Lyman Spitzer's Legacy of Innovation in the Quest for Fusion Energy

Greg Hammett, May 4, 2024
w3.pppl.gov/~hammett/

Princeton Plasma Physics Laboratory (PPPL)
& Princeton University Ph.D. Program in Plasma Physics

Science on Saturday Lecture / Fusion Energy Week

(fixed typos, 2024-07-11)

Lyman Spitzer's Legacy of Innovation in the Quest for Fusion Energy

- An informal history of early PPPL fusion research
- Some history of Spitzer's big ideas / innovations:
  - 1946: Telescopes in space (Hubble Space Telescope)
  - 1951: Figure-8 stellarator trick to make a fusion power source

- A fluid picture of the trick for how a figure-8 stellarator works (and basis for later stellarators).

- Continuing innovations at PPPL and elsewhere to improve fusion energy concepts
  - including ideas for further improving the stellarator concept, which is undergoing a renaissance.

I never officially met Prof. Spitzer, though I saw him at a few seminars, and was friends with his last graduate student. (I was a grad student here 1980-1986.) Heard many stories from Prof. Tom Stix, Prof. Russell Kulsrud, & others, learned from the insights in his book and his ideas in other books.

Lyman Spitzer, Jr.
1914-1997

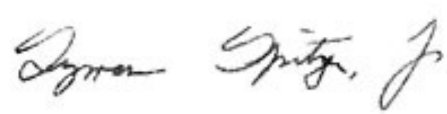
Born in Toledo, Ohio.

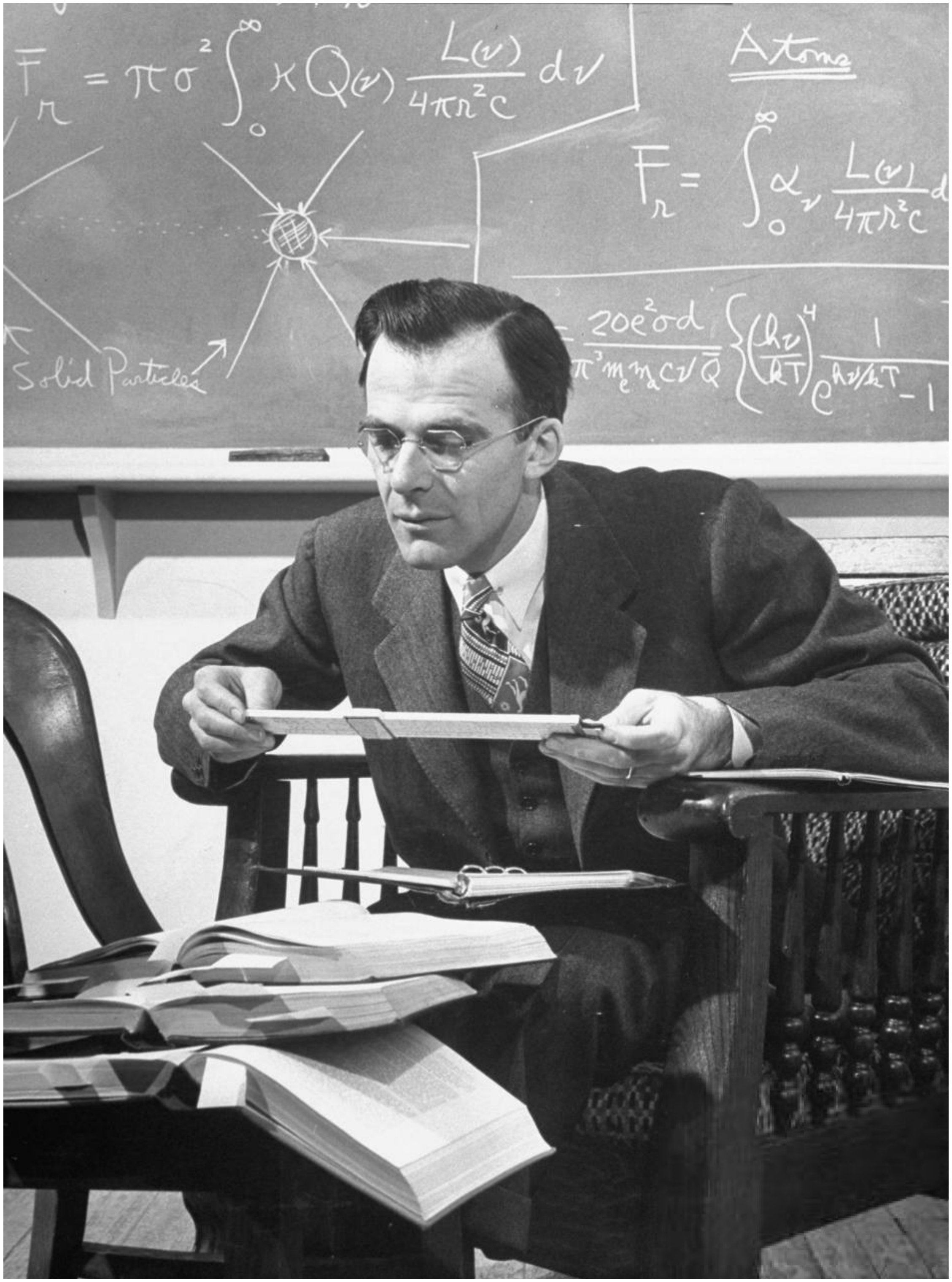
Yale B.S. (1935), Cambridge (1936)
Princeton Ph.D. Physics (1938)

Yale professor
World War 2: worked on sonar

Chair of Princeton Department of
Astrophysical Sciences, 1947-1979

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





LIFE Magazine, Apr 28, 1948

LIFE Photo Collection, March 1948
http://sliderulemuseum.com/SR_Ephemera.htm
http://www.google.com/culturalinstitute/asset-viewer/uwHIsK8XRqgCXw?hl=en
https://books.google.com/books?id=d0EEAAAAMBAJ&pg=PA98&dq=spitzer&hl=en&sa=X&ved=2ahUKEwjZkJzN5fKFAxVxD1kFHfrCAMsQ6AF6BAgBEAI#v=onepage&q=spitzer&f=false

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

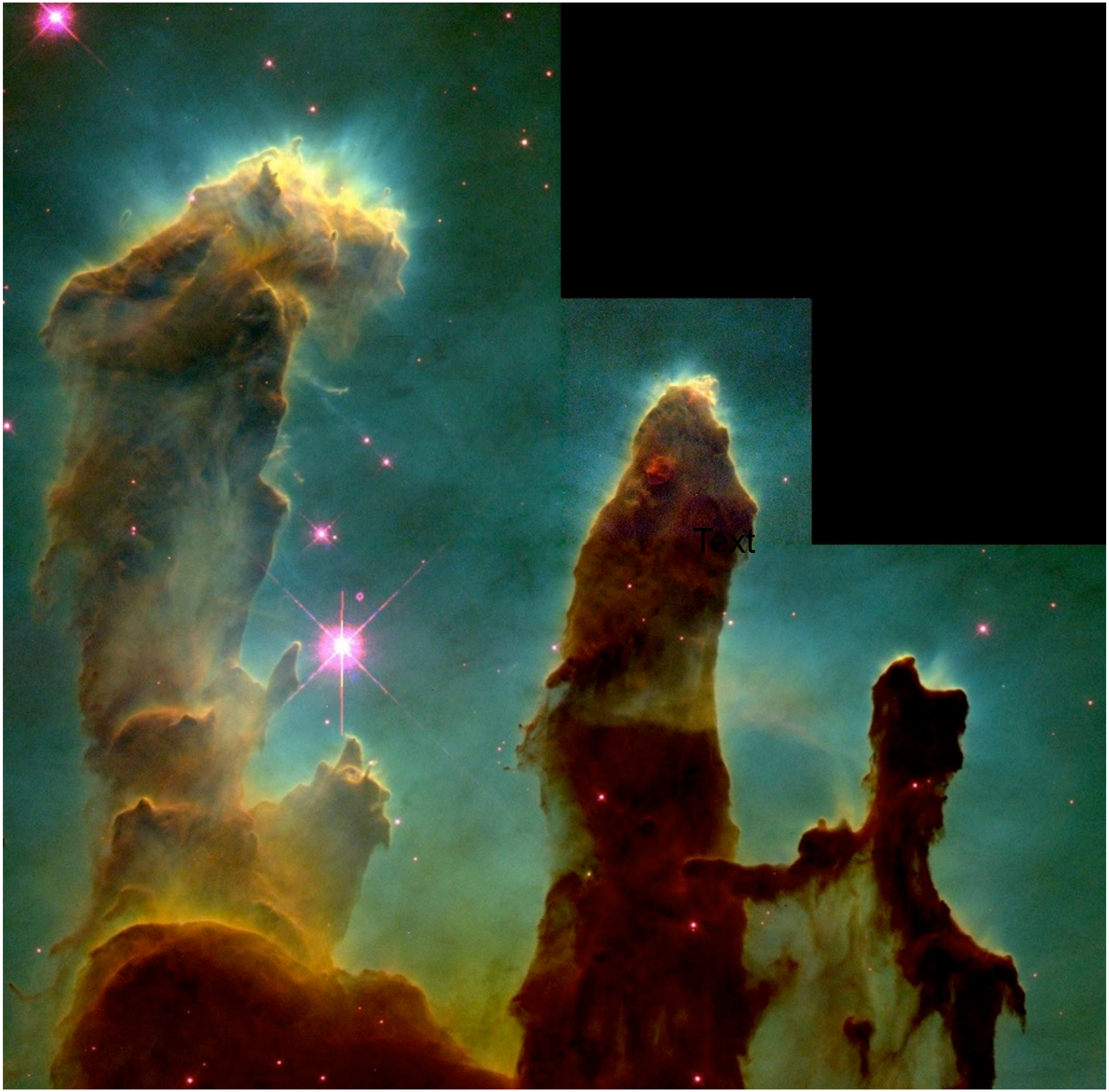
1946: Spitzer Proposes Telescopes in Space

- In 1946, Spitzer wrote a report for the RAND Corporation on "Astronomical Advantages of an Extra-Terrestrial Observatory"
- Spitzer credited with being "a visionary behind the Hubble Space Telescope" [1], documenting the advantages it would have, and seeing that it would be feasible. "While the fundamental concept of sending a large telescope into space wasn't new, the reality of doing so was." [1]
- "The most important champion of the project was Lyman Spitzer" [2].
- Hubble Space Telescope launched 1990 (optics fixed in 1993)
  (predecessor to the James Webb Telescope)
- NASA infrared space observatory: the Spitzer Space Telescope (2003-2020)

Others had independently proposed a telescope in space, such "as 1923 by the German rocket pioneer Hermann Oberth" [2]

[1] https://science.nasa.gov/people/lyman-spitzer-making-space-for-hubble

[2] https://www.amnh.org/learn-teach/curriculum-collections/cosmic-horizons-book/lyman-spitzer-hubble-telescope

