(1) Spitzer's 100th: Founding PPPL & Pioneering Work in Fusion Energy

Greg Hammett

(2) Some Stories From Working with Spitzer In the Early Years

Russell Kulsrud

Princeton Plasma Physics Laboratory Colloquium
Dec. 4, 2013

These are shorter versions of talks we gave at the *100th Birthday Celebration for Lyman Spitzer*, October 19-20, 2013, Peyton Hall, Princeton University, http://www.princeton.edu/astro/news-events/public-events/spitzer-100/
https://www.princeton.edu/research/news/features/a/?id=11377

Video of a longer talk by Kulsrud, "My Early Years Spent Working with Lyman Spitzer":
https://mediacentral.princeton.edu/id/1_1kil7s0p

Thanks for slides: Dale Meade, Rob Goldston, Eleanor Starkman and PPPL photo archives, ...
PPPL Historical Photos: https://www.dropbox.com/sh/tjv8lbx2844fxoa/FtubOdFWU2

June 19, 2014: added historical info. Jul 9, 2015: pointer to updated figure

Lyman Spitzer Jr.'s 100th: Founding PPPL & Pioneering Work in Fusion Energy

Outline:

- Pictorial tour: from Spitzer's early days, the Model-C stellarator (1960's), to TFTR's 10 megawatts of fusion & the Hubble Space Telescope (Dec. 9-10, 1993)

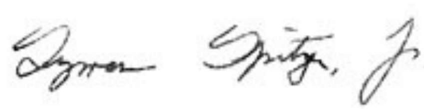
- Russell Kulsrud: A few personal reflections on early days working with Lyman Spitzer.

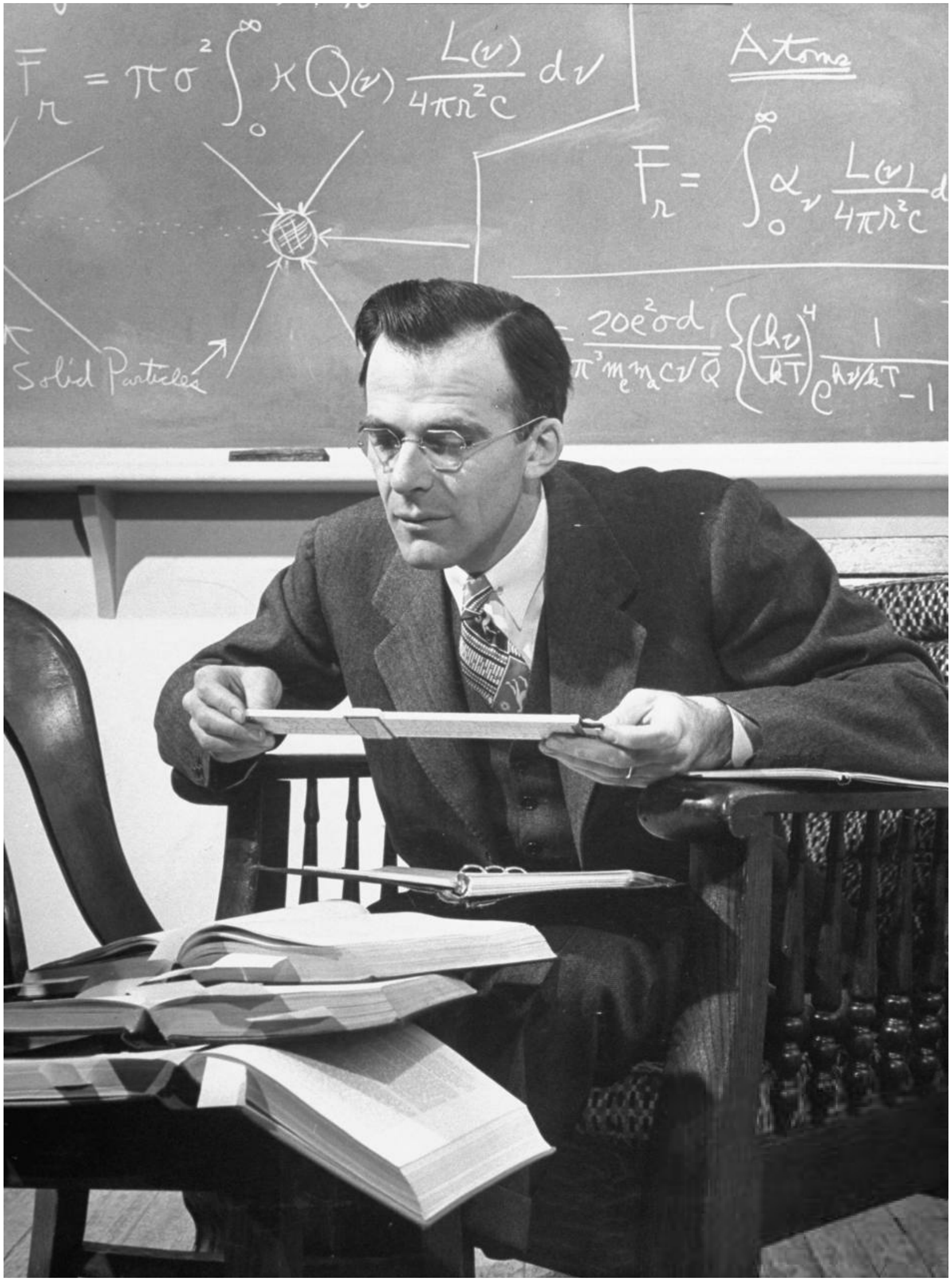
- The road ahead for fusion:
  - Interesting ideas being pursued in fusion, to improve confinement & reduce the cost of power plants

I never officially met Prof. Spitzer, though I saw him at a few seminars. Heard many stories from Tom Stix, Russell Kulsrud, & others, learned from the insights in his book and his ideas in other books. 2

Lyman Spitzer, Jr.
1914-1997

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 Photo Collection, March 1948

http://sliderulemuseum.com/SR_Ephemera.htm

http://www.google.com/culturalinstitute/asset-viewer/uwHIsK8XRqgCXw?hl=en

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

Spitzer's First Exploration of Fusion

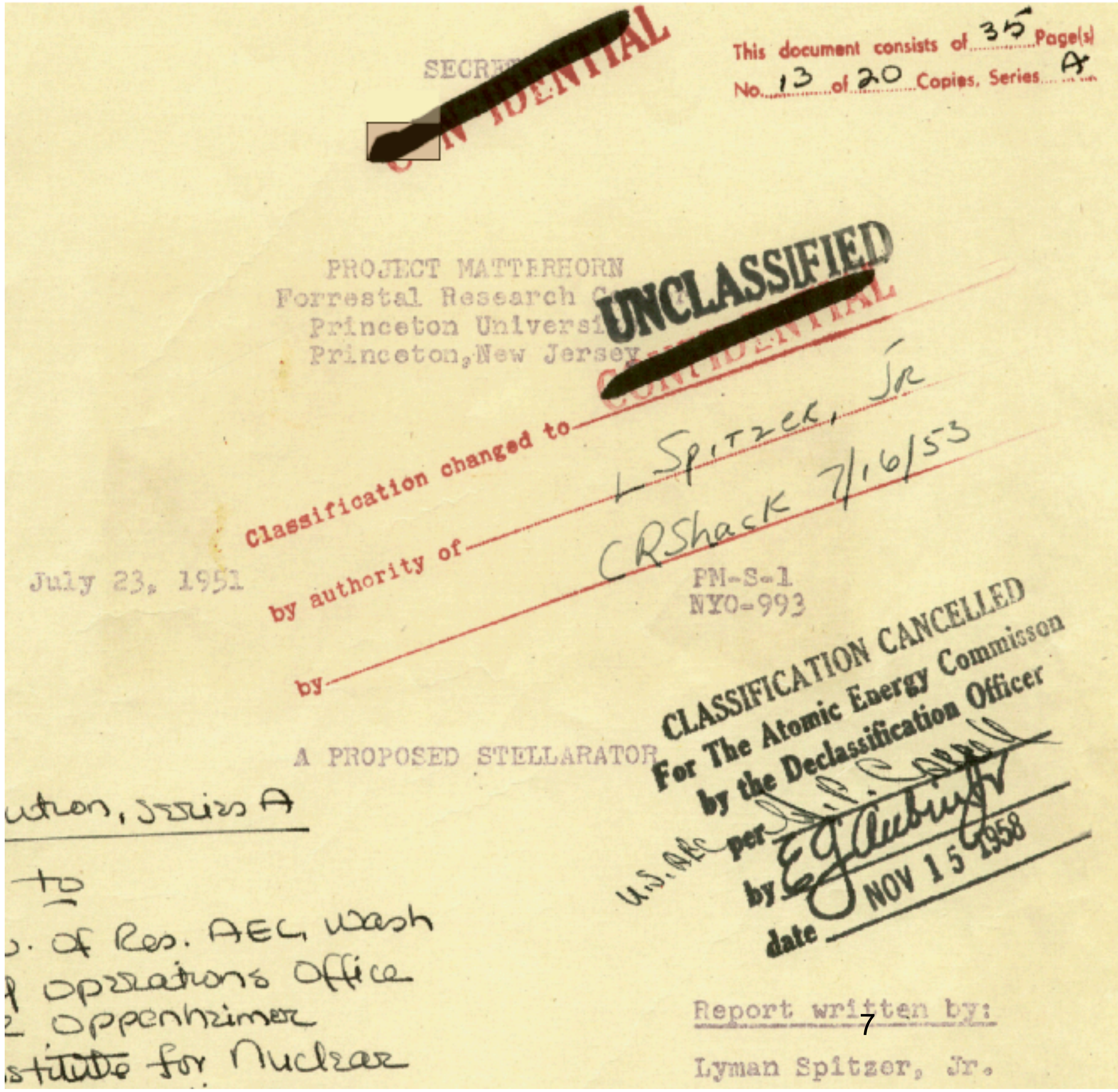
- 25 June, 1950, Korean war started.
- Lyman Spitzer and John Wheeler think about starting a theoretical program at Princeton studying thermonuclear explosions. (Spitzer worked on sonar in WWII)
- March 24, 1951, President Peron of Argentina claimed his scientist, Ronald Richter, had produced controlled 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 for several years and 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 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. Later named a "stellarator", a star generator.

