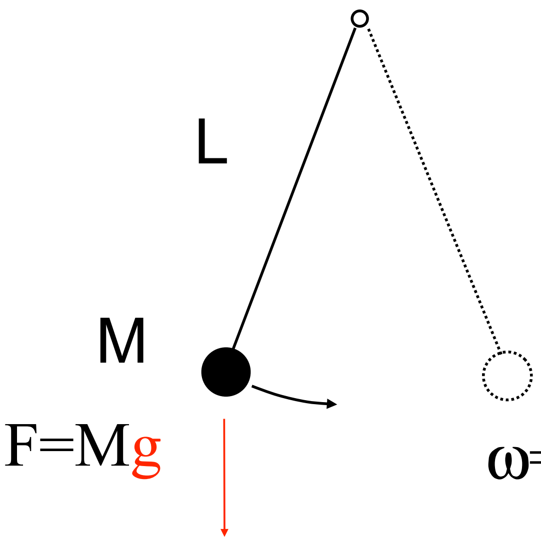


$$q = \frac{d\phi}{d\theta} = \frac{r}{R}\frac{B_\phi}{B_\theta}$$

q = "safety factor" = magnetic winding number. Follow field line q times toroidally, will get 1 poloidal twist.

Simple Physical Pictures Underlying Gyrokinetic & MHD Instabilities

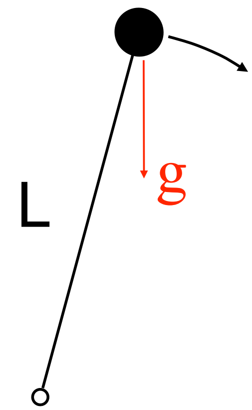
Stable Pendulum



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

Unstable Inverted Pendulum

(rigid rod)