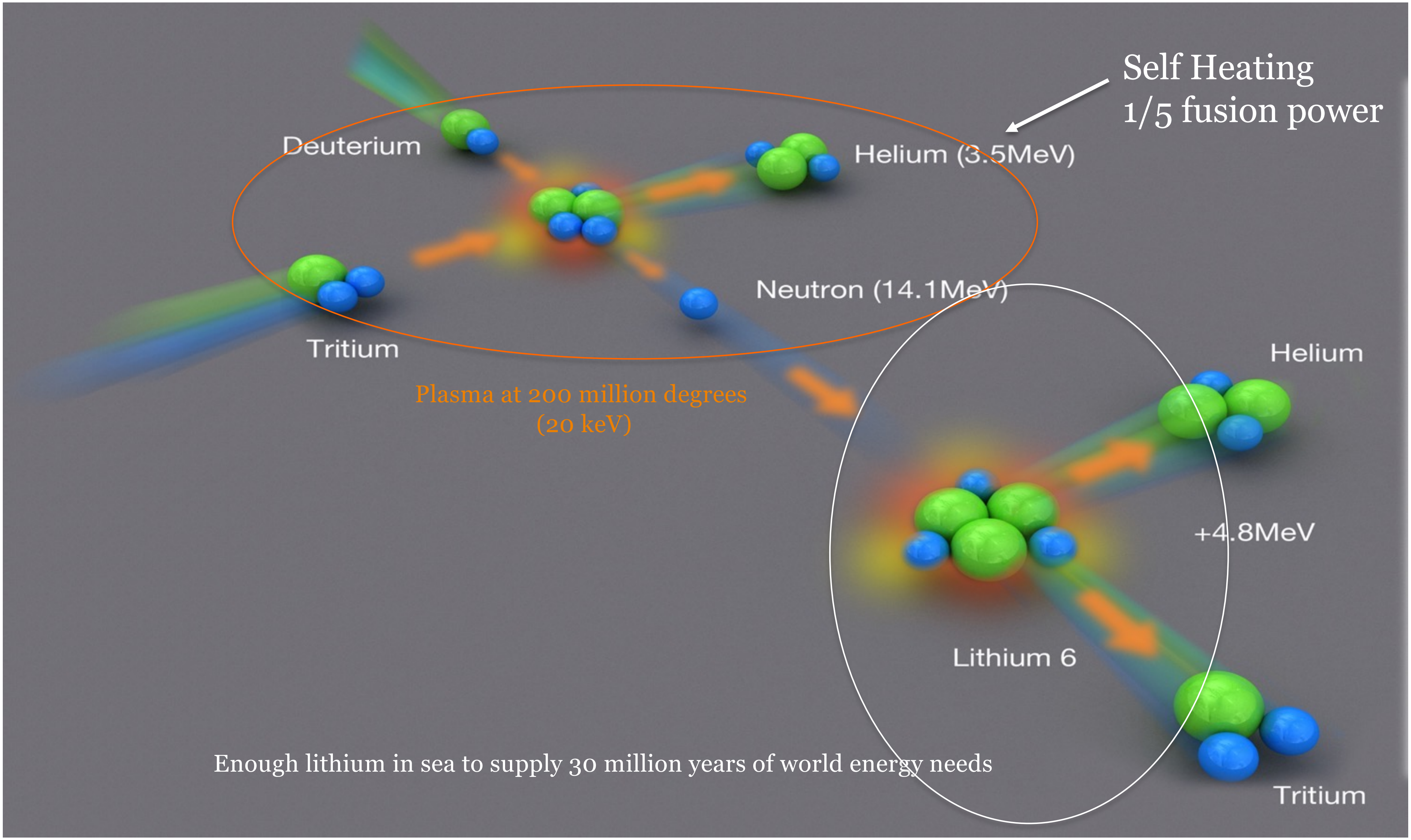


Famous image from the Hubble Space Telescope.

The Eagle Nebula: “Pillars of Creation” gas pillars in a star-forming region.

http://hubblesite.org/gallery/album/pr1995044a/

Deuterium and tritium: isotopes of hydrogen that fuse much more easily



Huge energy gain: 17.6 MeV out / 40 keV in = 440
But need to heat plasma to extreme temperatures

Spitzer's First Exploration of Fusion

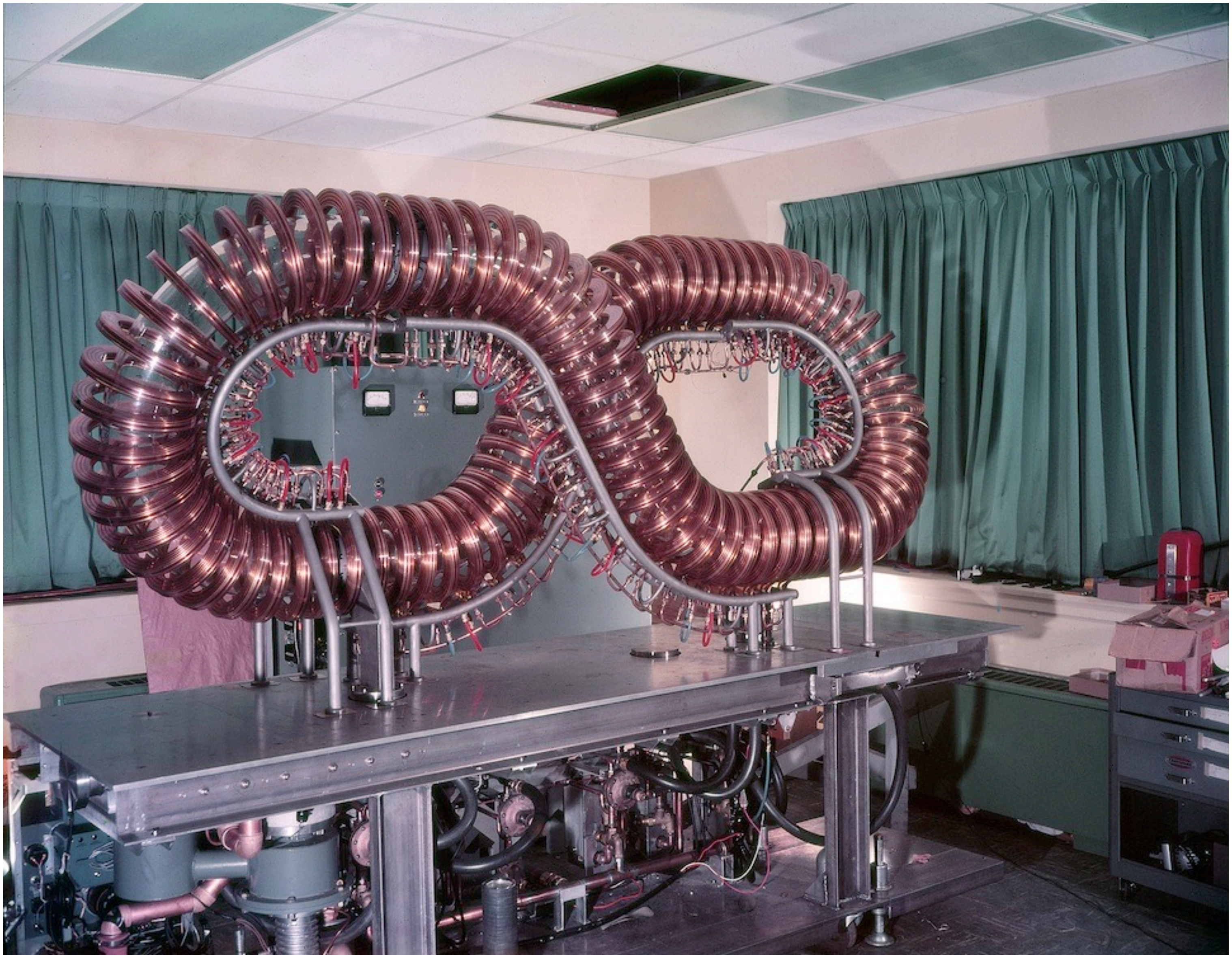
- 25 June, 1950, Korean war started.
- Lyman Spitzer and John Wheeler think about starting a theoretical program at Princeton studying thermonuclear explosions. (Spitzer worked on sonar in WWII)
- March 24, 1951, President Peron of Argentina claimed his scientist, Ronald Richter, had produced controlled 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 interstellar gas/plasma for several years & had recently heard a series of lectures by Hans Alfven on plasmas* (Alfven later got Nobel prize)
- Spitzer knew a simple toroidal magnetic field couldn't confine a plasma. The story (partially apocryphal?) is that on the chair lift rides in March 1951, he invented the tokamak (later invented in Russia by Igor Tamm and Andrei Sakharov), but dismissed it because it wasn't steady state. Somehow came up with the idea of twisting a torus into a figure-8.

- May 11, 1951, meeting at AEC to describe figure-8 and other approaches to fusion.
- May 12, Spitzer submits proposal to AEC to build a figure-8 stellarator.
- July 1, gets $50k (= $600k in 2024) from AEC for 1 year (Bromberg, p. 21, http://en.wikipedia.org/wiki/Perhapsatron)

CPI = 26.0 in 1951, 230. in 2013.

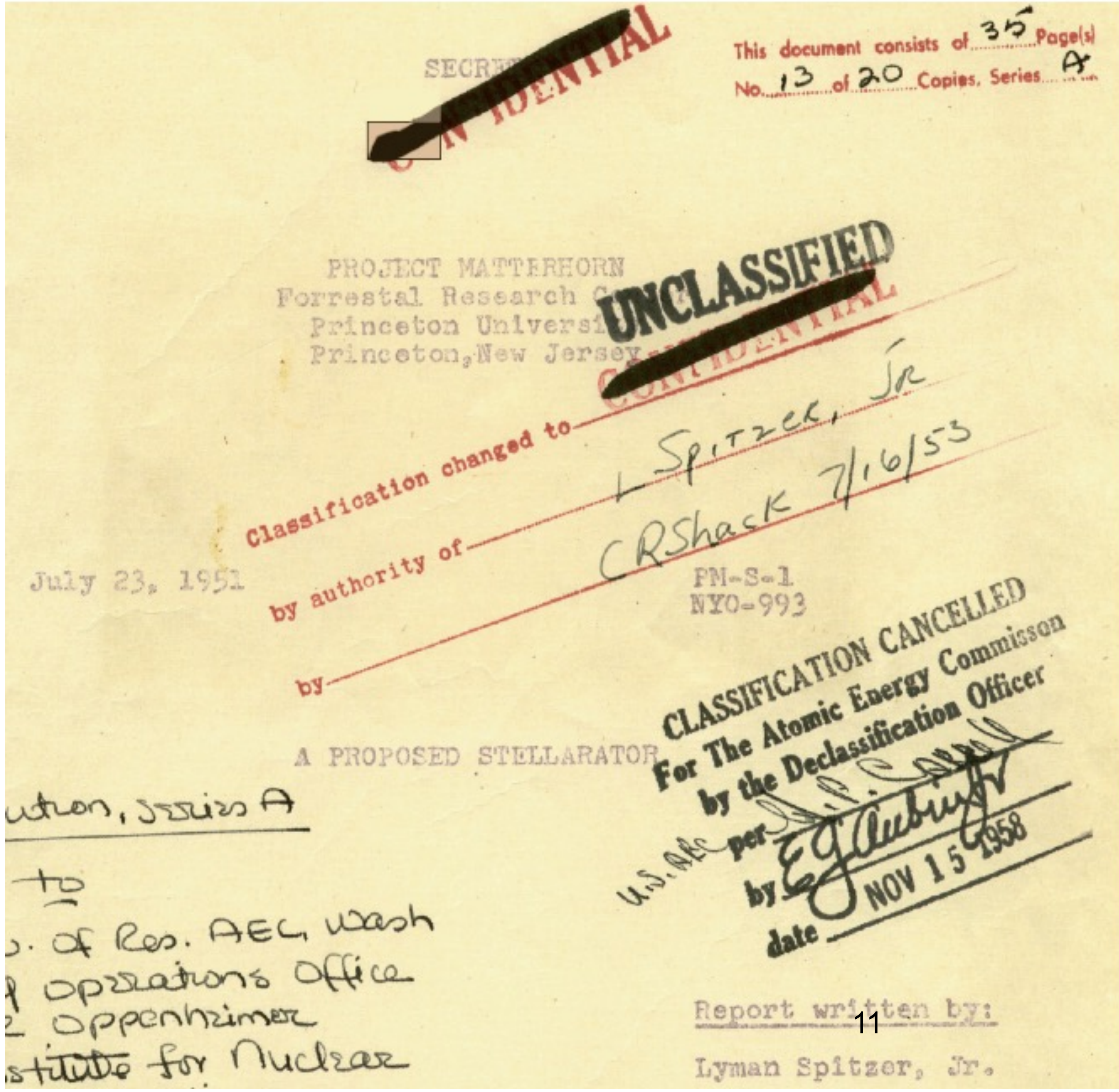
* John Johnson, personal communication.

2cd UN Atoms For Peace Conference, Geneva 1958.