- 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 (=$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.

* John Johnson, personal communication.

Spitzer's Original May 12, 1951 Proposal



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

PROJECT MATTERHORN
Forrestal Research C[redacted]
Princeton Universi[redacted]
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

A PROPOSED STELLARATOR

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

...ution, Series A
to
...D. 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

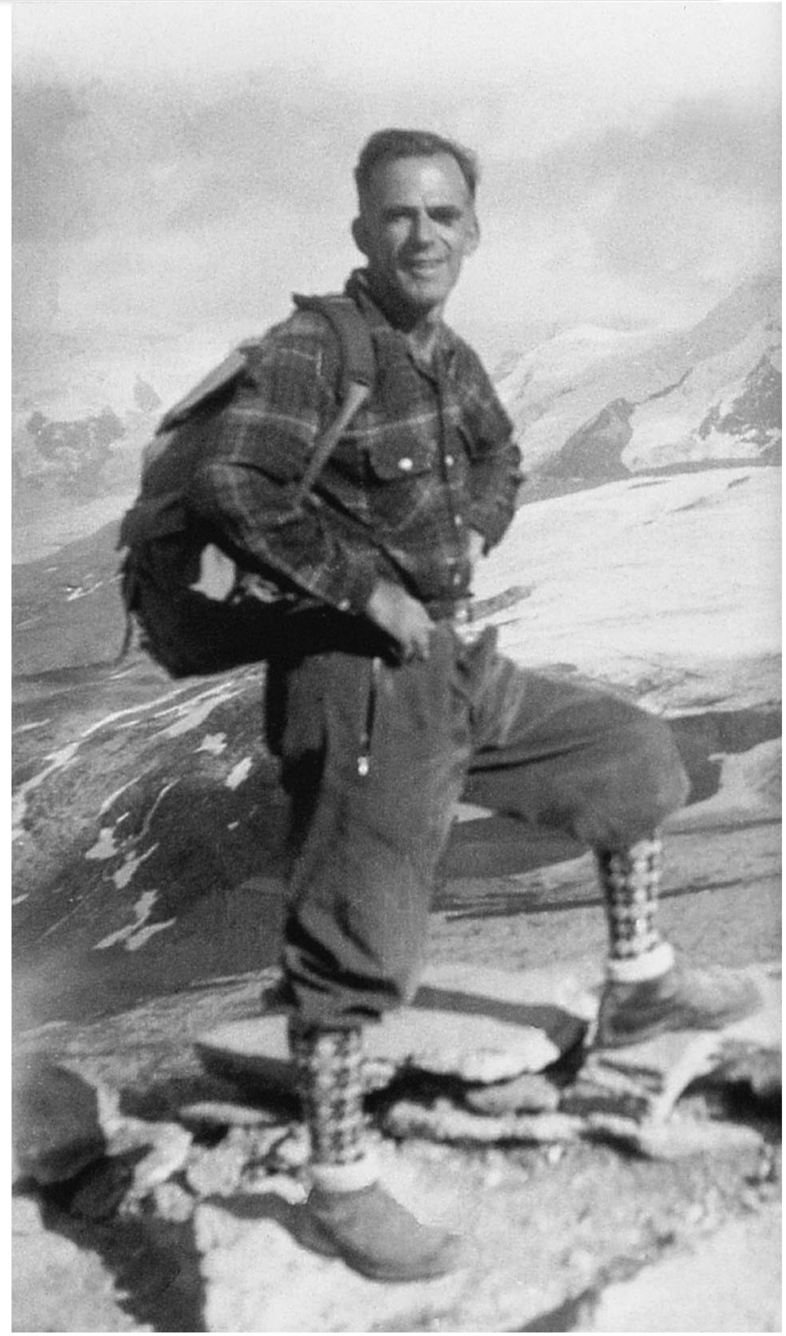
- Two sections:
  - S: headed by Spitzer, studying the stellarator concept
  - B: headed by John Wheeler

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

A serious mountain climber:

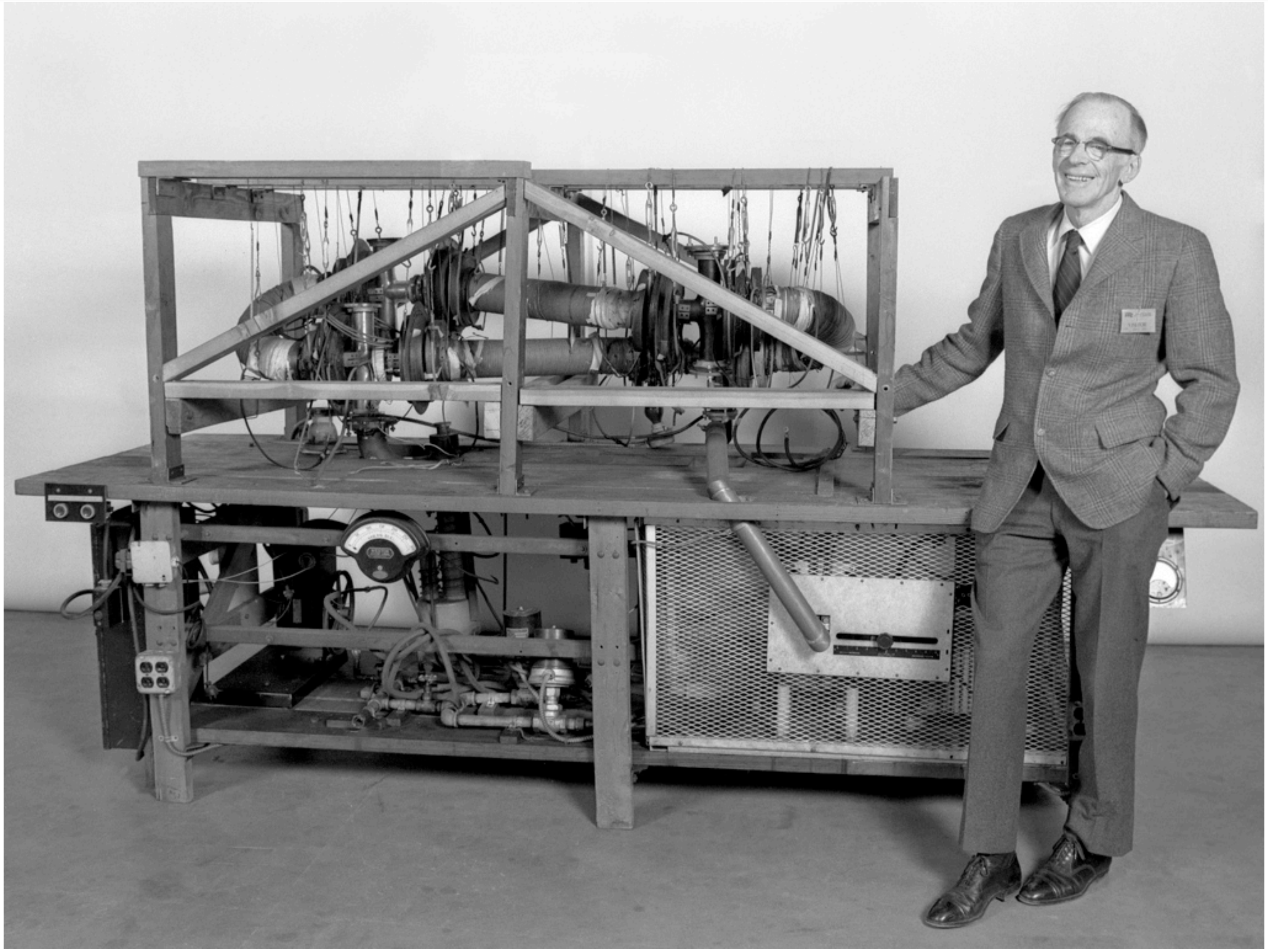
The American Alpine Club annually awards the Lyman Spitzer Cutting Edge Climbing Award.

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.