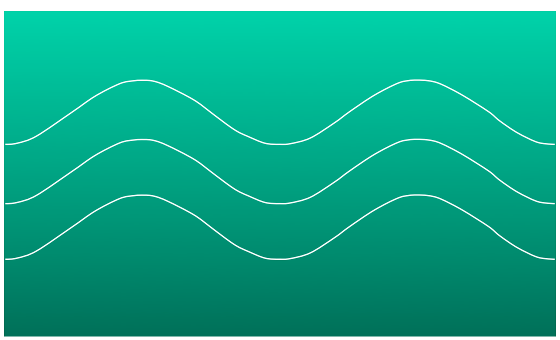


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

⎿ Instability

Density-stratified Fluid

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

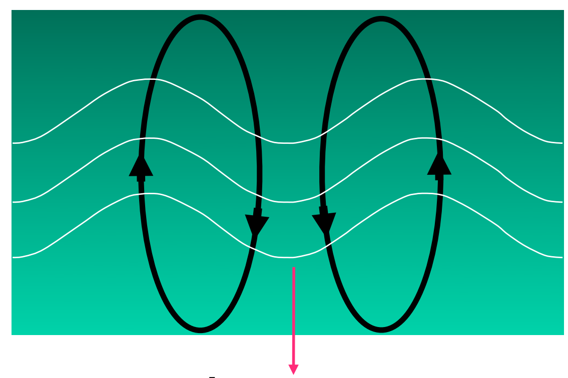


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

⇒Rayleigh-Taylor Instability

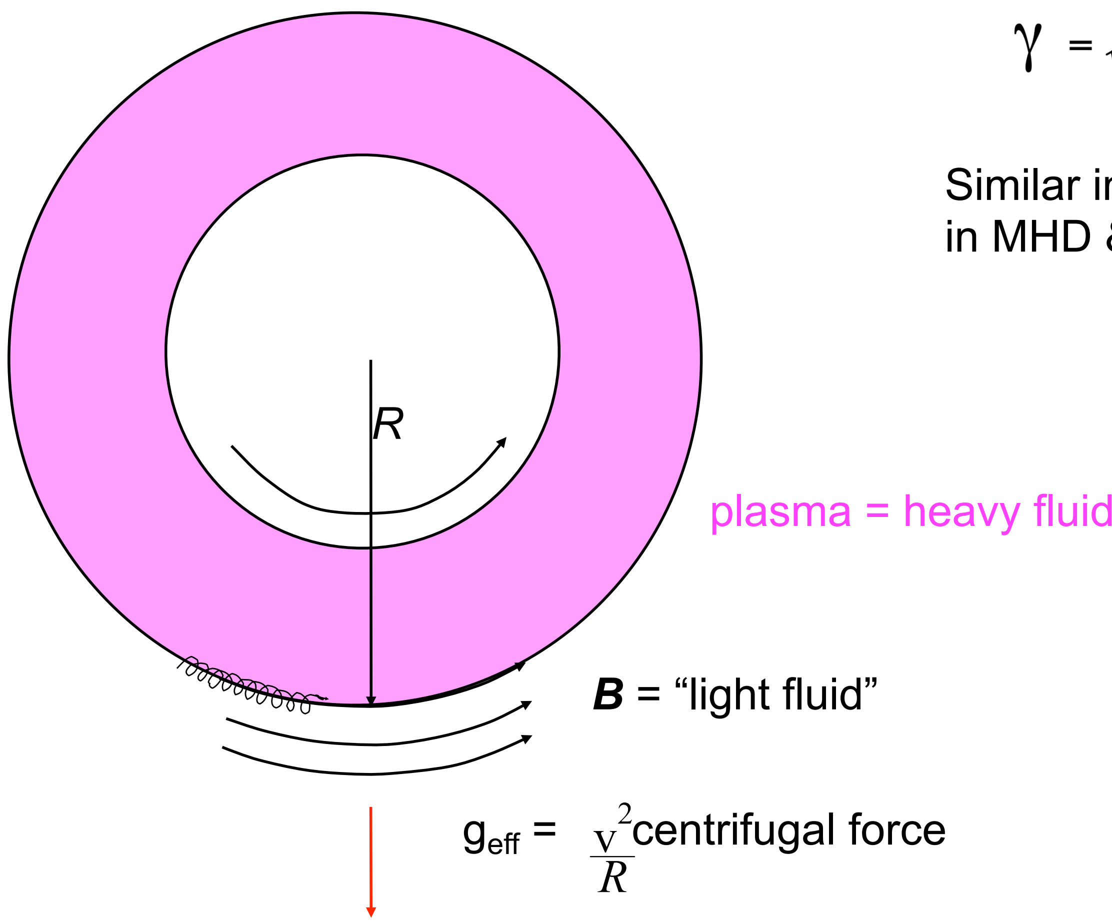
$\rho=\exp(y/L)$



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

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

Top view of toroidal plasma:



Growth rate:

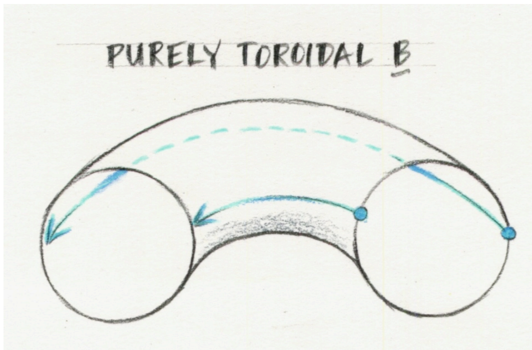
$$\gamma = \sqrt{\frac{g_{eff}}{L}} = \sqrt{\frac{V_t^2}{RL}} = \frac{V_t}{\sqrt{RL}}$$

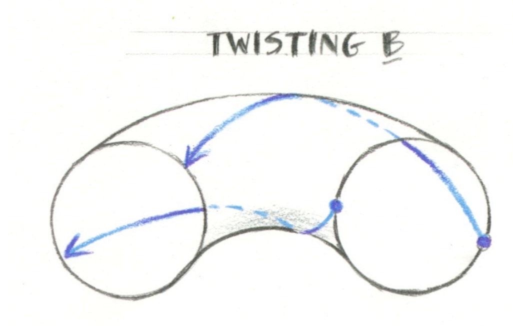
Similar instability mechanism
in MHD & drift/microinstabilities

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

The Secret for Stabilizing Bad-Curvature Instabilities

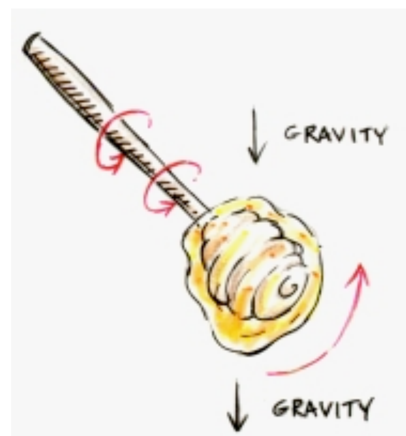
Twist in ***B*** carries plasma from bad curvature region to good curvature region:





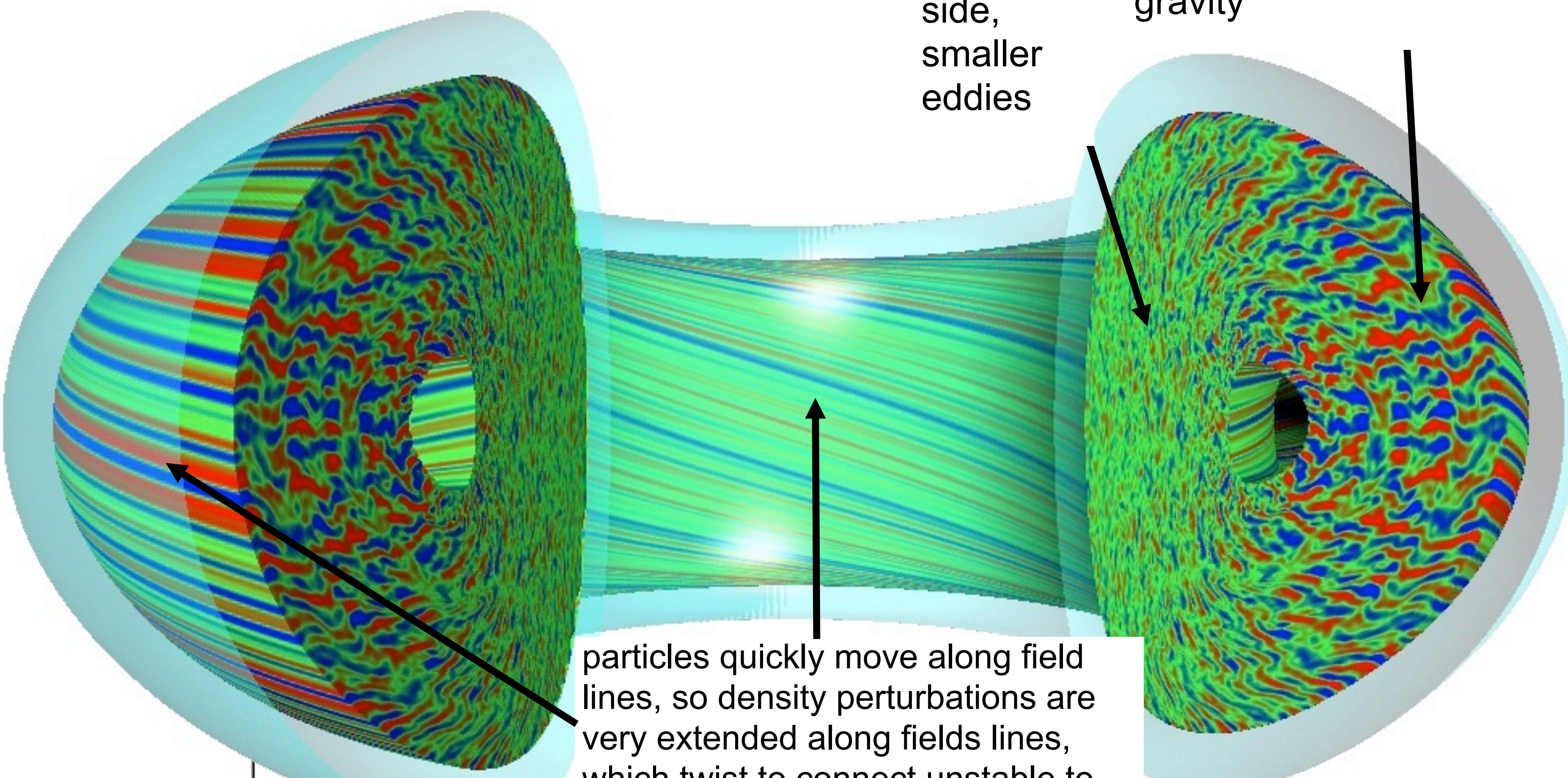
Unstable

Stable



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

These physical mechanisms can be seen in gyrokinetic simulations and movies



R. E. Waltz & J. Candy, General Atomics, http://fusion.gat.com/theory/Gyromovies

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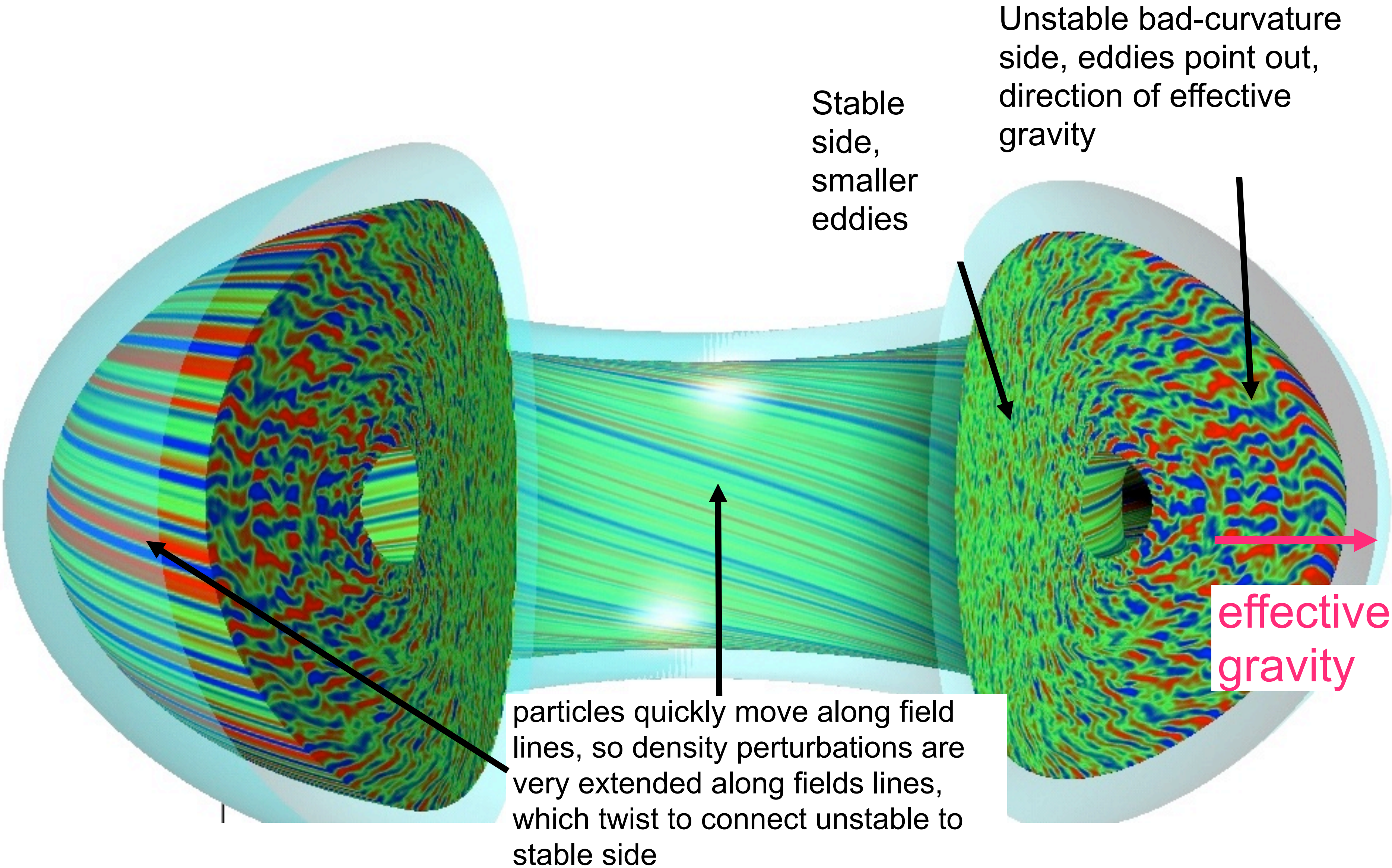


R. E. Waltz & J. Candy, General Atomics, http://fusion.gat.com/theory/Gyromovies

Bad-curvature mechanism for both MHD & Drift-type instabilites

- MHD: magnetic field lines & plasma move together, local bad curvature instability must be faster than Alfven wave propagation to good curvature side:

$$\gamma > \frac{v_A}{qR} \qquad \Rightarrow \qquad q^2 R \frac{\beta}{L_p} > \text{const.}$$