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

Spitzer's Original May 12, 1951 Proposal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SECR[redacted]IDENTIAL

PROJECT MATTERHORN
Forrestal Research C
Princeton Universi
Princeton, New Jersey

UNCLASSIFIED
[redacted]

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

July 23, 1951

PM-S-1
NYO-993

CLASSIFICATION CANCELLED
For The Atomic Energy Commission
by the Declassification Officer
U.S. AEC per
by
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 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)

July 1, 1951 Project Matterhorn Begins

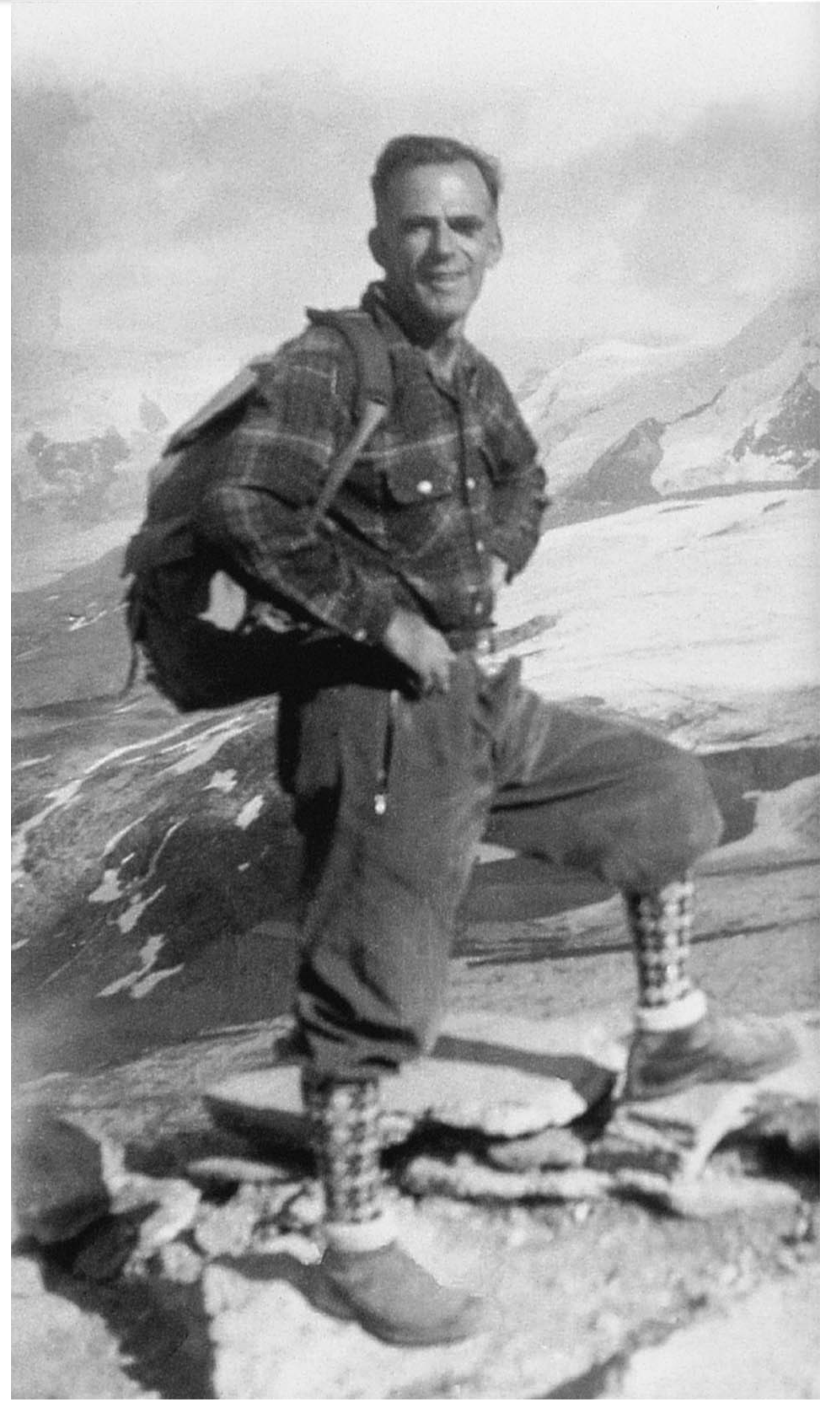
- Two sections:
  - S: headed by Spitzer, studying the stellarator concept
  - B: headed by John Wheeler

- "Project Matterhorn" name recommended by Spitzer, because "The work at hand seemed difficult, like the ascent of a mountain"*.
- "Stellarator" named by Wheeler, "a star generator"

A serious mountain climber:

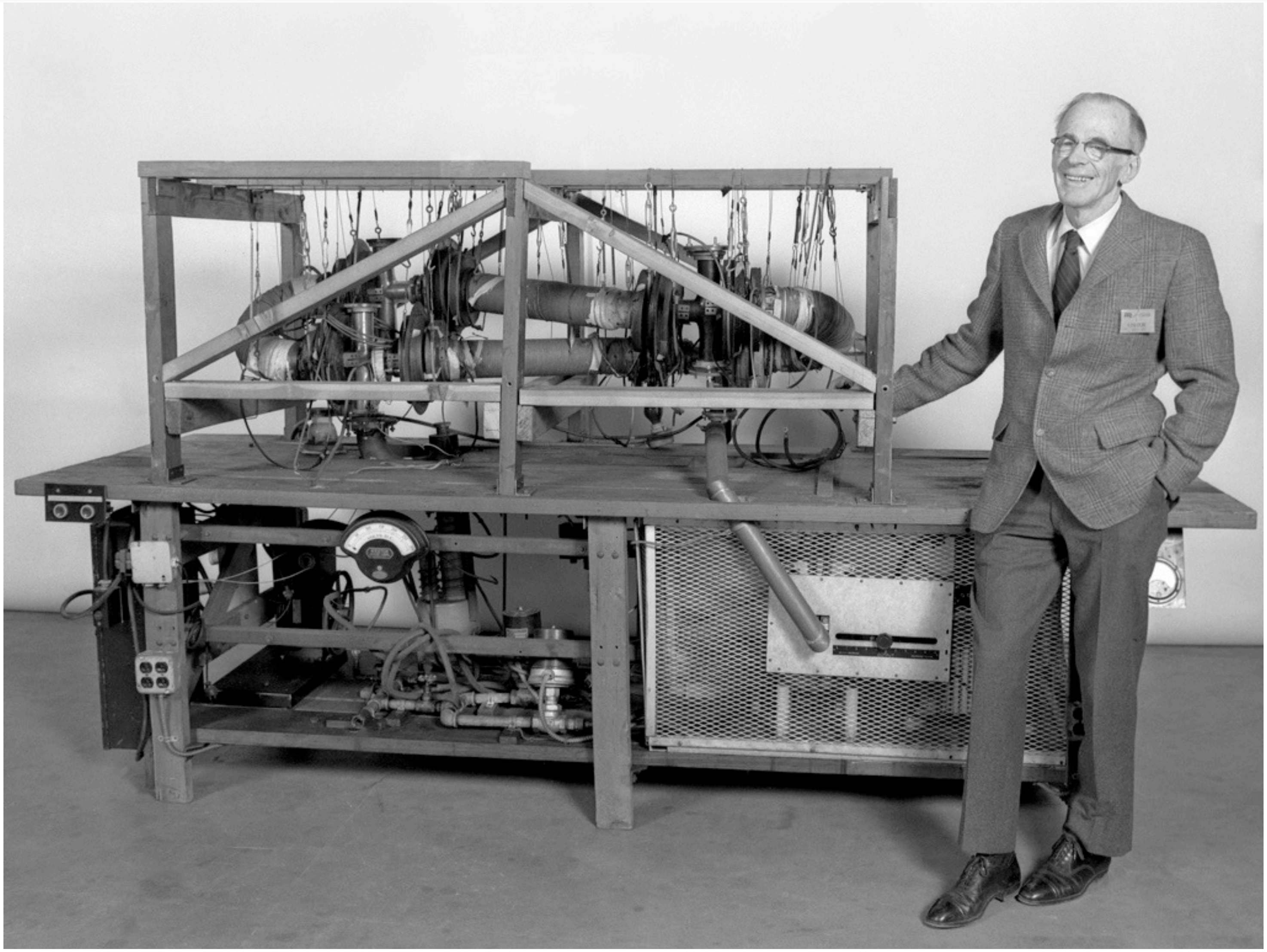
The American Alpine Club annually awards the Lyman Spitzer Cutting Edge Climbing Award.

Lyman Spitzer, Jr. once climbed the outside of the Graduate College tower...



*Tanner, Project Matterhorn

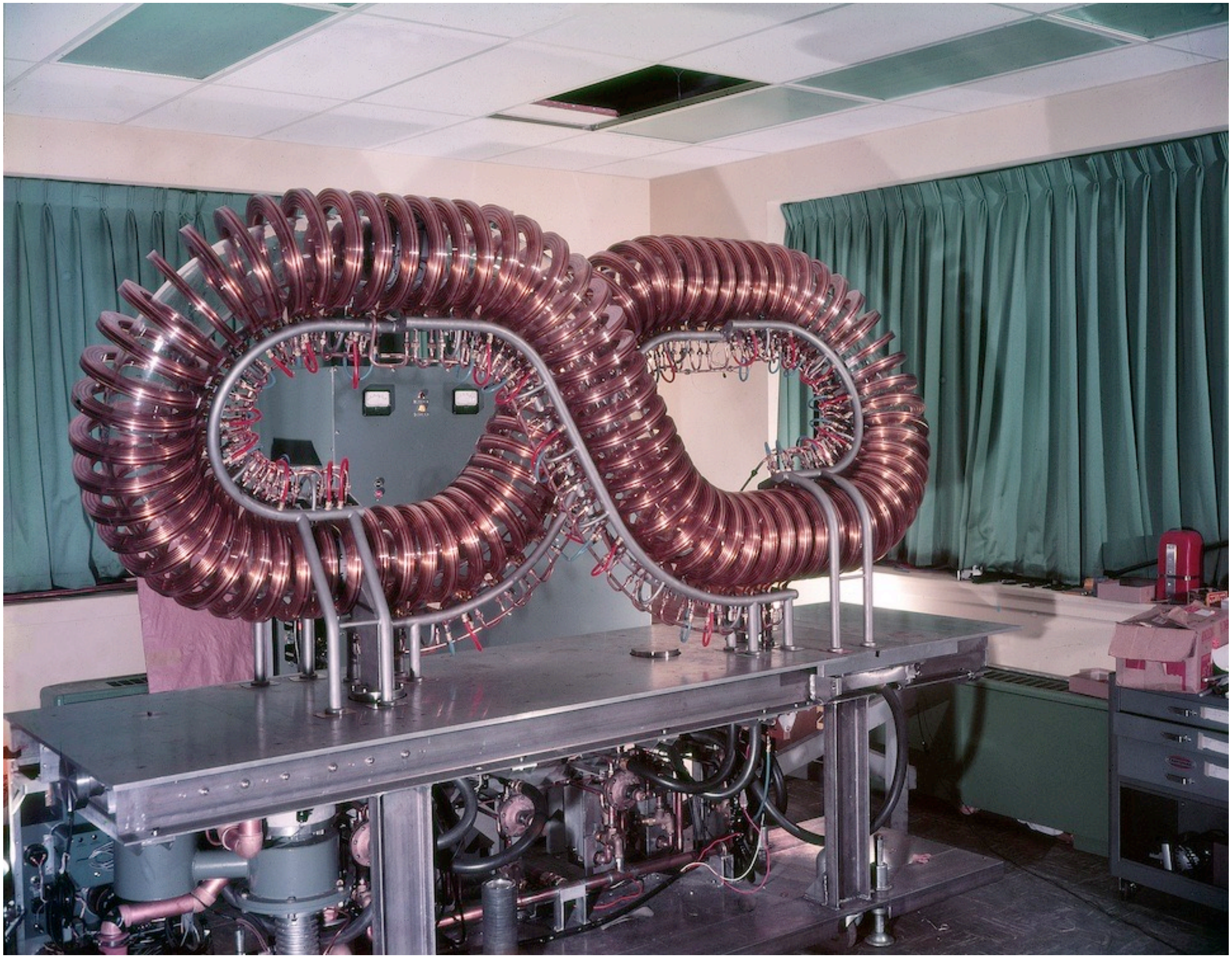
Spitzer’s Model-A Stellarator



- 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

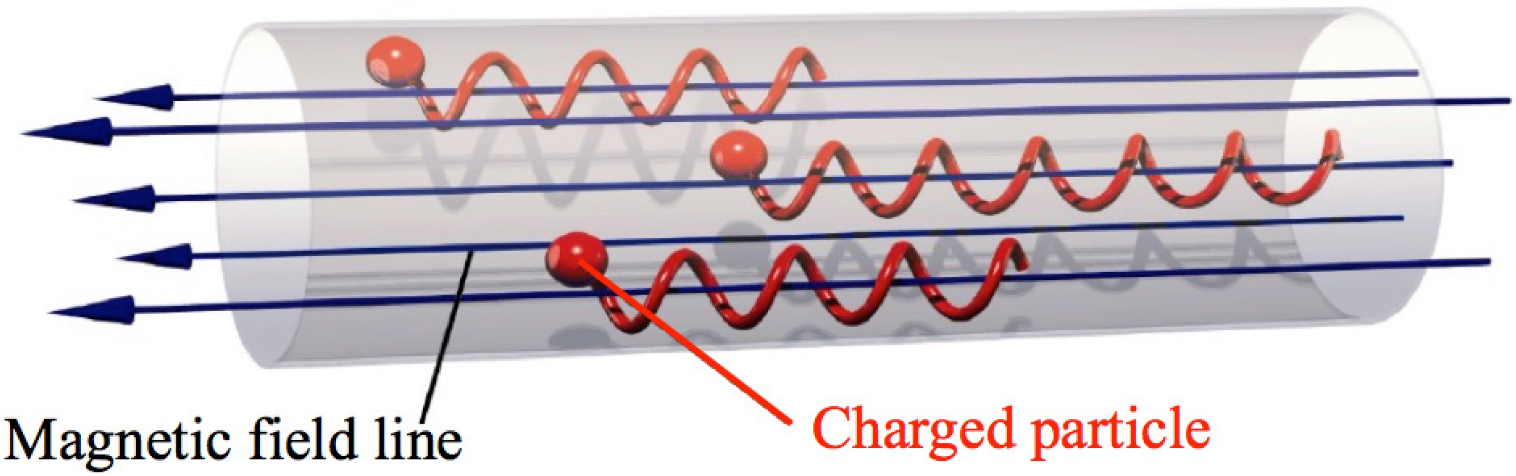
- This picture in 1983, just before donated to the Smithsonian.