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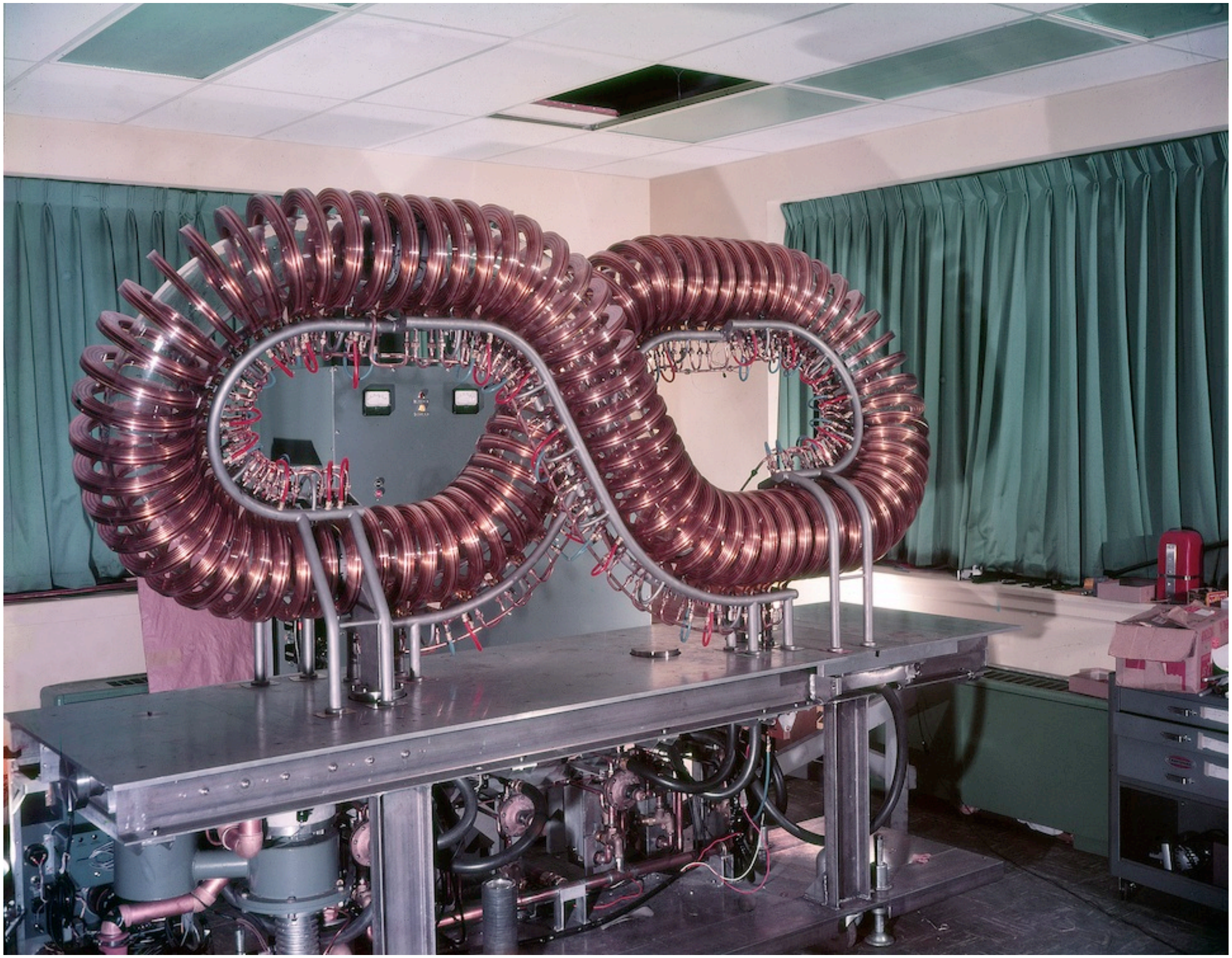
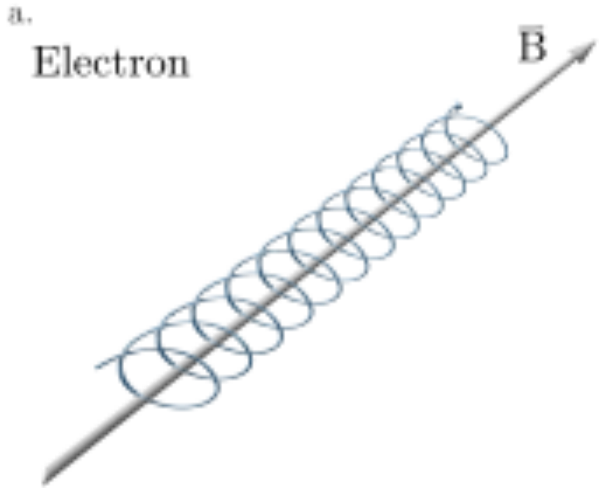
2cd UN Atoms For Peace Conference, Geneva 1958.



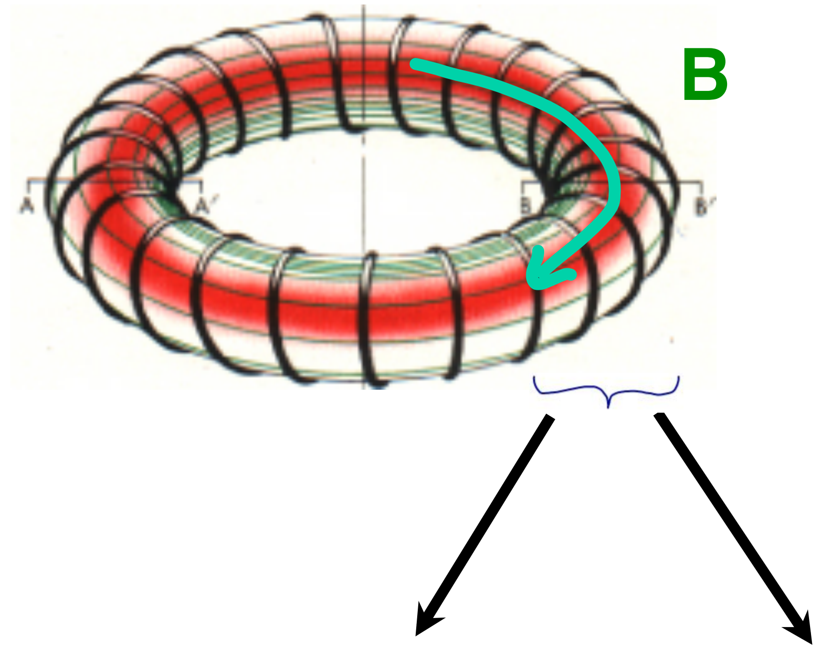
Perhaps SIM-8, one of the simulator stellarators (w/ e-beam) used in demonstrations at the 2cd Atoms-For-Peace Conference, Geneva (1958)

A Crash Course in Magnetic Confinement (in 3 slides)

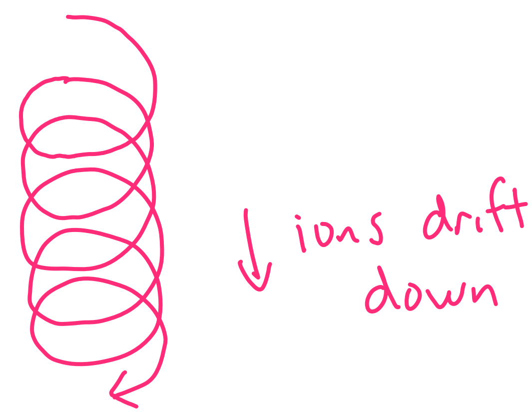
Particles have helical orbits in B field, not confined along B. Try to fix by wrapping B into a torus.