familiar MHD instability parameter

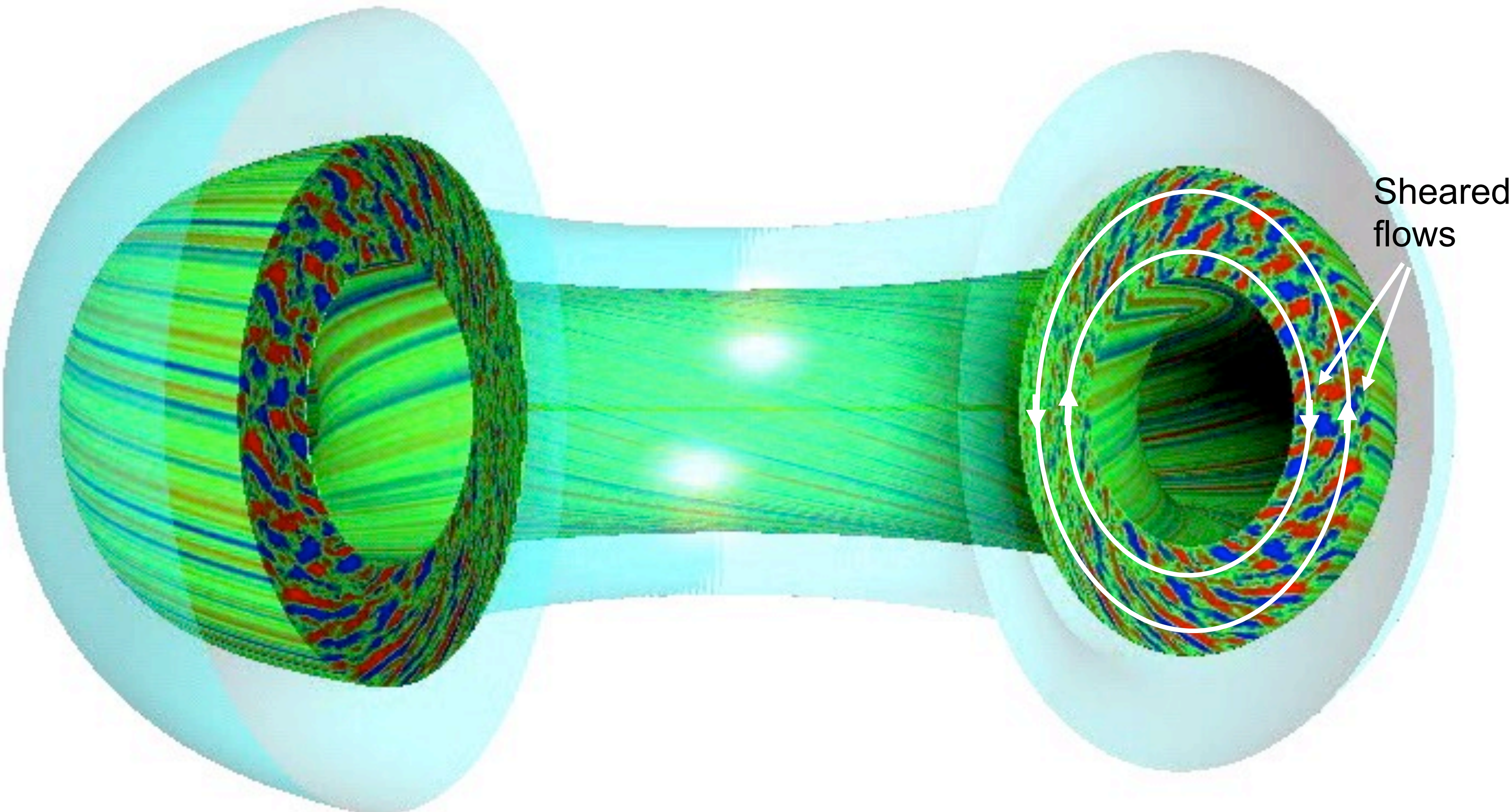
- Drift waves / gyrokinetics: $k_\perp \rho$ FLR corrections decouple magnetic field & plasma, --> electrostatic ExB flows, instability must be faster than sound wave propagation to good curvature side:

$$\gamma > \frac{v_t}{qR} \qquad \Rightarrow \qquad \frac{R}{L_p} > \frac{\text{const.}}{q^2}$$