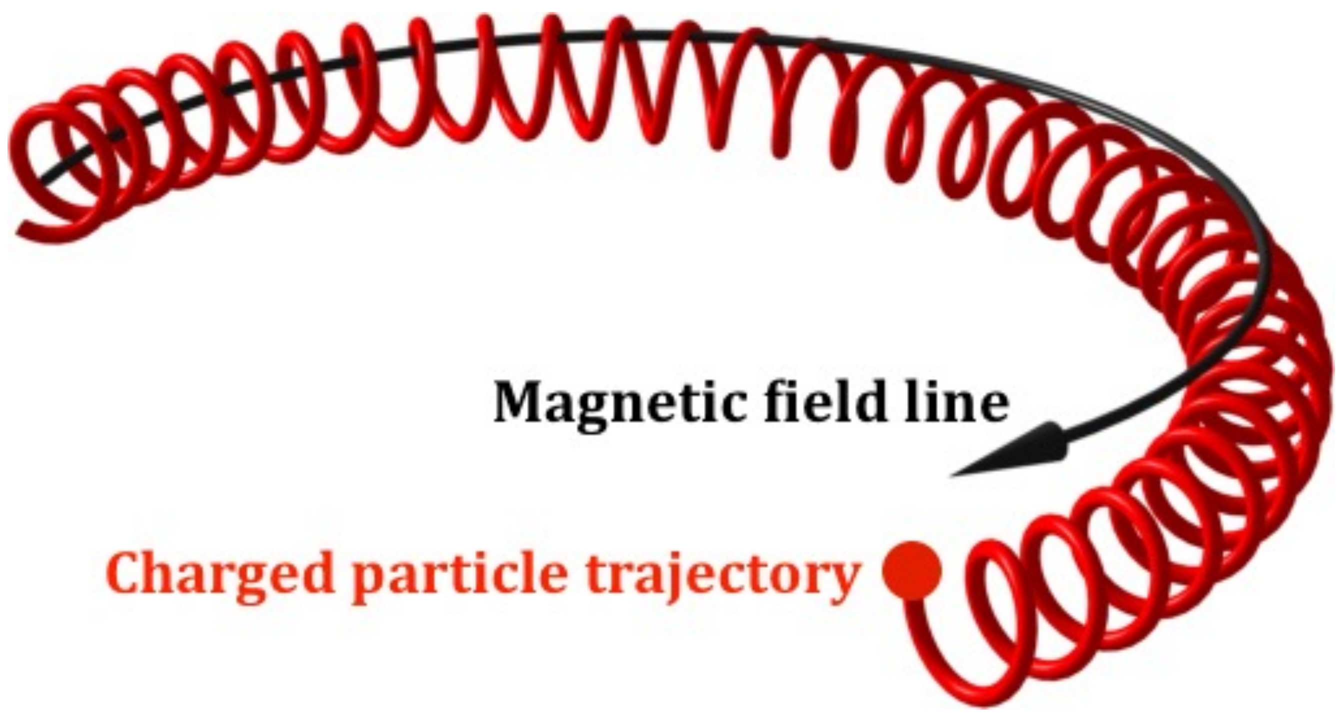
2cd UN Atoms For Peace Conference, Geneva 1958.



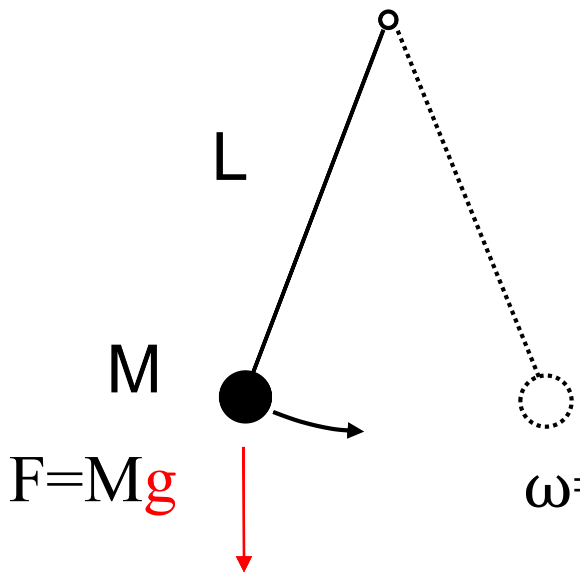
SIM-8, one of the simulator stellarators (w/ e-beam) used in demonstrations at the 2cd Atoms-For-Peace Conference, Geneva (1958)

Magnetic confinement of particles



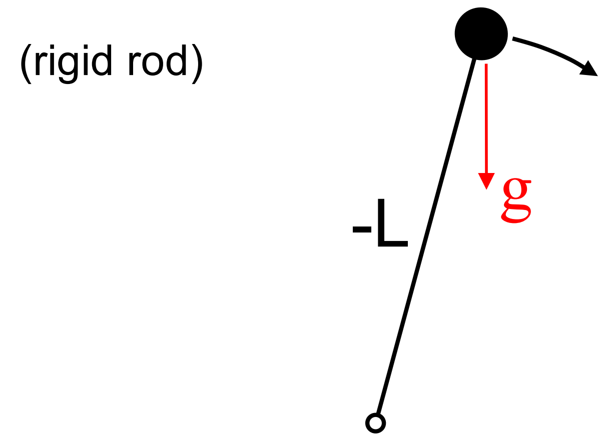


Stable Pendulum



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

Unstable Inverted Pendulum



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

↑ instability

$$X(t) = X_0 \cos(\omega t) + \cdots$$

$$X(t) = X_0\, e^{\gamma t} + \cdots$$

Famous Euler's Formula:

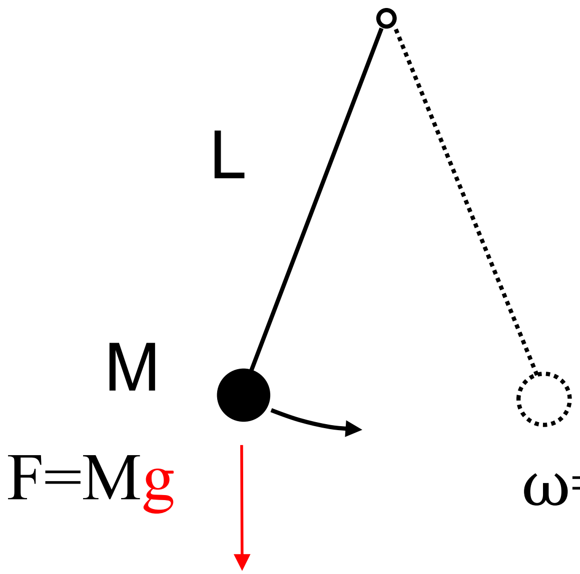
$$e^{-i\omega t} = \cos(\omega t) - i\,\sin(\omega t)$$

Replace ω with $i\,\gamma$:

$$e^{-i\omega t} = e^{-i(i\,\gamma)t} = e^{\gamma t}$$

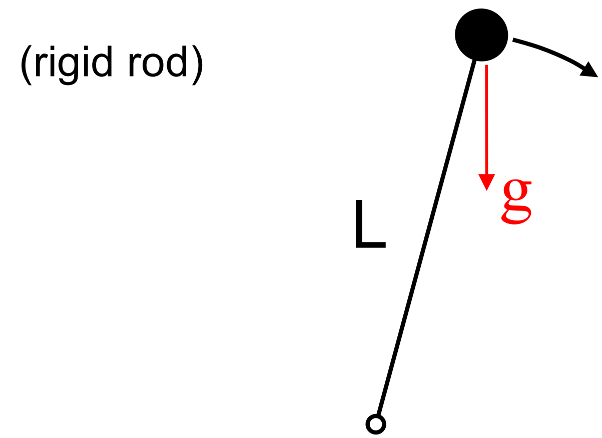
(broom demonstration)

Stable Pendulum



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

Unstable Inverted Pendulum

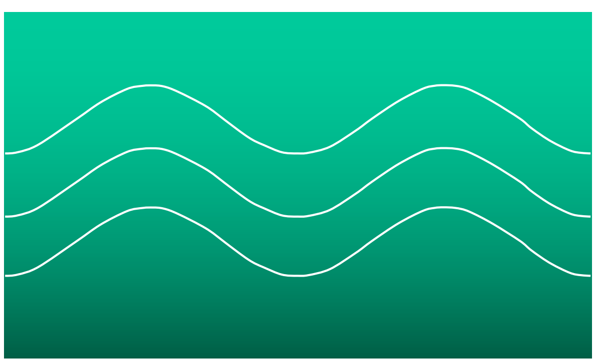


$\omega= (-g/|L|)^{1/2} = i(g/|L|)^{1/2} = i\gamma$

└ Instability

Density-stratified Fluid

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

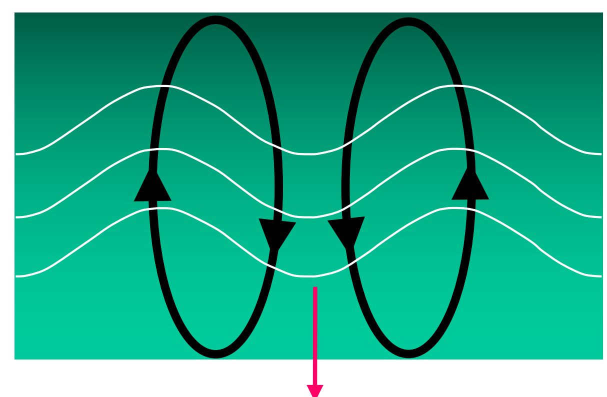


stable $\omega=(g/L)^{1/2}$

Inverted-density fluid

⇒Rayleigh-Taylor Instability

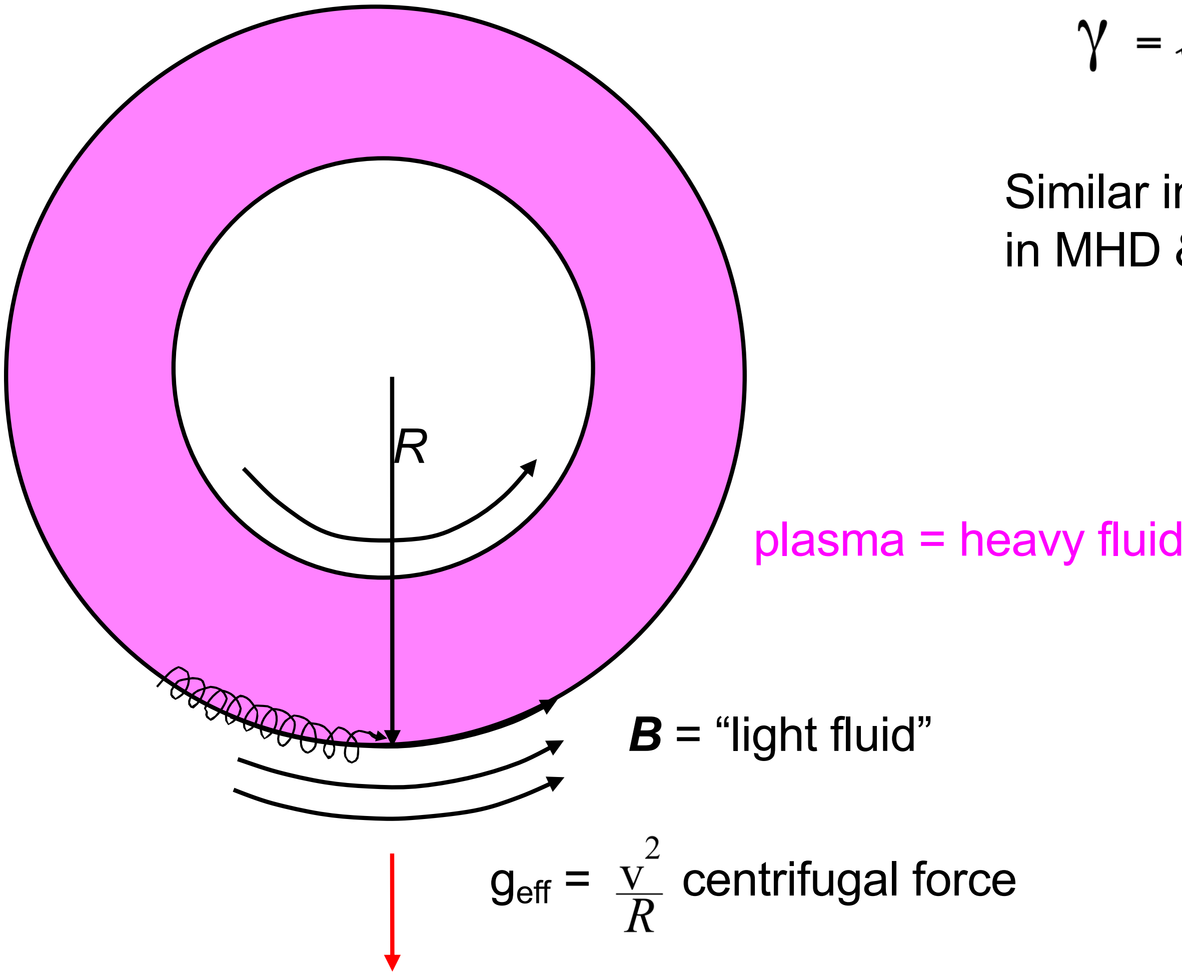
$\rho=\exp(y/L)$



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

Why a simple magnetic torus is unstable:
≈ Inverted Pendulum / Rayleigh-Taylor Instability