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

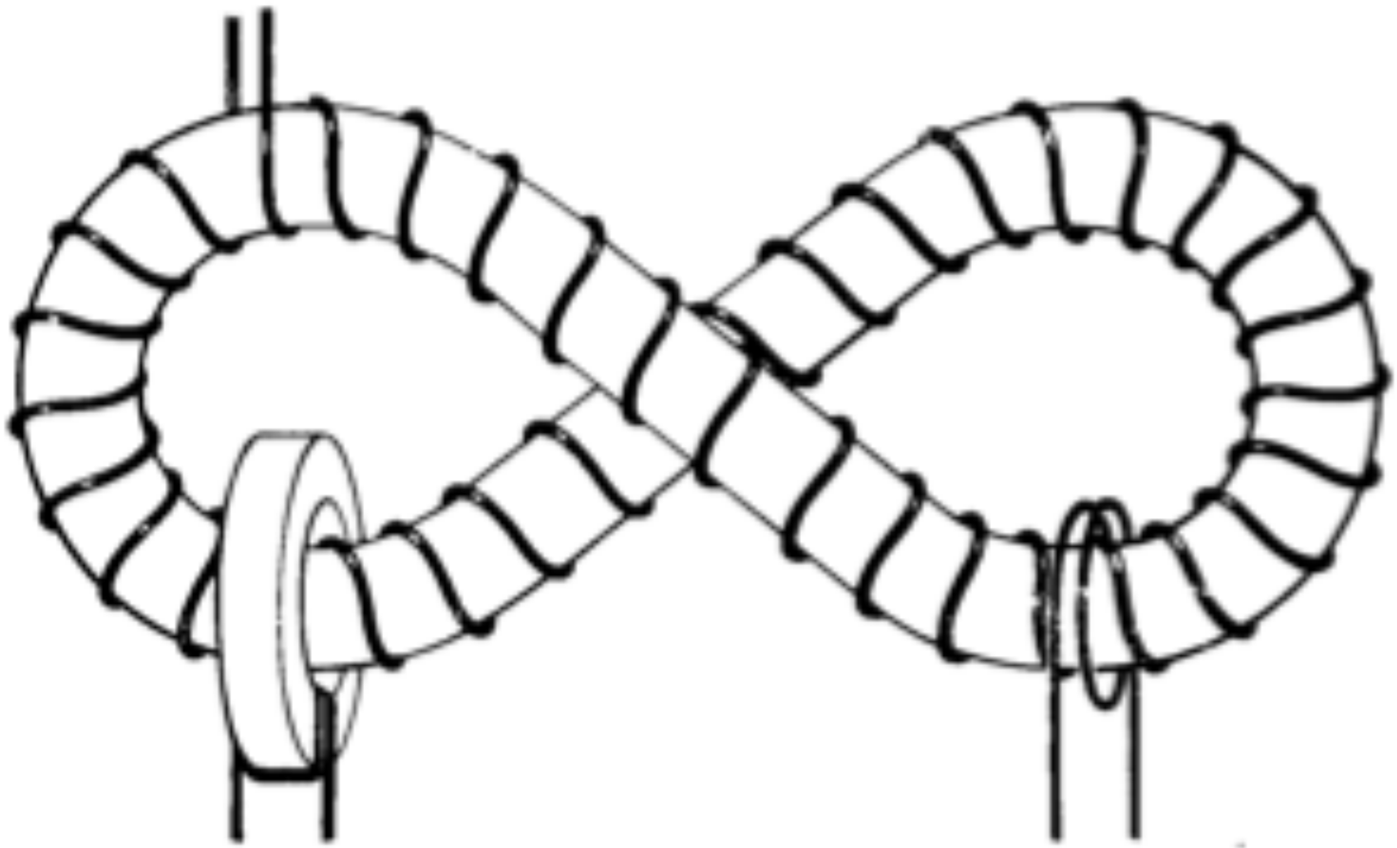


but now B ~ 1/R, so
particles will drift out:



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.



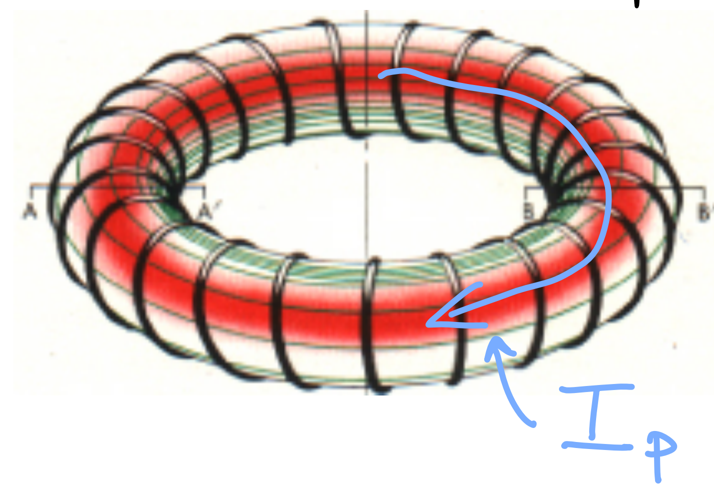
ions drift out of the page on one side of figure 8, but drift into page on other side.

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

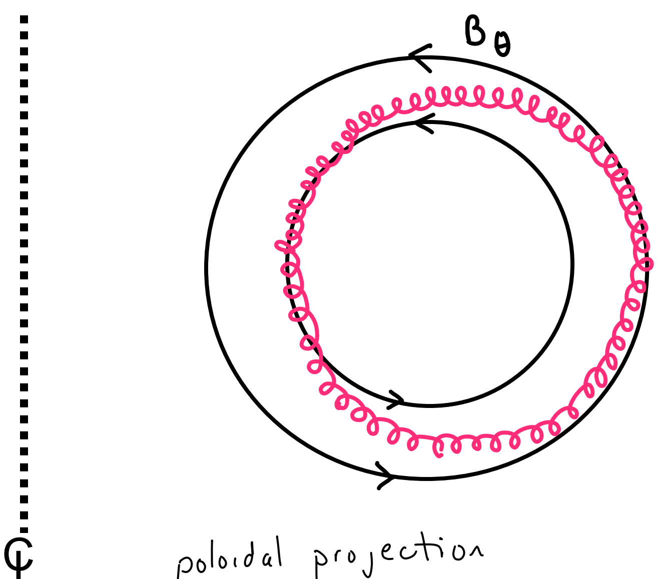
R. A. Ellis, Jr,, Princeton Alumni Weekly, Sept. 19, 1958

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

Induce a current in plasma:

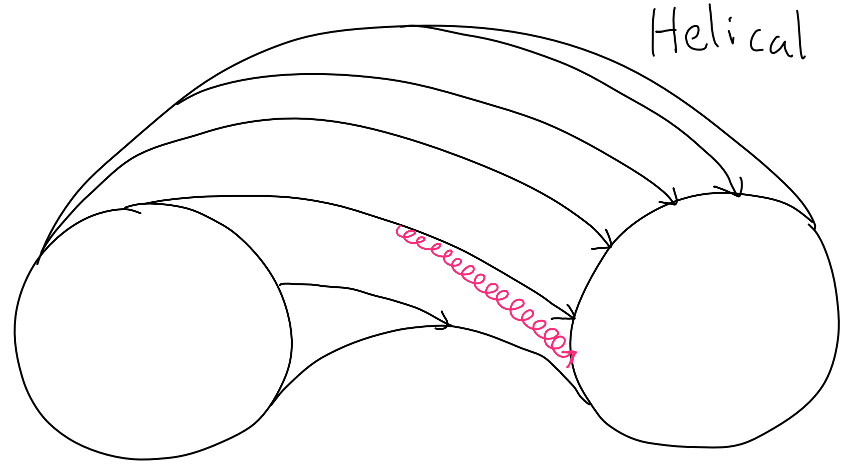


Ion motion along twisting $\underset{\sim}{B}$ field + downward drift:



poloidal projection

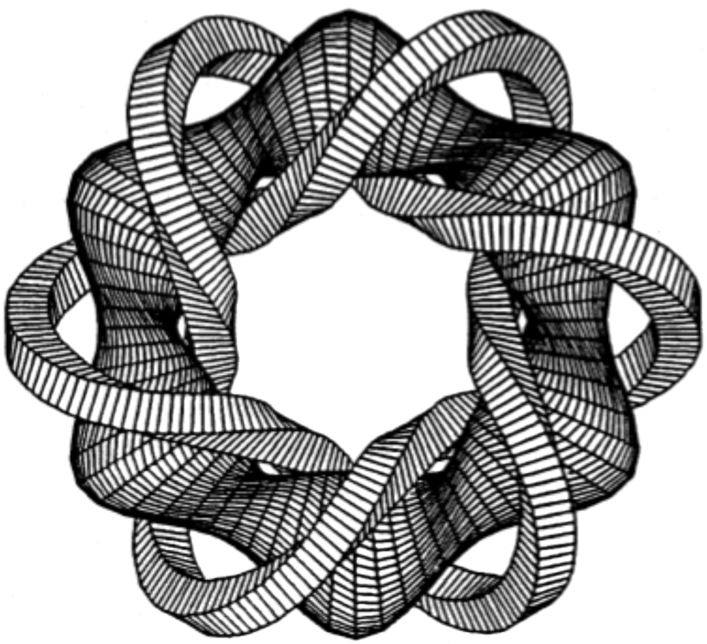
Helical twist in $\vec{B}$



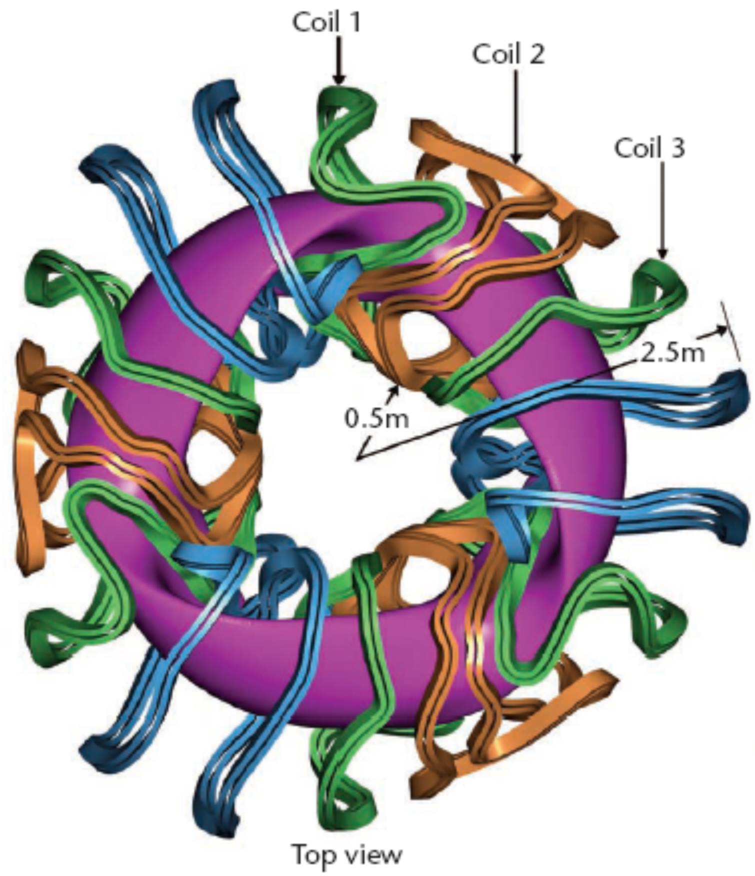
Perspective view

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. (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)