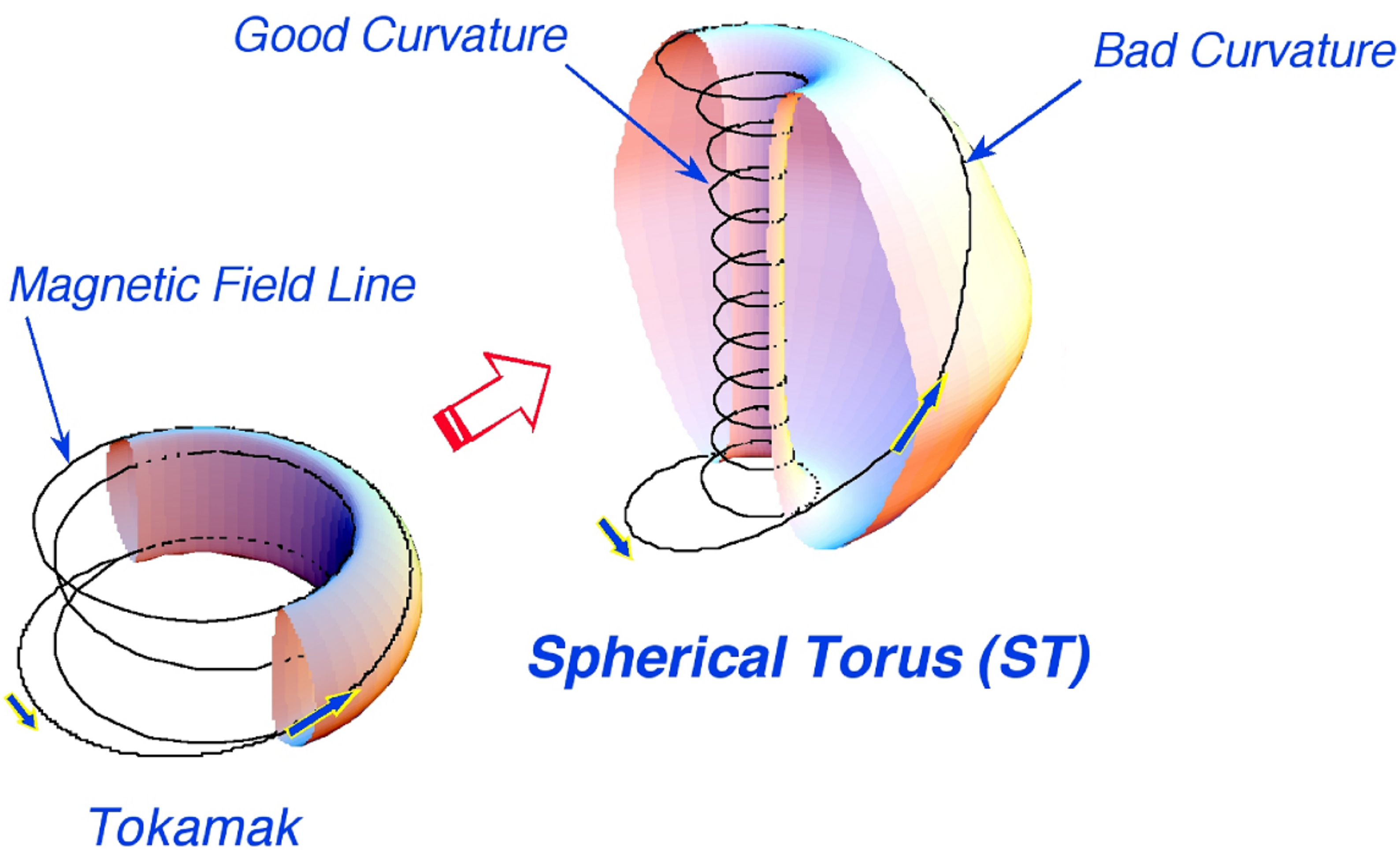
other mechanisms stabilize at high q

These physical pictures help explain how sheared flows & negative magnetic shear can be stabilizing.

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.