Top view of toroidal plasma:



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

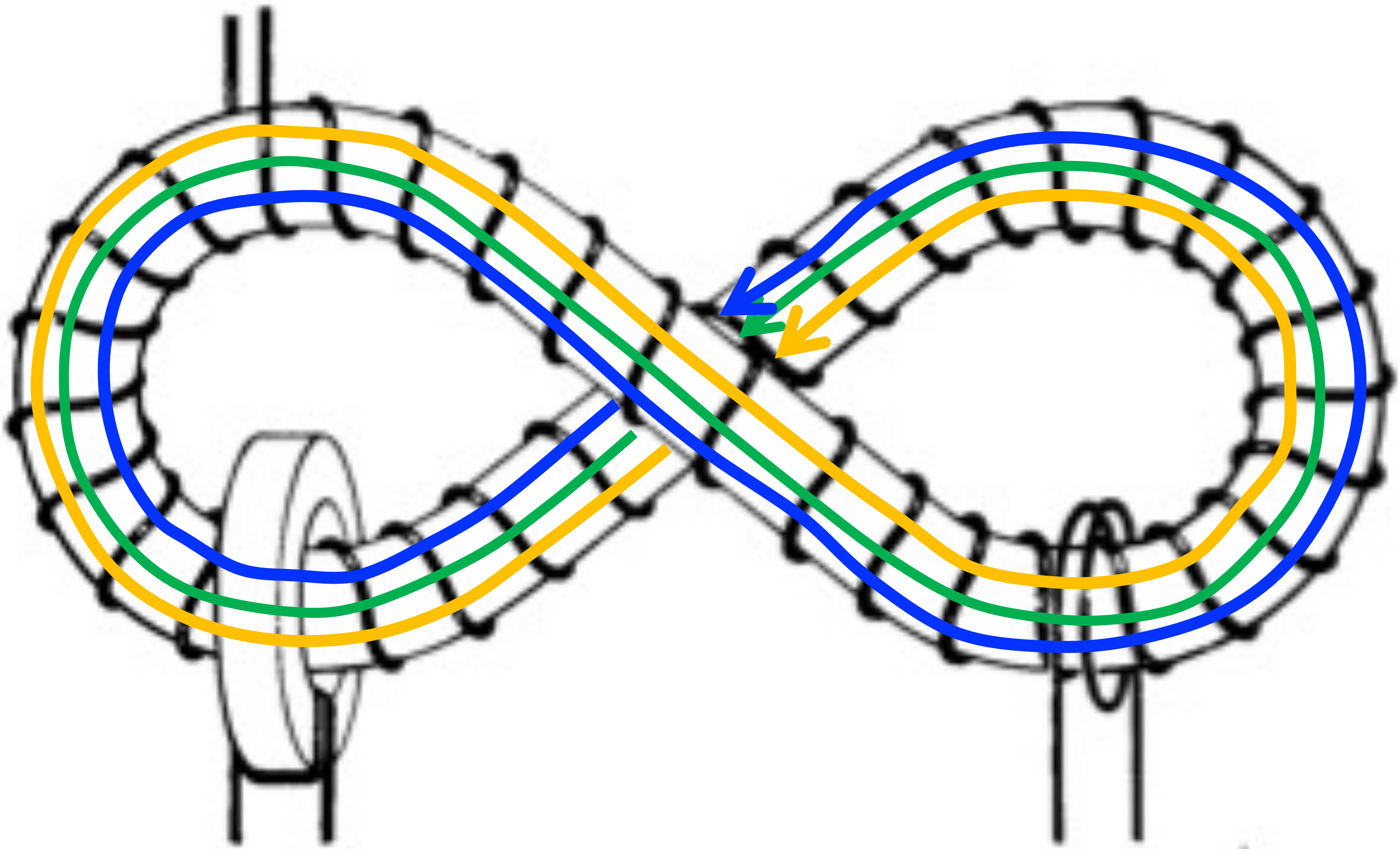
Growth rate:

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

Similar instability mechanism
in MHD & drift/microinstabilities

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

Spitzer's stellarator trick: twist torus into figure-8



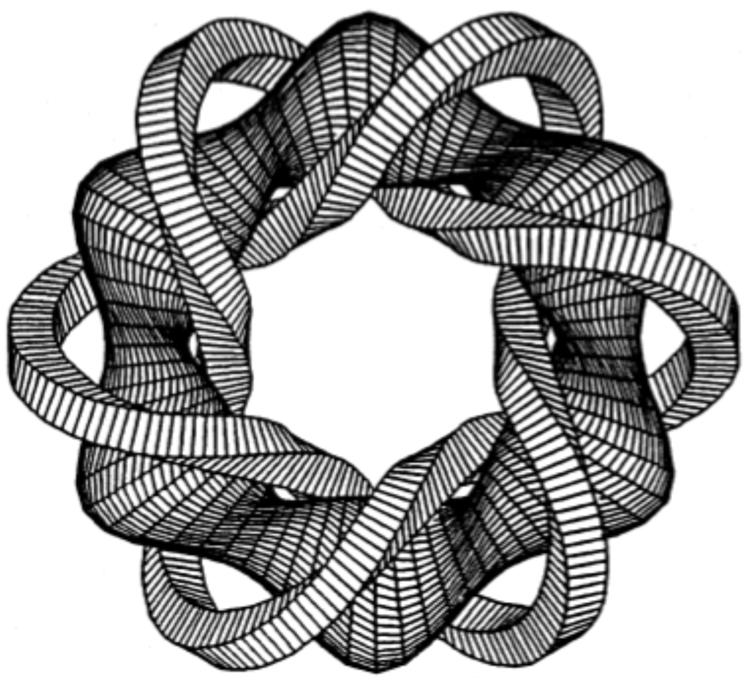
Centrifugal force alternates directions on each side
(relative to the plasma center – the green line)

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

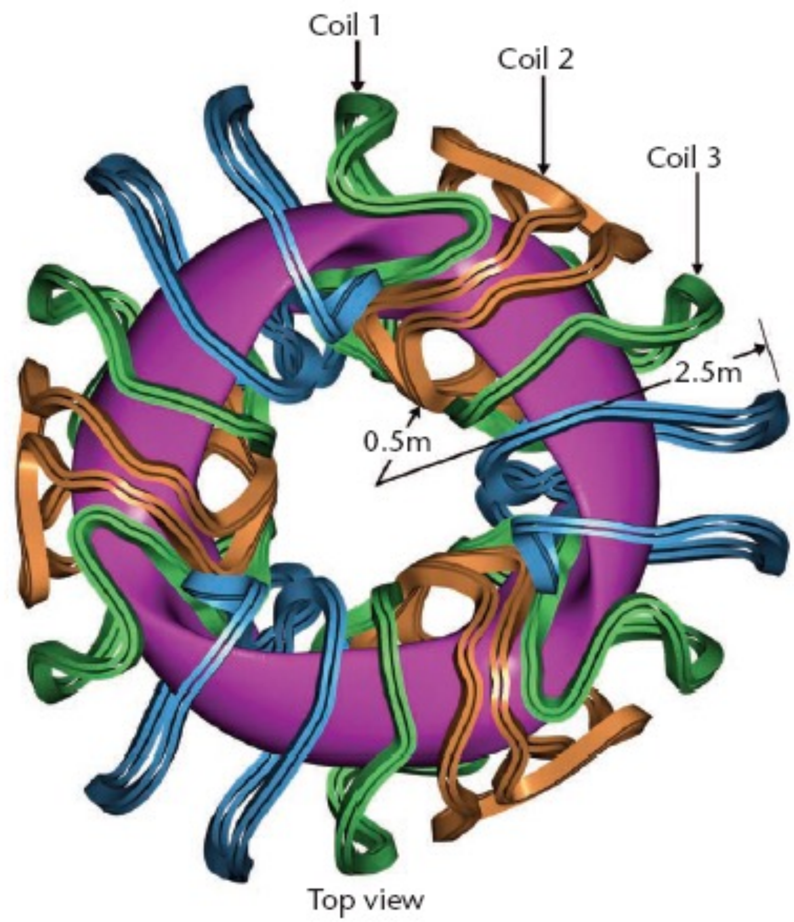
A Demonstration

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. (First realization of the “Berry Phase”*.) 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) / NCSX

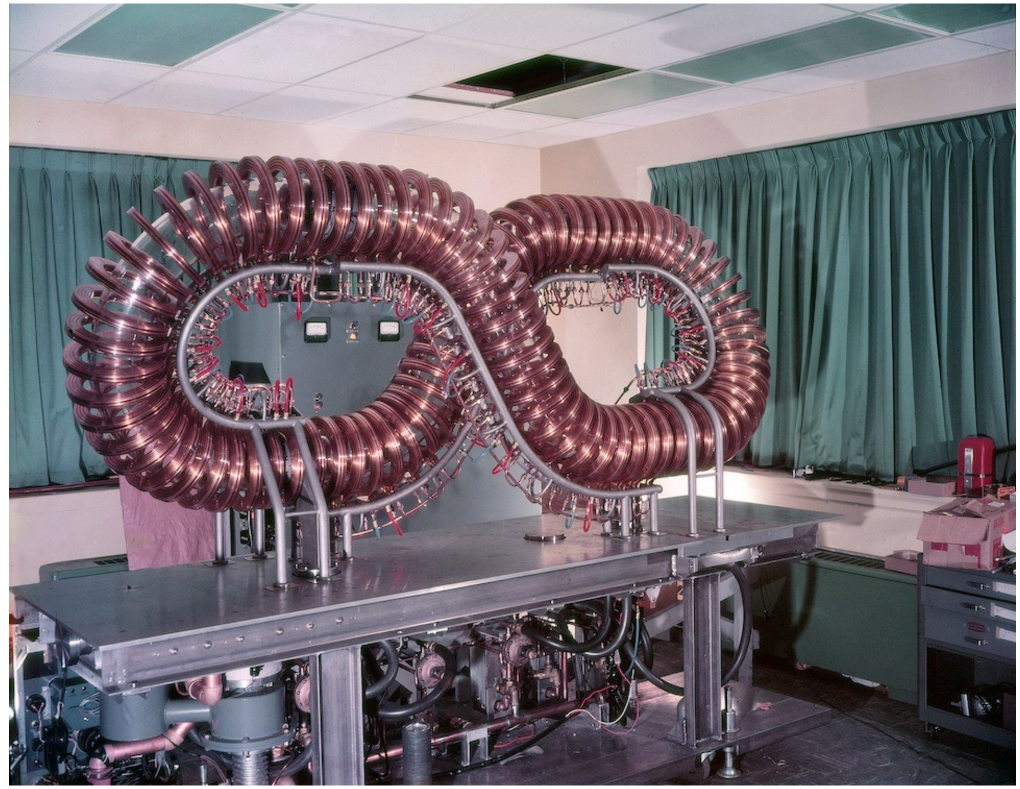
* pointed out in Bhattacharjee, 1992

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."