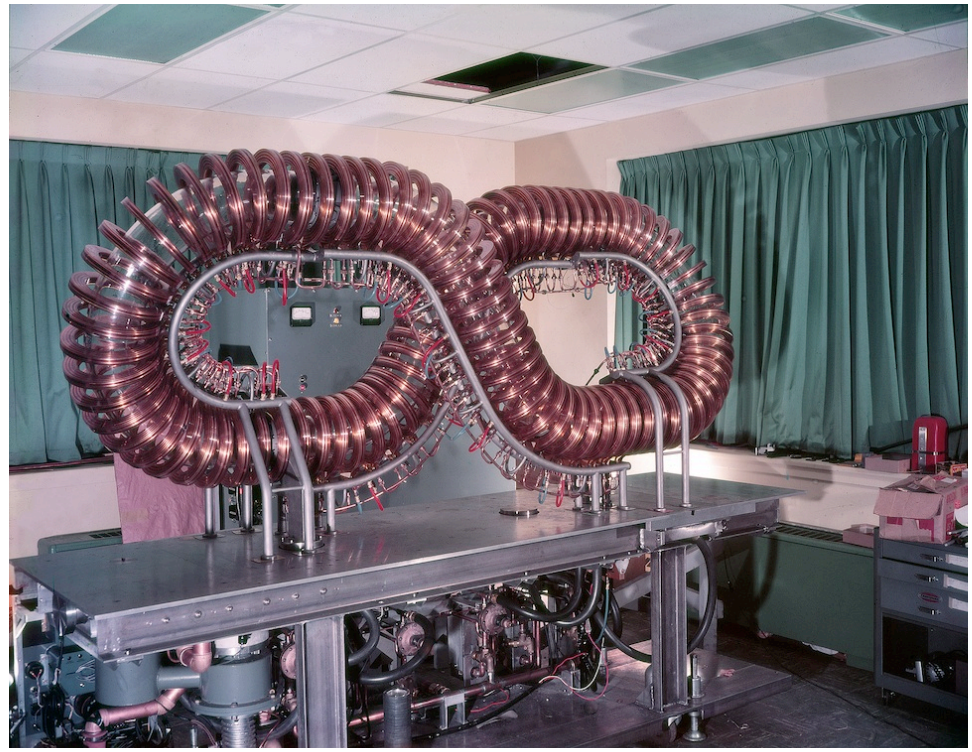
* pointed out in Bhattacharjee, 1992

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."

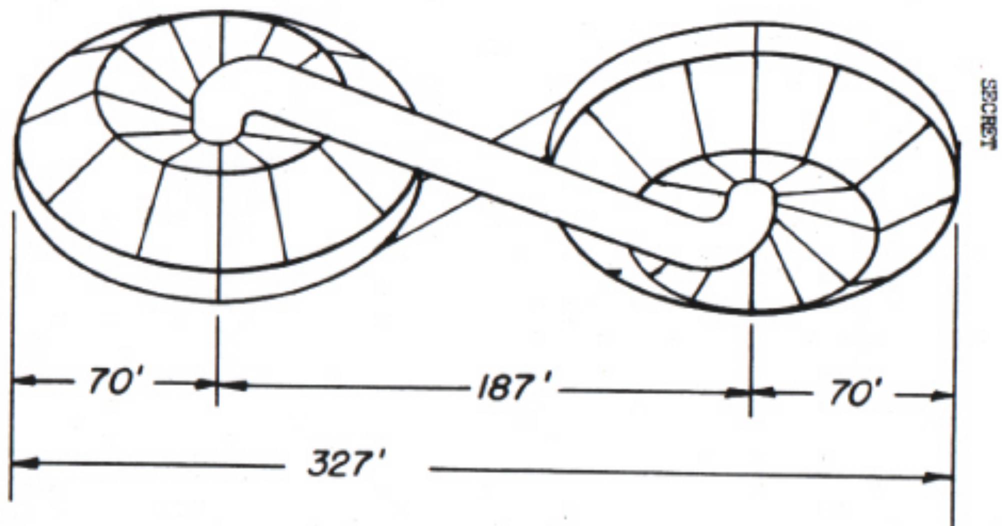


Perhaps SIM-8, one of the simulator stellarators (w/ e-beam) used in demonstrations at the 2cd Atoms-For-Peace Conference, Geneva (1958)

"... 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 very good, T~10 keV, $n \approx 10^{21}$ m^{-3}
  - β = 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

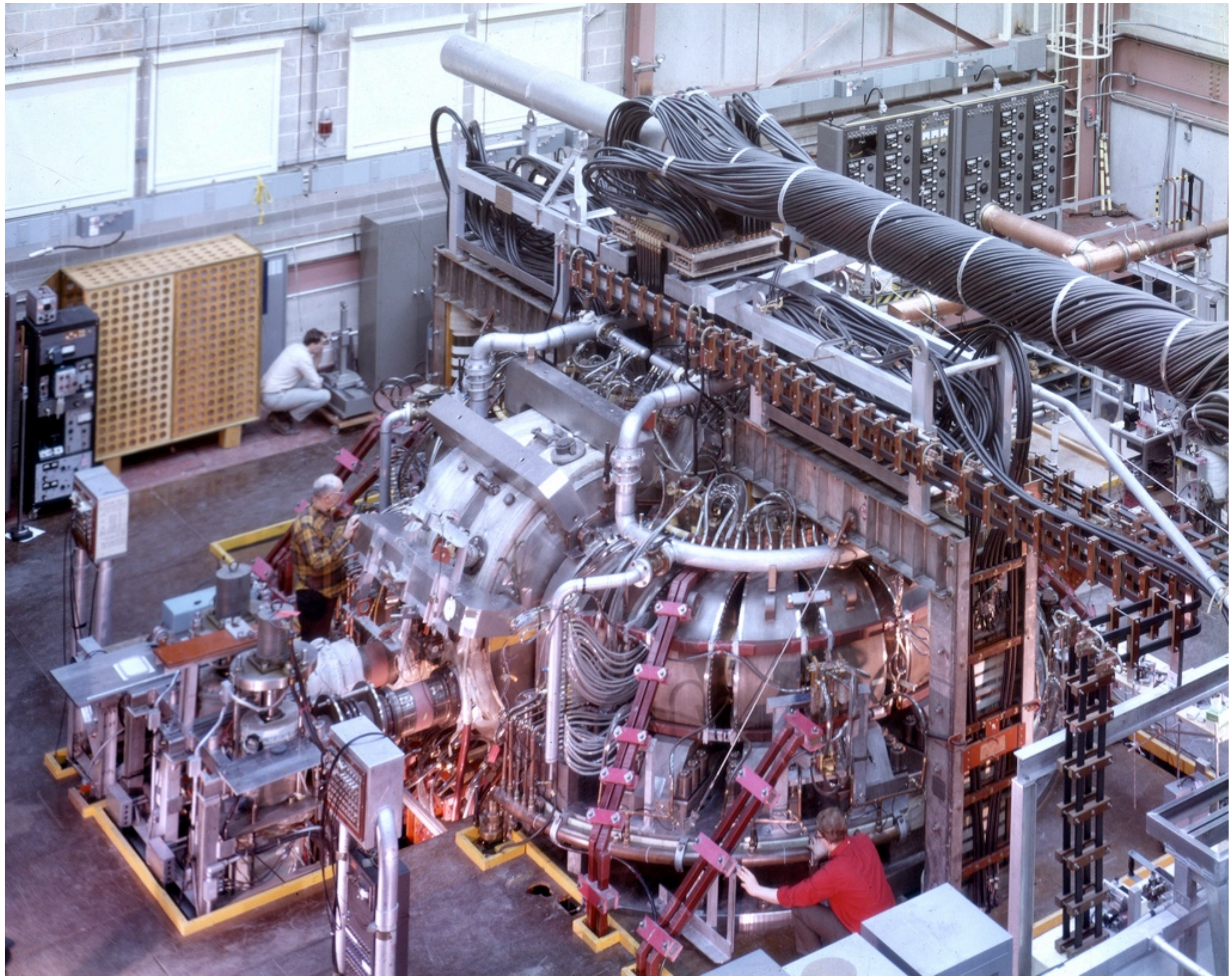
R ~ 1.9 m
a = 5 - 7.5 cm

Principal finding: strong turbulent diffusion limited performance:

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

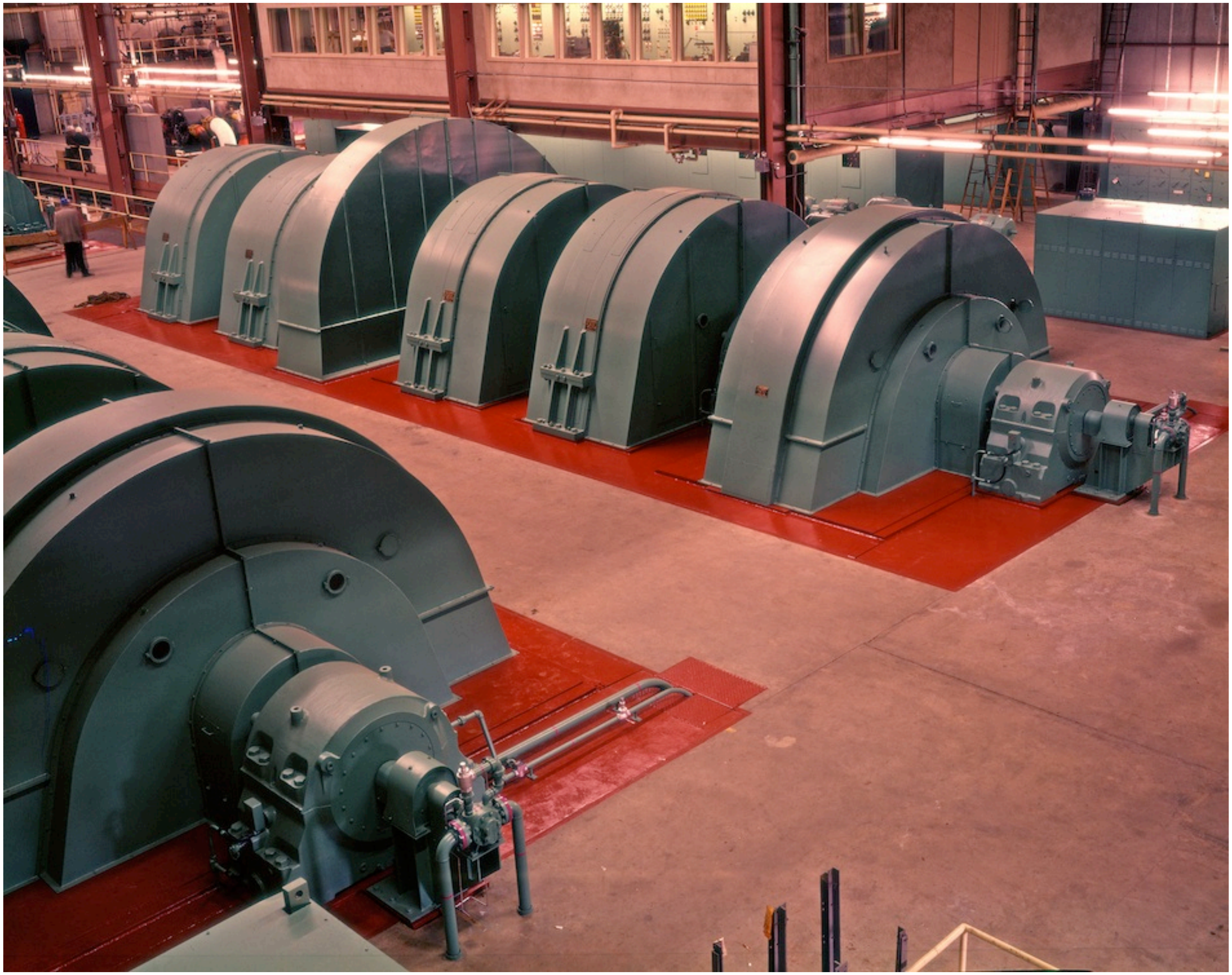
But with 4MW ICRF heating, got mirror trapped
$T_i \sim 8$ keV,
avg $T_i \sim 400$ eV

Stix, 1998



(1967). Converted to ST Symmetric Tokamak in 1970, 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).

Motor-Generators used to power Model-C Stellarator



(1961) Motor generators used through the 1990's to power many experiments 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.
  - Spitzer was the father of the Hubble Space Telescope. He made the case for a space telescope in a 1946 RAND report.

- 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

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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

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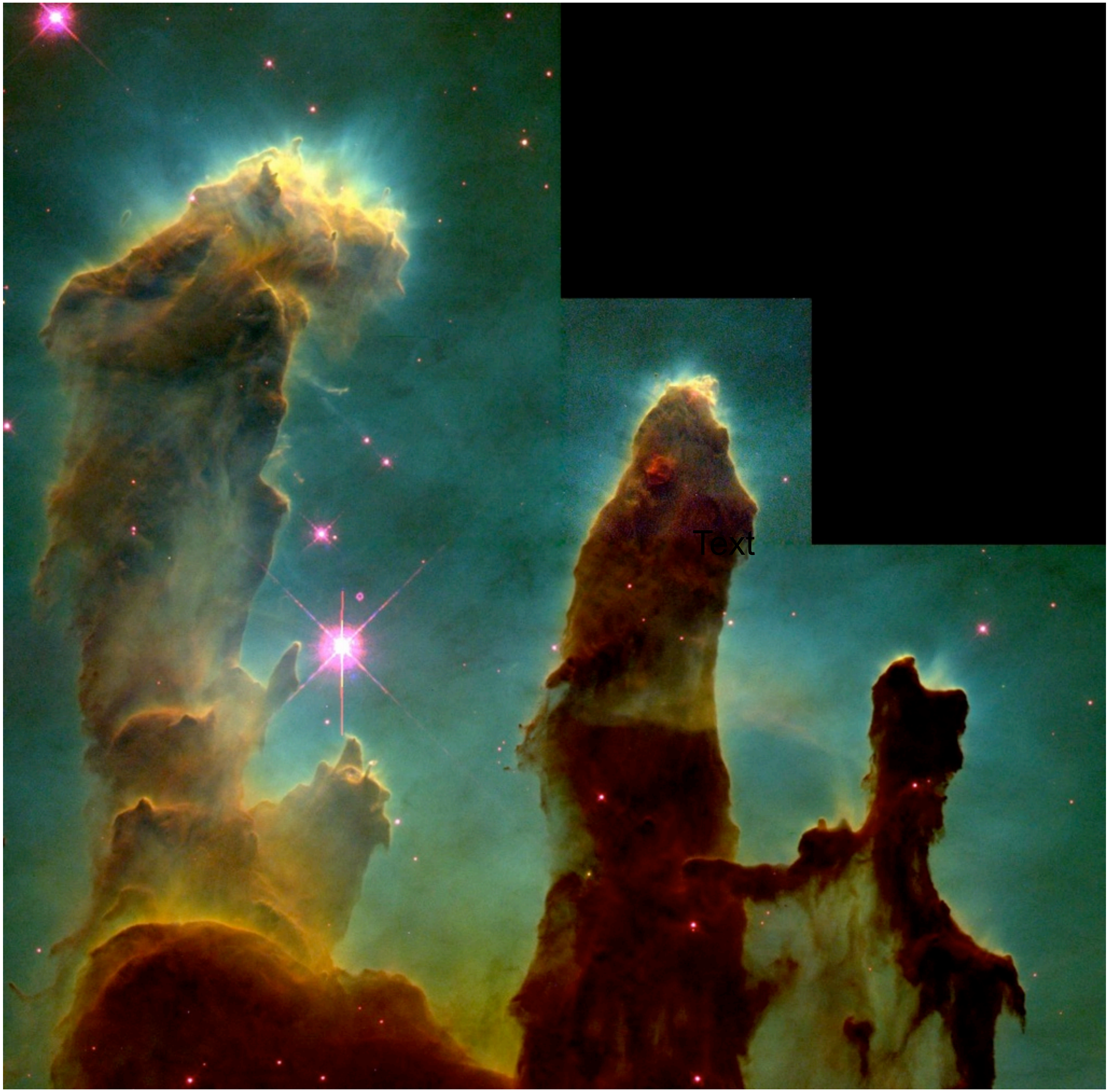
The New York Times
NEW YORK, FRIDAY, DECEMBER 10, 1993
Scientists at Princeton Produce World's Largest Fusion Reaction
Chicago Tribune
Circulation 740,713
2nd fusion test again 'replicates the sun'
The Dallas Morning News
Sunday, December 19, 1993
STAR POWER
Do we have the vision to harness it?
The Star-Ledger
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 County
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
EDITORIALS
Nuclear Fusion's Hopeful Promise
Princeton Plasma Physics lab engineer Doug Loesser kneels in Tokamak Fusion Test Reactor.
Fusion lab clones power of
THE SUN
Circulation 494,057
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 nuclear fusion experiments begin
SCIENCE
Fusion power: The fire finally lights
Princeton team's success seen as a major step but
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