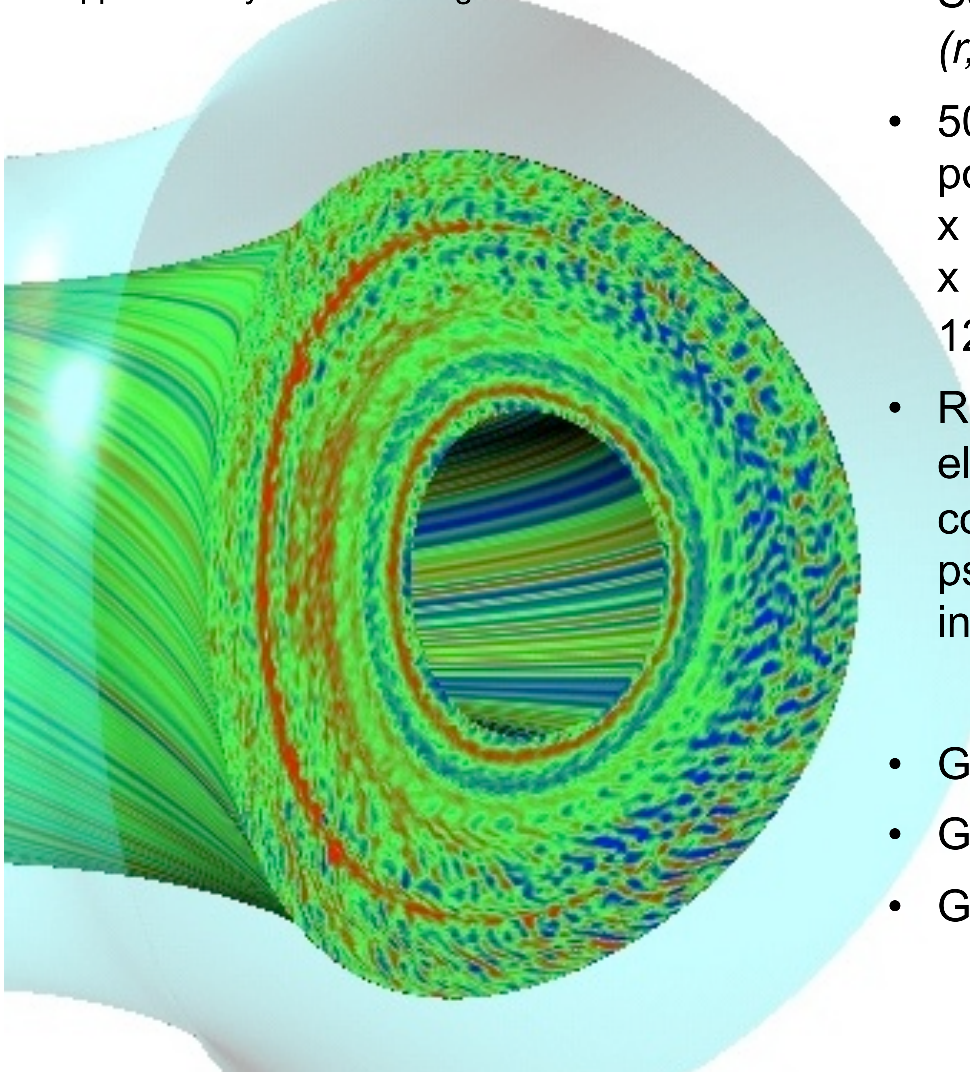


Spherical Torus has improved confinement and pressure limits (but less room in center for coils)



Fairly Comprehensive 5-D Gyrokinetic Turbulence Codes Have Been Developed

small scale, small amplitude density fluctuations (<1%) suppressed by reversed magnetic shear



- Solve for the particle distribution function $f(r,\theta,\alpha,E,\mu,t)$ (avg. over gyration: 6D → 5D)
- 500 radii x 32 complex toroidal modes (96 grid points in real space)
  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: mixed pseudo-spectral, high-order Gauss-Legendre integration in velocity space, ...

- GS2 (Dorland & Kotschenreuther)
- GYRO (Candy & Waltz)
- GENE (Jenko et al.)

Movie of density fluctuations from GYRO simulation http://fusion.gat.com/THEORY/images/0/0f/N32o6d0.8.mpg from http://fusion.gat.com/theory/Gyromovies

Waltz, Austin, Burrell, Candy, PoP 2006

The electrostatic gyrokinetic equation, in a "full-f" drift-kinetic-like form, for the gyro-averaged, guiding-center distribution function $\bar{f}(\vec{R}, v_{||}, \mu, t) = \bar{f}_0 + \delta \bar{f}$:

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

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

using gyroaveraged potential:

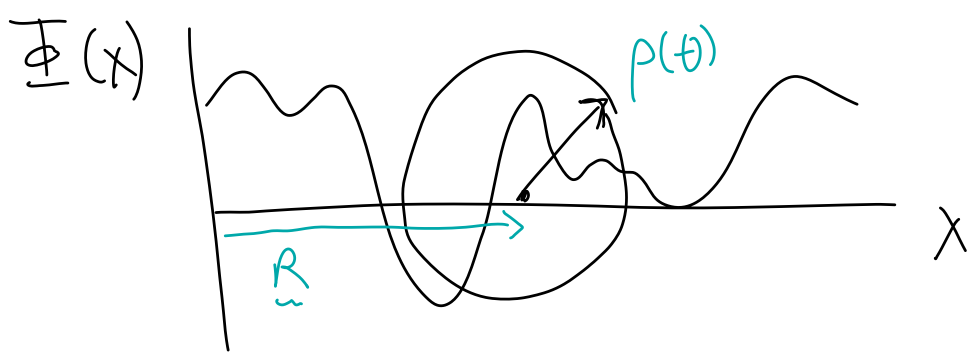
$$\langle\phi\rangle(\vec{R}) = \frac{1}{2\pi}\int d\theta\, \phi(\vec{R} + \vec{\rho}(\theta))$$

$$= \frac{1}{2\pi}\int d\theta \sum_{\vec{k}} \phi_{\vec{k}}\, e^{i\vec{k}\cdot(\vec{R}+\vec{\rho}(\theta))}$$

$$= \sum_{\vec{k}} J_0(k_\perp \rho)\phi_{\vec{k}}\, e^{i\vec{k}\cdot\vec{R}} = J_0\phi$$

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

$$v_d = \frac{v_{||}^2}{\Omega}\hat{b} \times (\hat{b}\cdot\nabla\hat{b}) + \frac{\mu}{\Omega}\hat{b} \times \nabla B$$