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

B-3 Stellarator Group

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

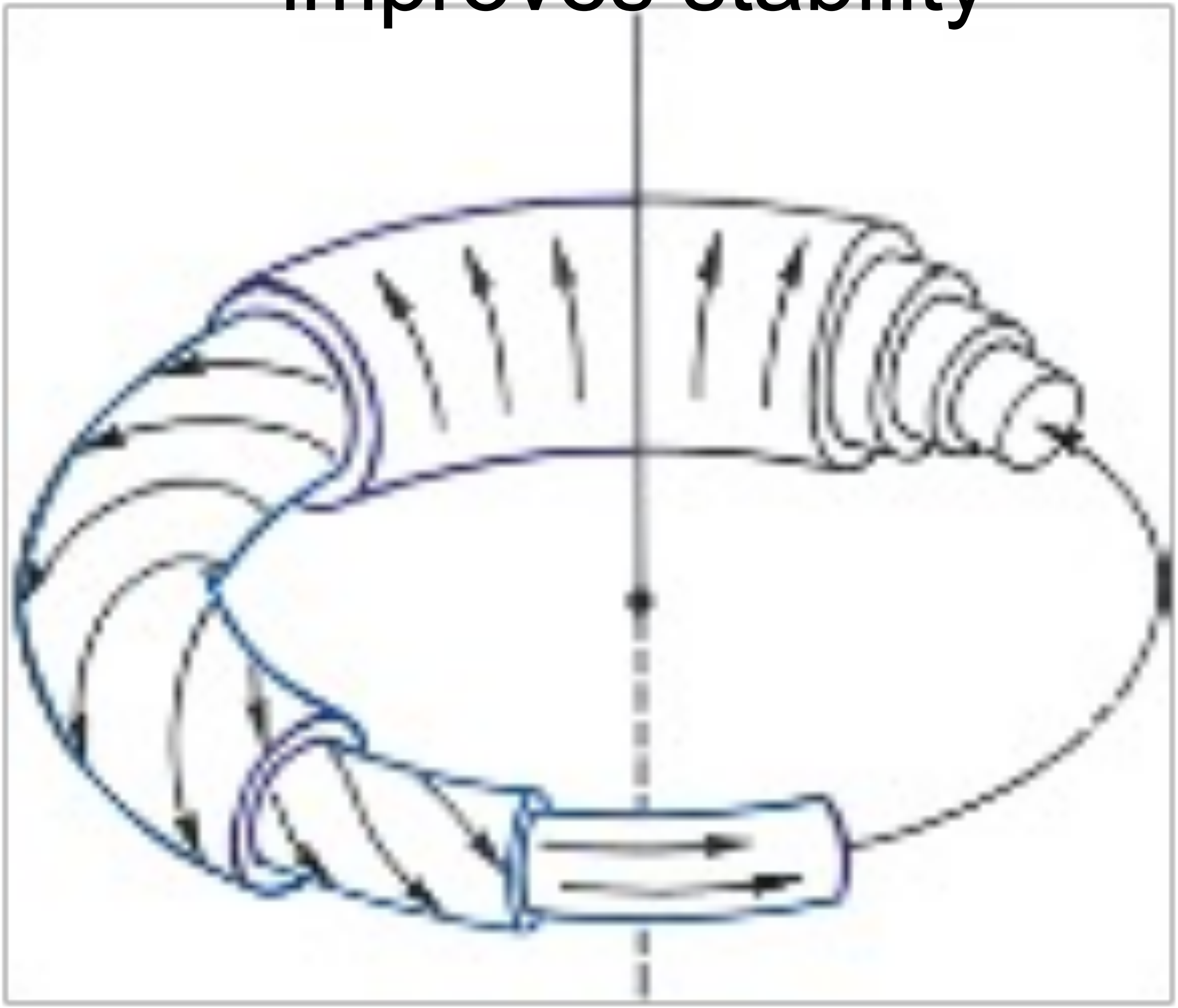
Model A showed basic advantage of figure 8 over racetrack.

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 $\ell = 3$ 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 Bob Ellis (3rd from left on bottom), who led the PPPL experimental program for decades.

Sheared helical magnetic fields improves stability



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

Model-C Stellarator, 1961-1969

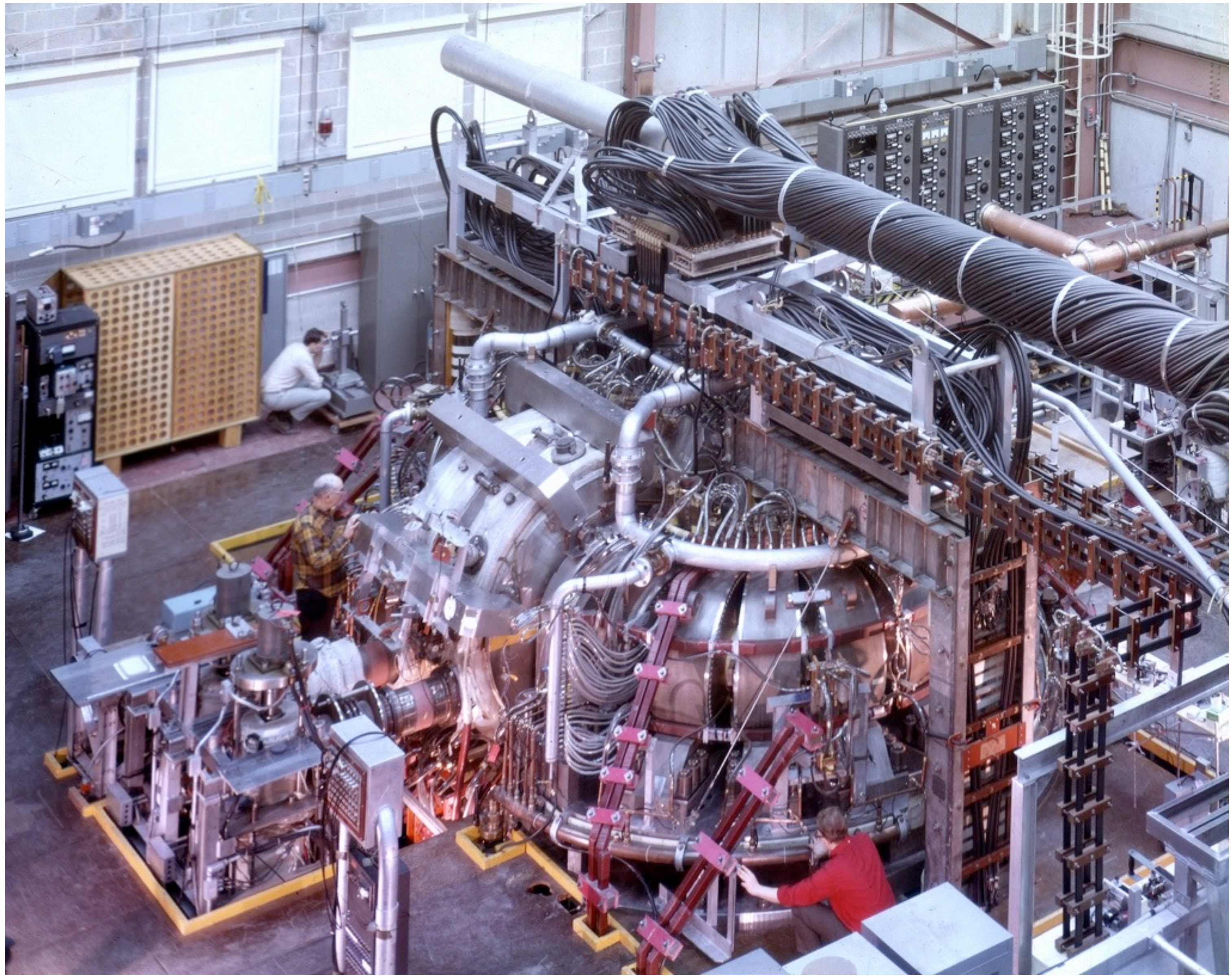
R ~ 1.9 m
a = 5 - 7.5 cm

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, in 4 months, after breakthrough results by Russian tokamak reported at 1968 IAEA meeting, much better than Bohm diffusion. British laser team went to Russia, confirmed $T_e \sim 1$ keV with just ohmic heating (Nature, Nov. 1969).

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 experiment 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 made 10 MW of fusion power. Joint European Torus (JET) eventually make 17 MW.
- Fusion power gain Q = (Fusion power out) / (Heating power in)
  "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


The New York Times
NEW YORK, FRIDAY, DECEMBER 10, 1993
Scientists at Princeton Produce World's Largest Fusion Reaction
New Age of
By MALCOLM W. BROWNE
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
URDAY, 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 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
THE NEWS-JOURNAL
Serving Volusia And Flagler Counties
DAYTONA BEACH, FLA.
SATURDAY
Chicago Tribune
Making progress toward fusion
San Francisco Chronicle
THE VOICE OF THE WEST
EDITORIALS
Nuclear Fusion's Hopeful Promise
IT ALL SOUNDS so elegantly simple: Take some deuterium, with one proton and one neutron, and combine it with a bit of tritium, with one proton and two neutrons
THE SUN
Circulation 494,857
Fusion reactor generates record energy in tests
Princeton Plasma Physics lab engineer Doug Loesser kneels in Tokamak Fusion Test Reactor.
Fusion lab clones power of
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
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 DT Fusion 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

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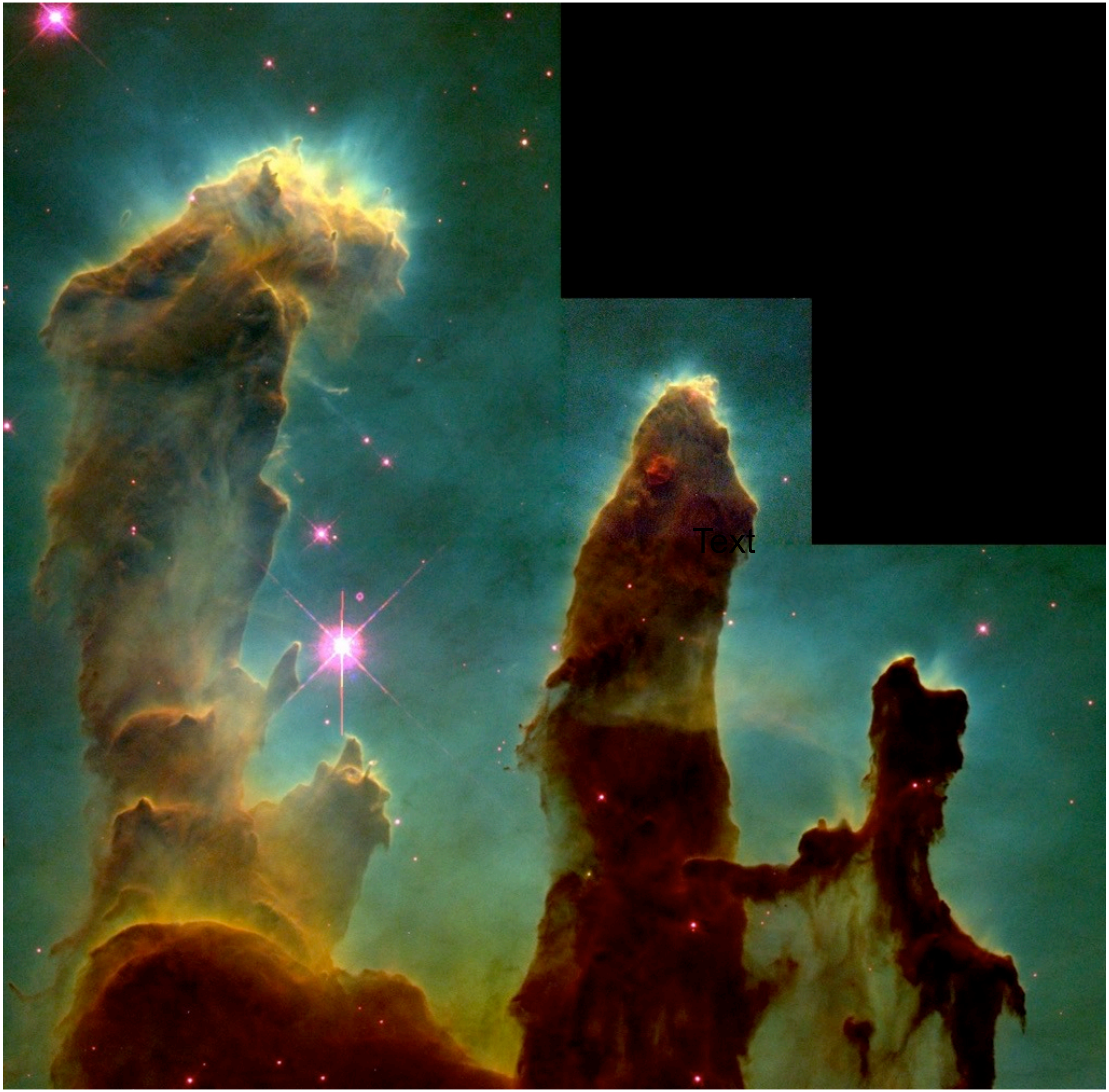
TFTR First Plasma, 3:06 am, Dec. 24, 1982

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



The Eagle Nebula: “Pillars of Creation” gas pillars in a star-forming region.

http://hubblesite.org/gallery/album/pr1995044a/

The road ahead for fusion:

- Continuing innovation: Interesting ideas being pursued in fusion, & reduce the cost of power plants

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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.