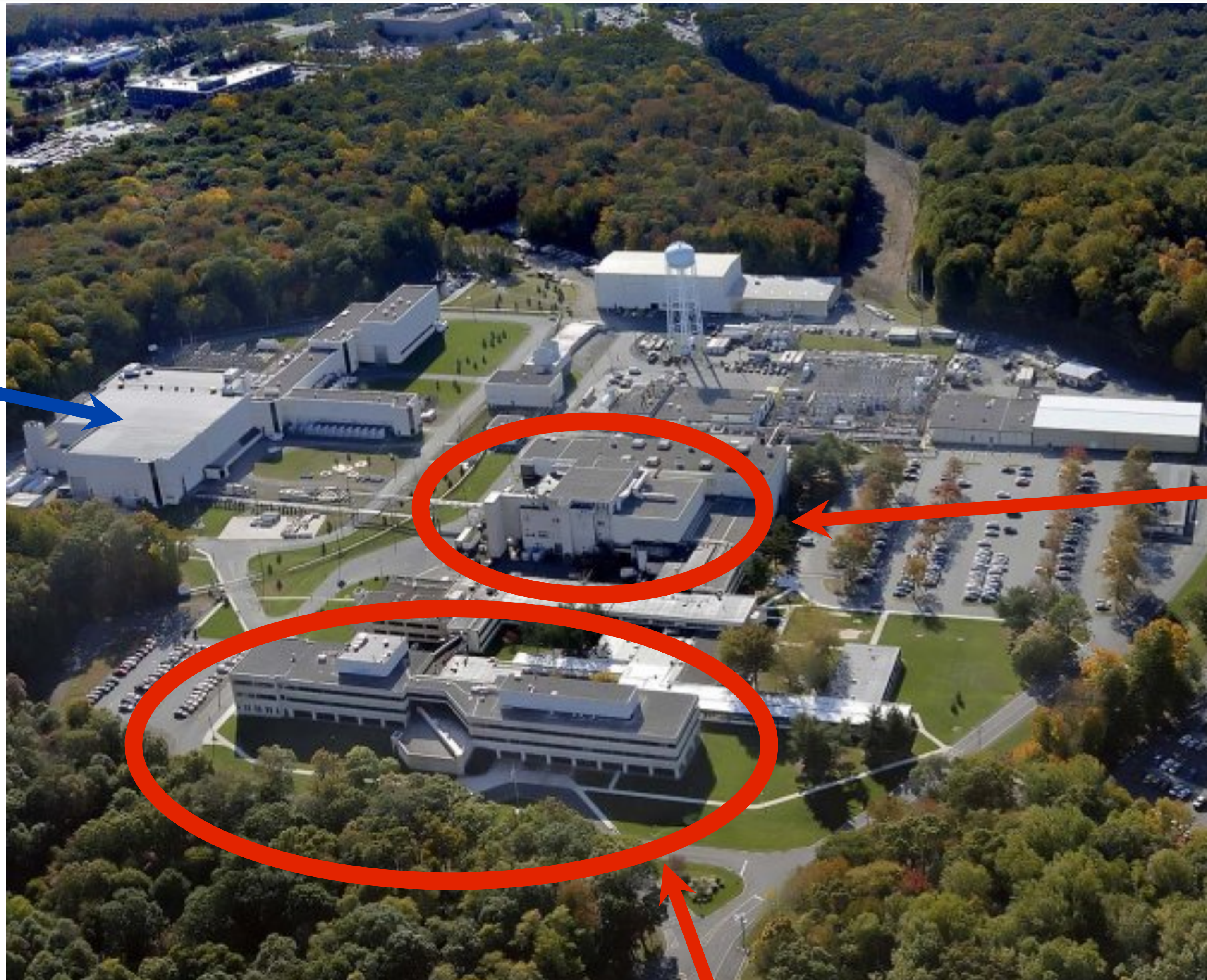


The Eagle Nebula: gas pillars in a star-forming region.

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

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)

2010

Some Stories From Working with Spitzer In the Early Years

Russell Kulsrud

Princeton Plasma Physics Laboratory Colloquium
Dec. 4, 2013

(See separate slides)

Video of a longer talk by Kulsrud, “My Early Years Spent Working with Lyman Spitzer“:
https://mediacentral.princeton.edu/id/1_1kil7s0p

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- The road ahead for fusion:
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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.

Good confinement needed for fusion

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

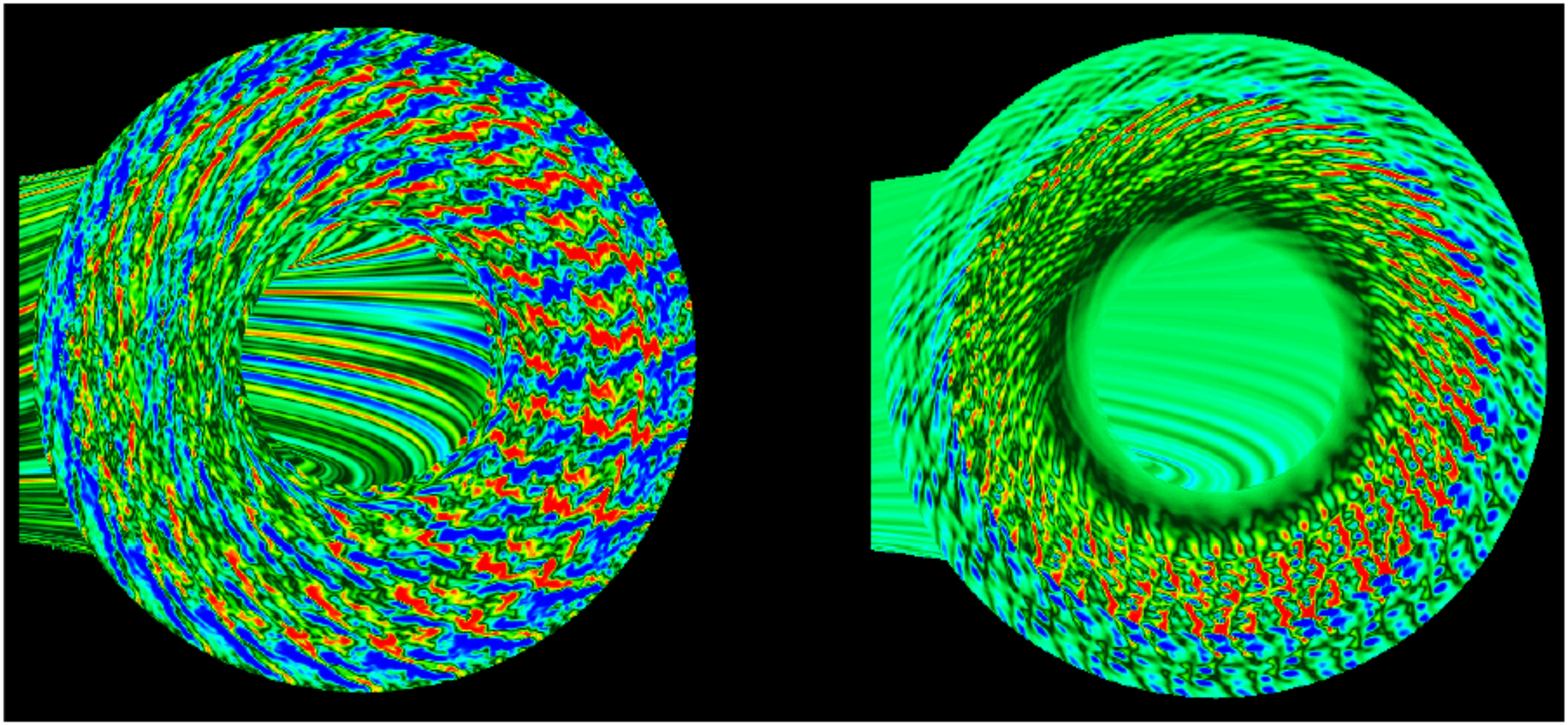
$P_{fusion,\alpha} \sim n^2 \quad \langle \sigma v \rangle$
V,
and $\langle \sigma v \rangle \sim T^2$

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

- 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% or more.

Sheared ExB Flows can reduce turbulence

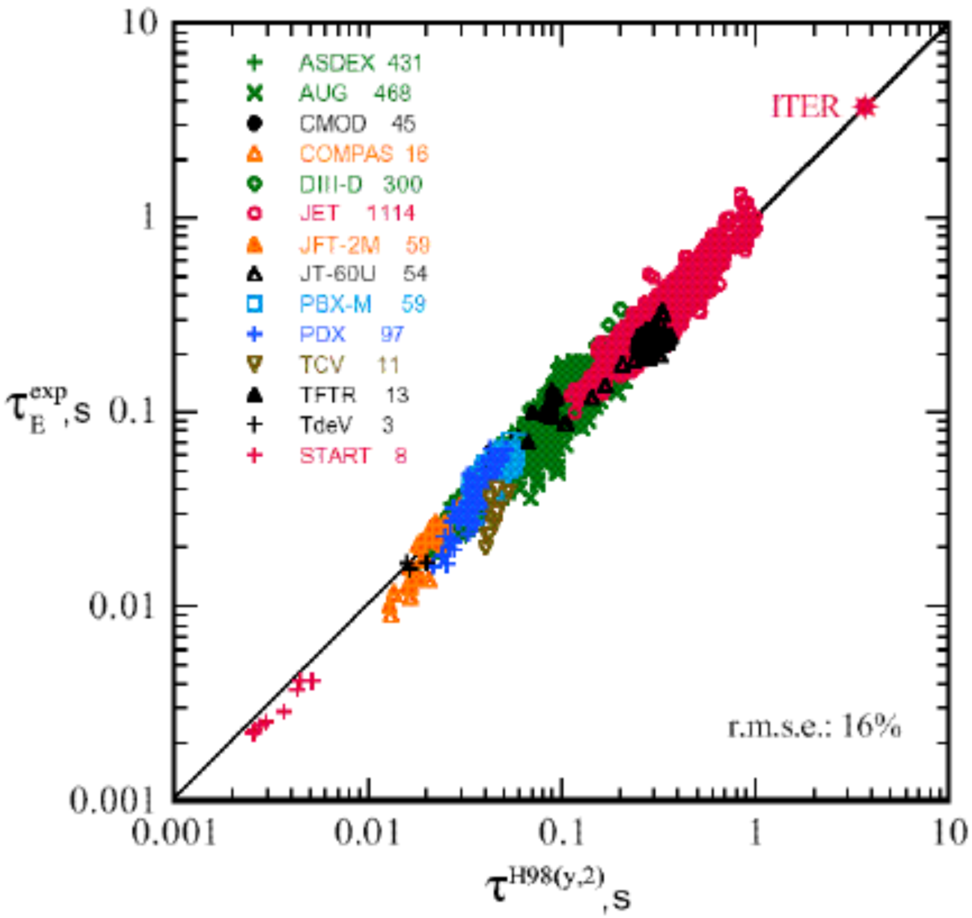


Snapshot of density fluctuations driven by small-scale drift-wave turbulence
(small amplitude fluctuations, $\delta n/n_0 \sim 1\%$)

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.