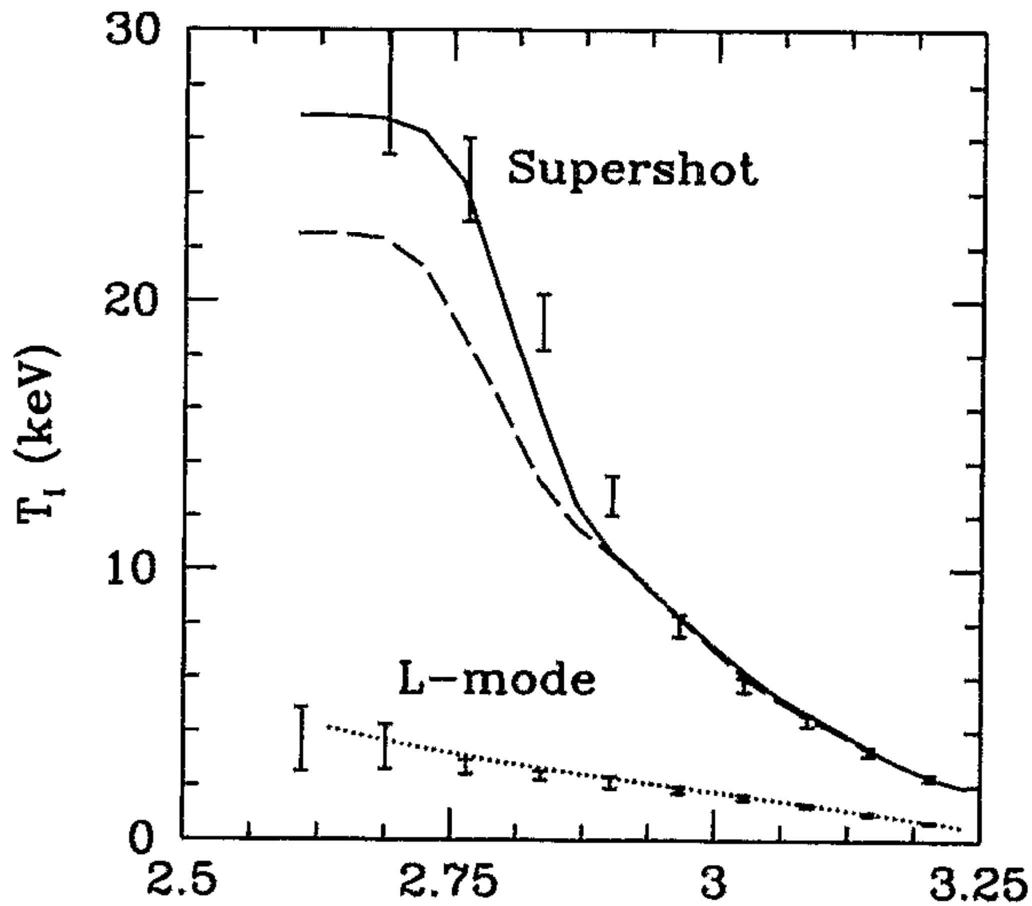
Gyrofluid Turbulence Simulations Explained Why TFTR Supershots (and Lithium Walls) are Super

* reduced recycling at wall, reduced influx of cold neutrals & raised edge T_i

* Profiles stiff for critical ITG:

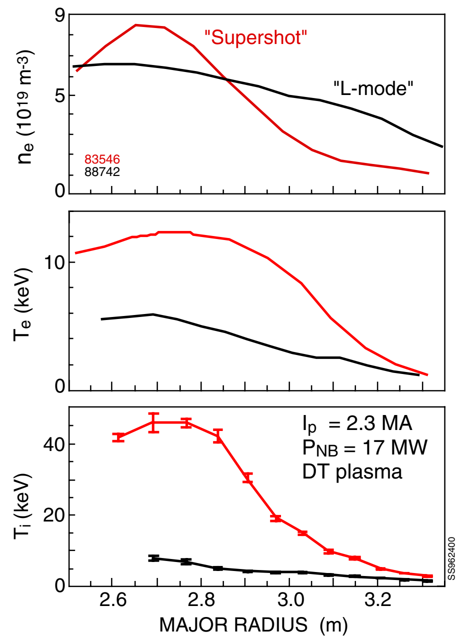
  Core $T_i \propto$ Edge T_i

* high T_i/T_e, moderate density peaking and beam-driven ExB shear raised critical temperature gradient



Kotschenreuther, Dorland, Beer, Hammett (1995)

Lithium Wall Conditioning Techniques Delivered High Performance in TFTR



$n_i(0)\cdot T_i(0)\cdot\tau_E$ increased by a factor of 20:

L-mode: 0.48 $\times 10^{20}$ $m^{-3}\cdot$keV$\cdot$sec

"Supershot": 9.9 $\times 10^{20}$ $m^{-3}\cdot$keV$\cdot$sec
(with lithium wall conditioning)

Theoretical models of ion heat transport successfully described strong dependence on edge conditions.

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

From pppl50th_goldston.pdf

In the Tokamak Fusion Test Reactor, the first wall was coated with a thin layer of lithium, which had a dramatic impact on plasma performance. The thin layer of lithium strongly absorbs hydrogen, and so reduces gas reflux and edge cooling. The dramatic increase in ion temperature in the core could be understood in terms of recent theoretical models in which the ion temperature and density gradients determine the onset of the instability - resulting in the profiles being in marginal stability. By reducing the edge density, the edge temperature increases enabling a reduction in the core transport from these models.