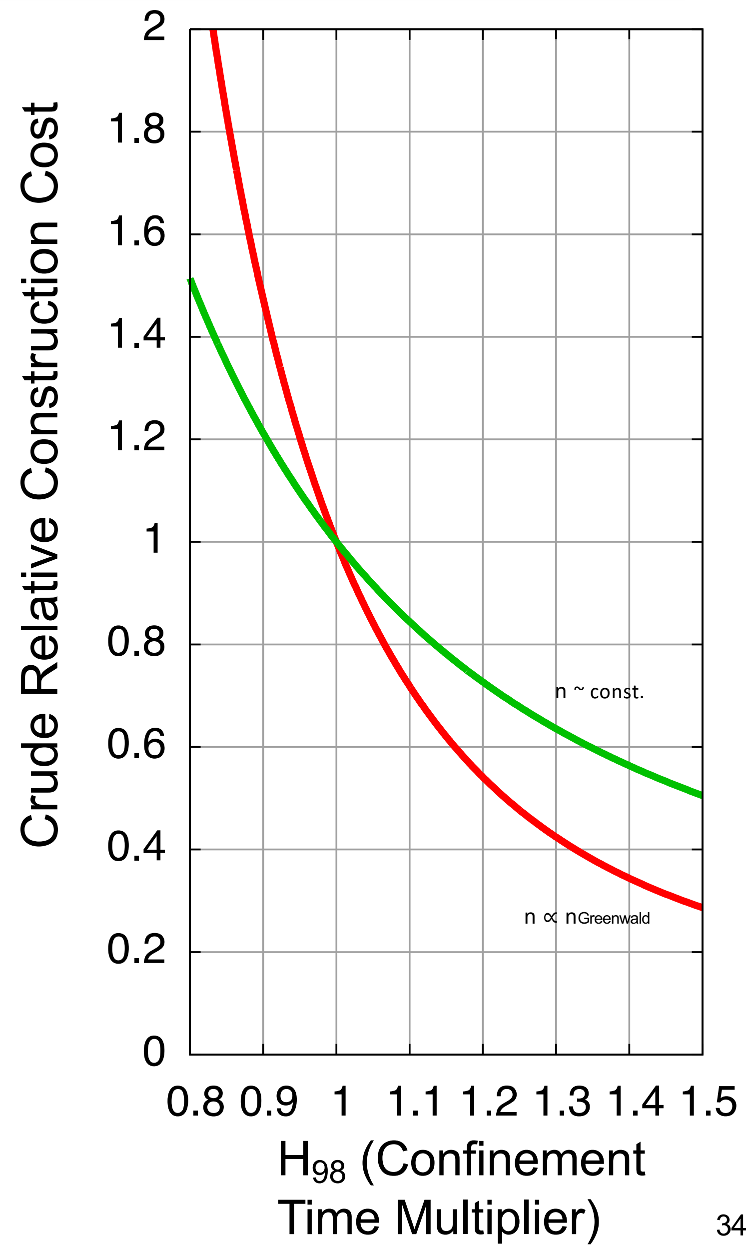
- Fusion energy is hard, but it’s an important problem, we’ve been making progress, and there are interesting ideas to pursue that could make it more competitive.

Improving Confinement Can Significantly ↓ Size & Construction Cost of Fusion Reactor

Well known that improving confinement & stability limits can lower Cost of Electricity / kWh, at fixed power output.

Even stronger effect if consider smaller power: better confinement allows significantly smaller size/cost at same fusion gain Q ($nT\tau_E$).

Comprehensive computer simulations on supercomputers are helping us search for improved fusion concepts. Want to be confident of extrapolation to larger sizes when building billion $ experiments.



Hammett & Dorland, "The Impact of Potential Breakthroughs on Fusion", Community Workshop on U.S. Magnetic Fusion Research (MFR) Strategic Directions , Madison, Wisconsin, July 24-28, 2017.

Interesting Ideas To Improve Fusion

* Liquid metal (lithium, tin) films or flows on walls: (1) protects solid wall (2) absorbs incident hydrogen ions, reduces turbulence, and improves global performance.

* Spherical Tokamaks (STs) appear to be able to suppress much of the ion turbulence: PPPL upgrading the National Spherical Tokamak Experiment (NSTX-U) to test scaling

* Advanced tokamaks, alternative operating regimes (reverse magnetic shear or “hybrid”), methods to control Edge Localized Modes, negative triangularity. Tokamaks sometimes spontaneously spin (like a smoke ring vortex) and reduce the turbulence some.

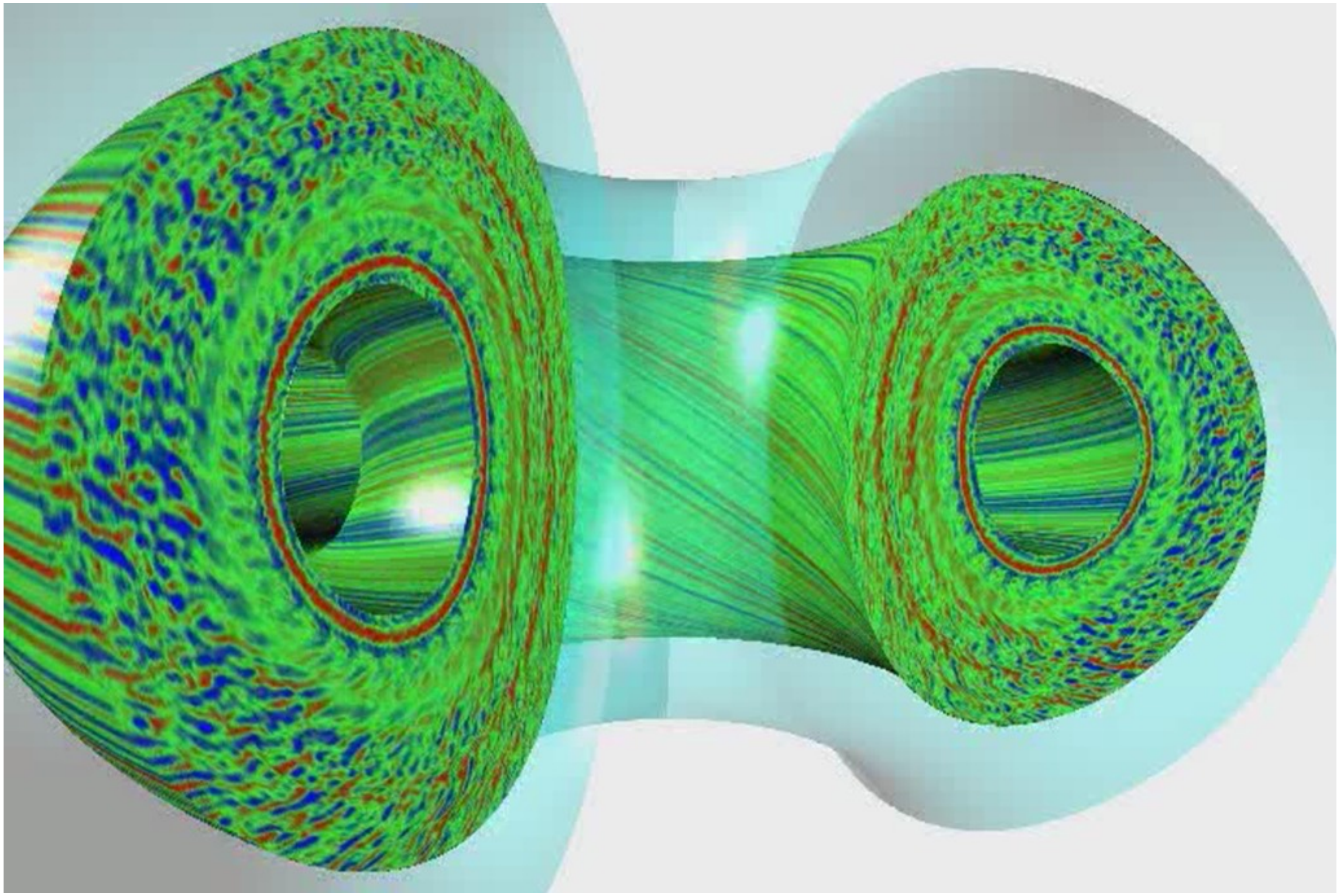
* Many possible stellarator designs, room for further optimization: Quasi-symmetry / quasi-omnigenity improvements discovered relatively recently, after 40 years of fusion research. Stellarators fix disruptions, steady-state, density limit.

* Tokamaks & stellarators furthest along, but some researchers & companies pursuing more speculative concepts (mirrors, FRCs, pinches, …), sometimes with interesting new twists. Might be cheaper. Can shear flow help stabilize one of these concepts? Plasma smoke ring?

* Advances in magnet technology (high-temperature superconductors, higher field) and other fusion-related technologies could help all fusion concepts.

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

Fairly Comprehensive 5-D Gyrokinetic Turbulence Codes Have Been Developed



Major progress in developing computer simulations of plasma turbulence,

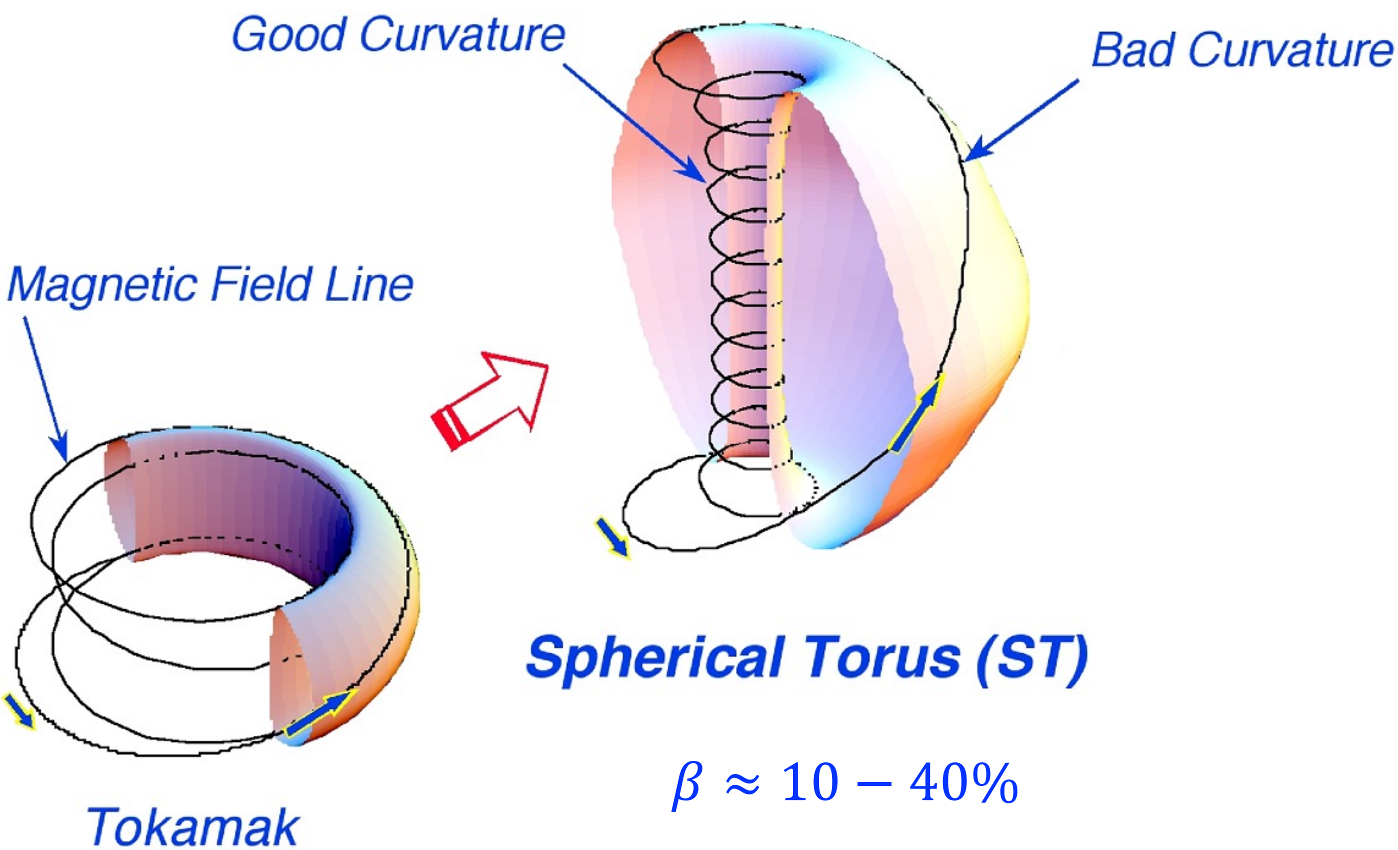
but still important unfinished work, including edge region.

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

- 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

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



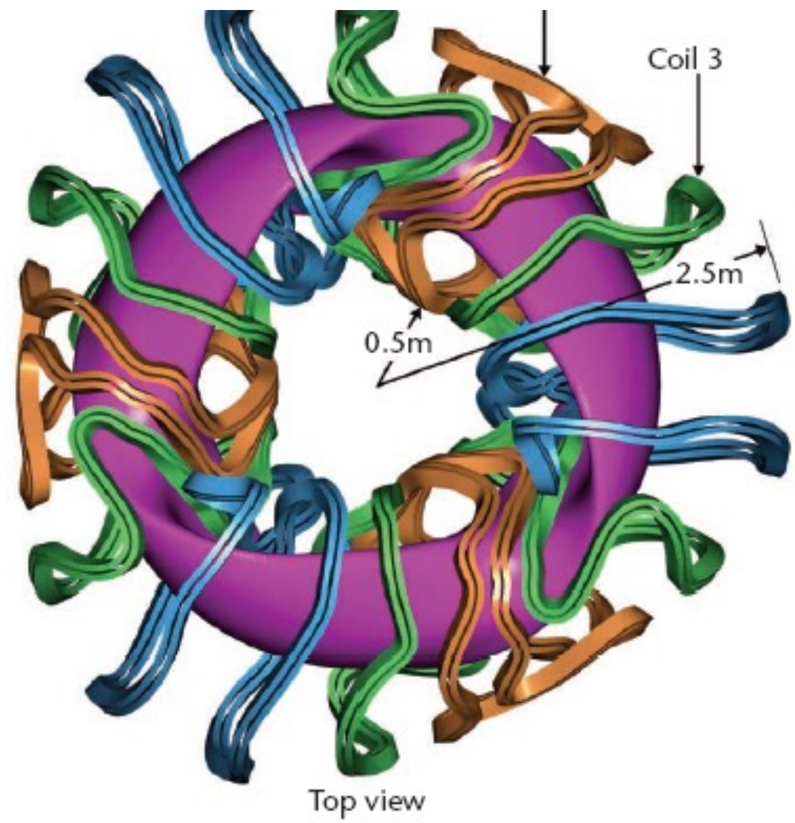
$\beta \approx 10 - 40\%$

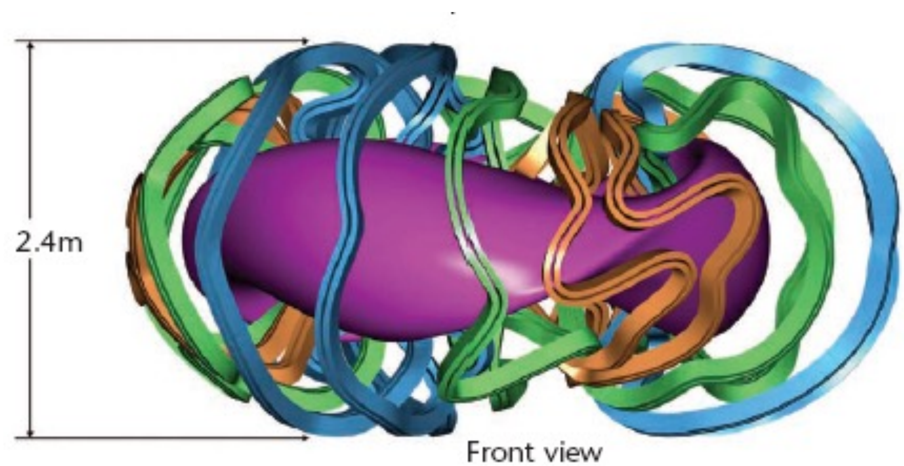
$\beta \approx 3 - 10\%$

National Spherical Tokamak Experiment Upgrade (NSTX-U) at PPPL being rebuilt and enhanced. Has twice the magnetic field and heating power as original NSTX, to see how performance scales towards a real reactor scale.

Improved Stellarators Being Studied

- Originally invented by Spitzer ('51), the unique idea when fusion declassified ('57)
- Mostly abandoned for tokamaks in 1969. But computer designs now much better.
- Hidden quasi-symmetry discovered in 80's-90's: don't need vector ***B*** exactly symmetric toroidally, |***B***| symmetric in field-aligned coordinates sufficient to be as good as tokamak.
- Magnetic field provided by external coils, inherently more stable, intrinsically steady state, no hard stability limit.
- Robotic manufacturing / 3-D printing might reduce cost a lot?





~$1B W7-X stellarator in Germany getting good performance.

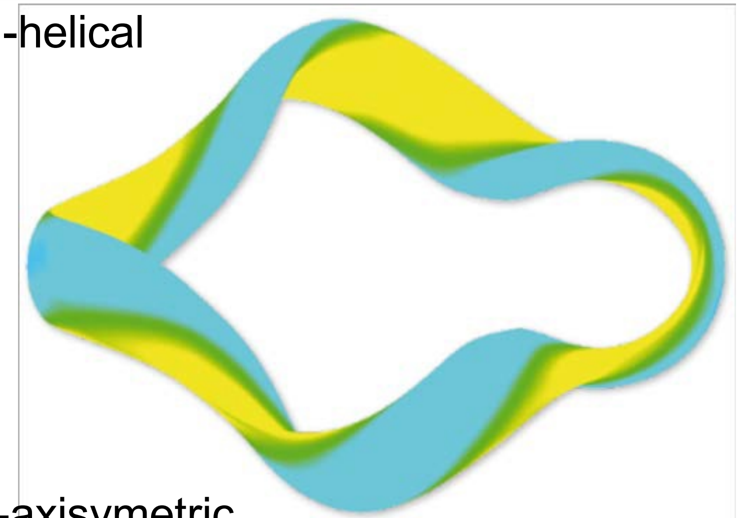
Many types of stellarators possible

Quasisymmetry discovered in 80’s, but full range of possibilities still being explored.
(Color contours indicate magnetic field strength.)

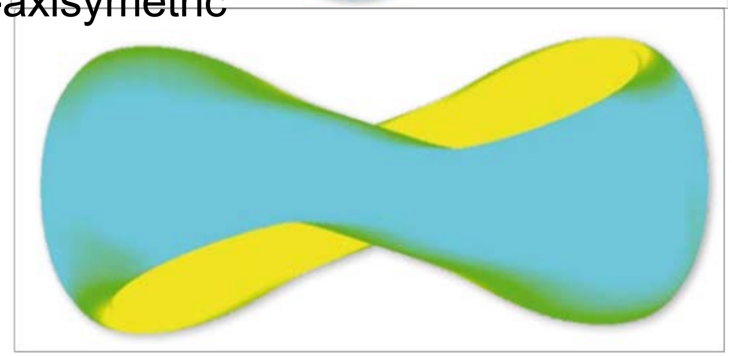
Recently discovered designs that confine single-particle orbits extremely well, even for energetic particles. (Paul & Landreman PRL 2022.)

Ongoing research: particles can interact collectively and cause small scale turbulent fluctuations. Not sure how these will scale to a larger reactor-scale. Comprehensive computer codes being developed.

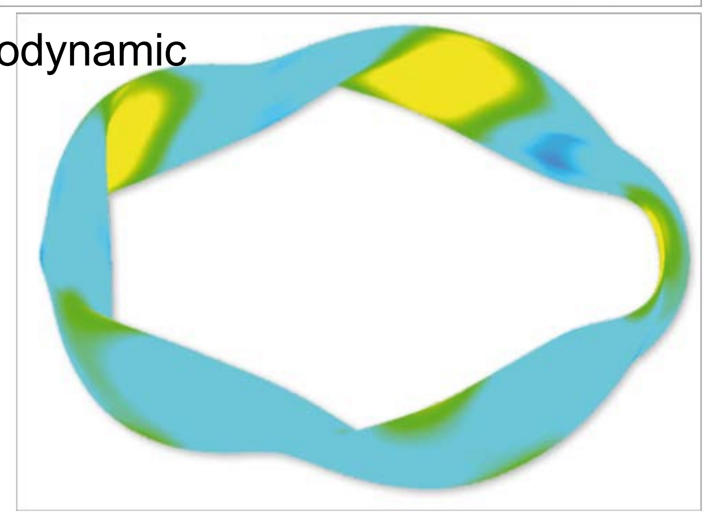
QH, quasi-helical



QA, quasi-axisymetric



QI, quasi-isodynamic



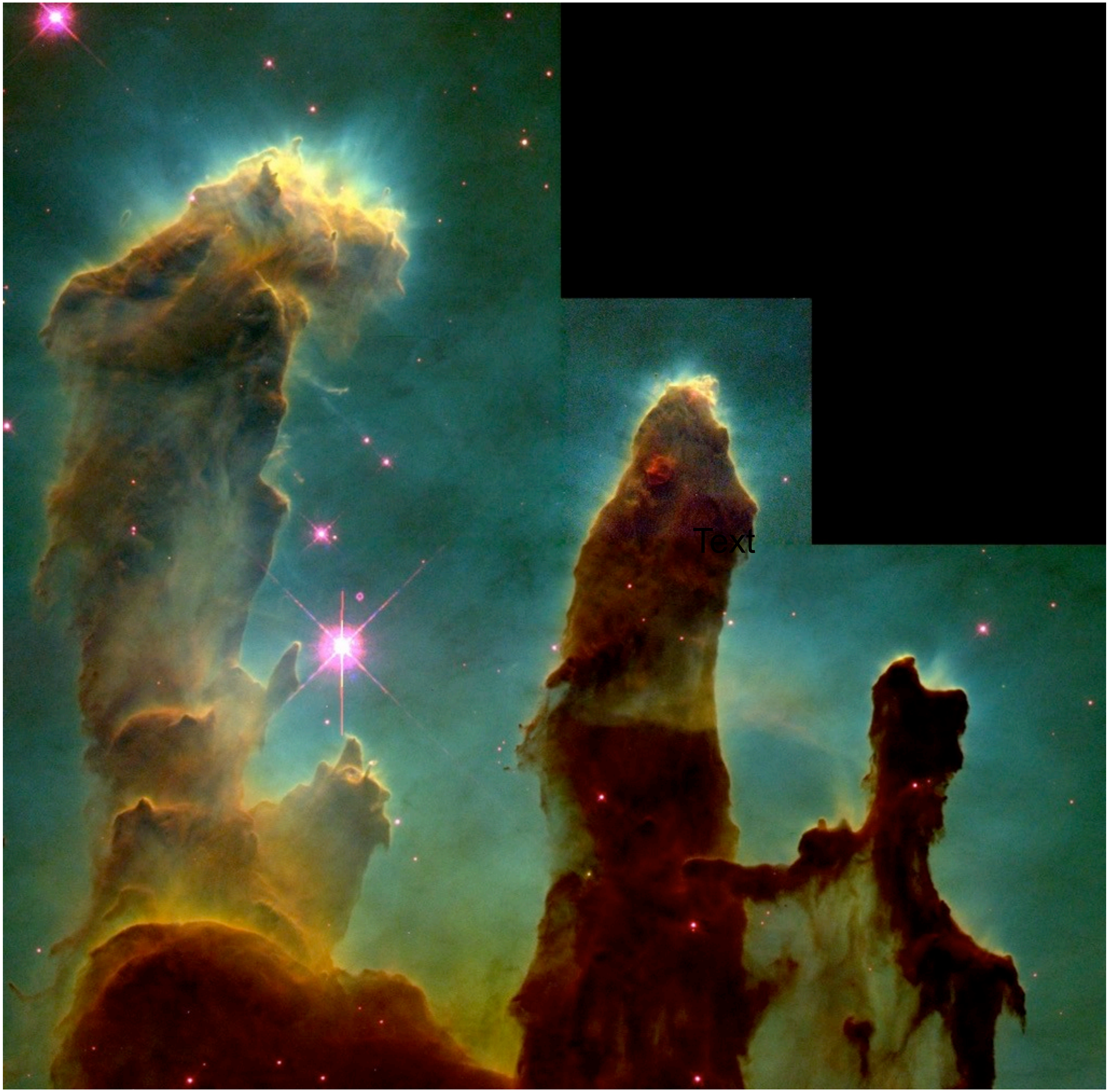
Lyman Spitzer's Legacy of Innovation in the Quest for Fusion Energy

- Some history of Spitzer's big ideas / innovations:
  - 1946: Telescopes in space (Hubble Space Telescope)
  - 1951: Figure-8 stellarator trick to make a fusion power source

- A fluid picture of the trick for how a figure-8 stellarator works (and basis for later stellarators).

- Continuing innovations at PPPL and elsewhere to improve fusion energy concepts
  - including ideas for further improving the stellarator concept, which is undergoing a renaissance.

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



The Eagle Nebula:
"Pillars of Creation"
gas pillars in a star-forming region.

http://hubblesite.org/gallery/album/pr1995044a/

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  - Marshall Rosenbluth (2003) http://www.aip.org/history/ohilist/28636_1.html
- ...