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

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

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

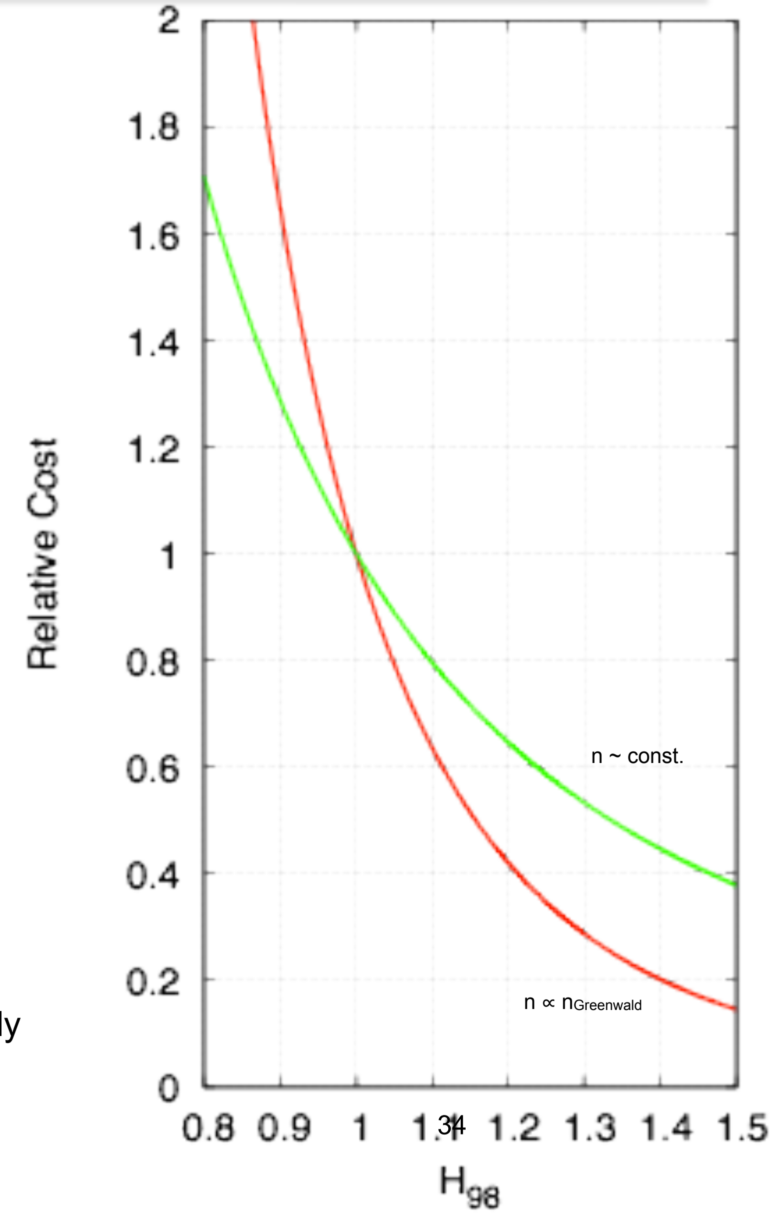
Well known that improving confinement factor H & beta limit can significantly lower Cost of Electricity (COE $/kWhe) at fixed power output.

If one considers lower power devices (but with fixed fusion gain Q), H has even stronger impact on construction cost, because higher H allows smaller machine to achieve same Q. (I.e., what is the smallest pilot plant possible? The COE $/kWhe optimizes at larger device sizes.)

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 designed with conservative 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.



For an improved version of this plot, see
http://w3.pppl.gov/~hammett/talks/2014/Hammett-2014-US-Japan-DG.pdf

Interesting Ideas To Improve Fusion

* Liquid metal (lithium, tin) films or flows 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?

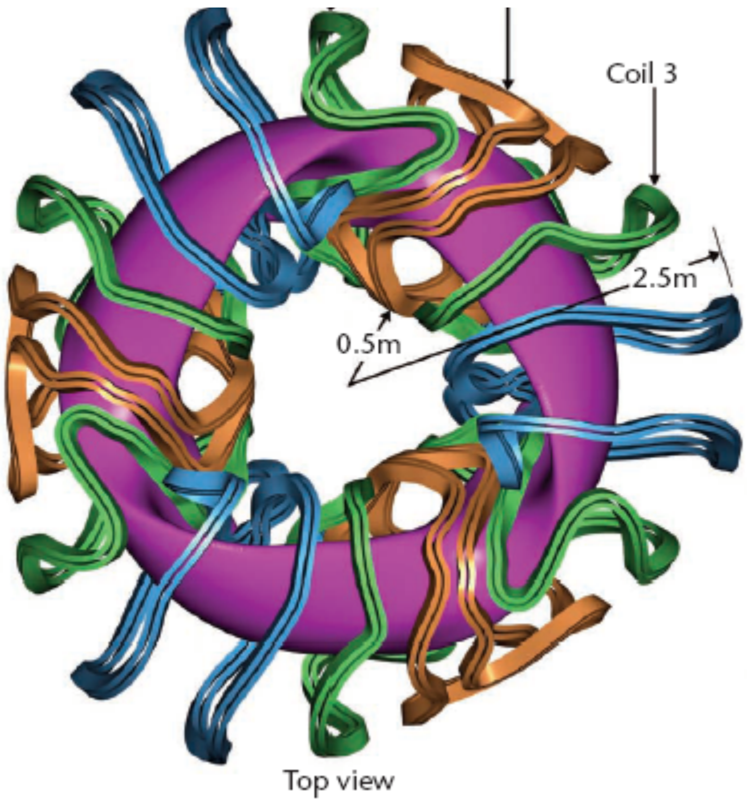
* Tokamaks spontaneously spin: can reduce turbulence and improve MHD stability. Can we enhance this with up-down-asymmetric tokamaks or non-stellarator-symmetric stellarators with quasi-toroidal symmetry?

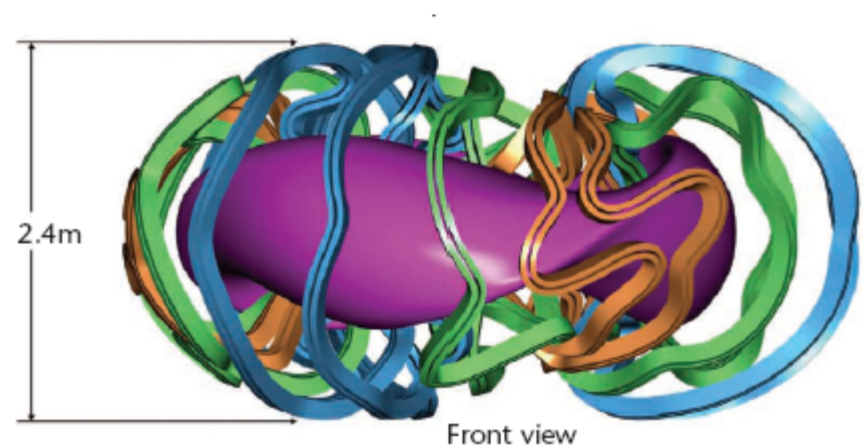
* Many possible stellarator designs, room for further optimization: Quasi-symmetry / quasi-omnigenity improvements discovered relatively recently, after 40 years of fusion research. Stellarators fix disruptions, steady-state, density limit.

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

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 $\boldsymbol{B}$ exactly symmetric toroidally, $|\boldsymbol{B}|$ symmetric in field-aligned coordinates sufficient to be as good as tokamak.
- 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

Lyman Spitzer Jr.'s 100th: Founding PPPL & Pioneering Work in Fusion Energy

Outline:

- Pictorial tour: from Spitzer's early days, the Model-C stellarator (1960's), to TFTR's 10 megawatts of fusion & the Hubble Space Telescope (Dec. 9-10, 1993)

- Russell Kulsrud: A few personal reflections on early days working with Lyman Spitzer.

- The road ahead for fusion:
  - Interesting ideas being pursued in fusion, to improve confinement & reduce the cost of power plants

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- Robin Herman, "Fusion: the search for endless energy", Cambridge University Press, 1990
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- A. Bhattacharjee, G.M. Schreiber, & J. B. Taylor, "Geometric phase, rotational transforms, and adiabatic invariants in toroidal magnetic fields", Phys. Fluids B 4, 2737 (1992). (Points out that the magnetic twist in Spitzer's stellarator concept is the first realization of the geometrical Berry phase of quantum & classical dynamics.
- http://www.amnh.org/education/resources/rfl/web/essaybooks/cosmic/p_spitzer.html
- 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

Other Historical Tidbits

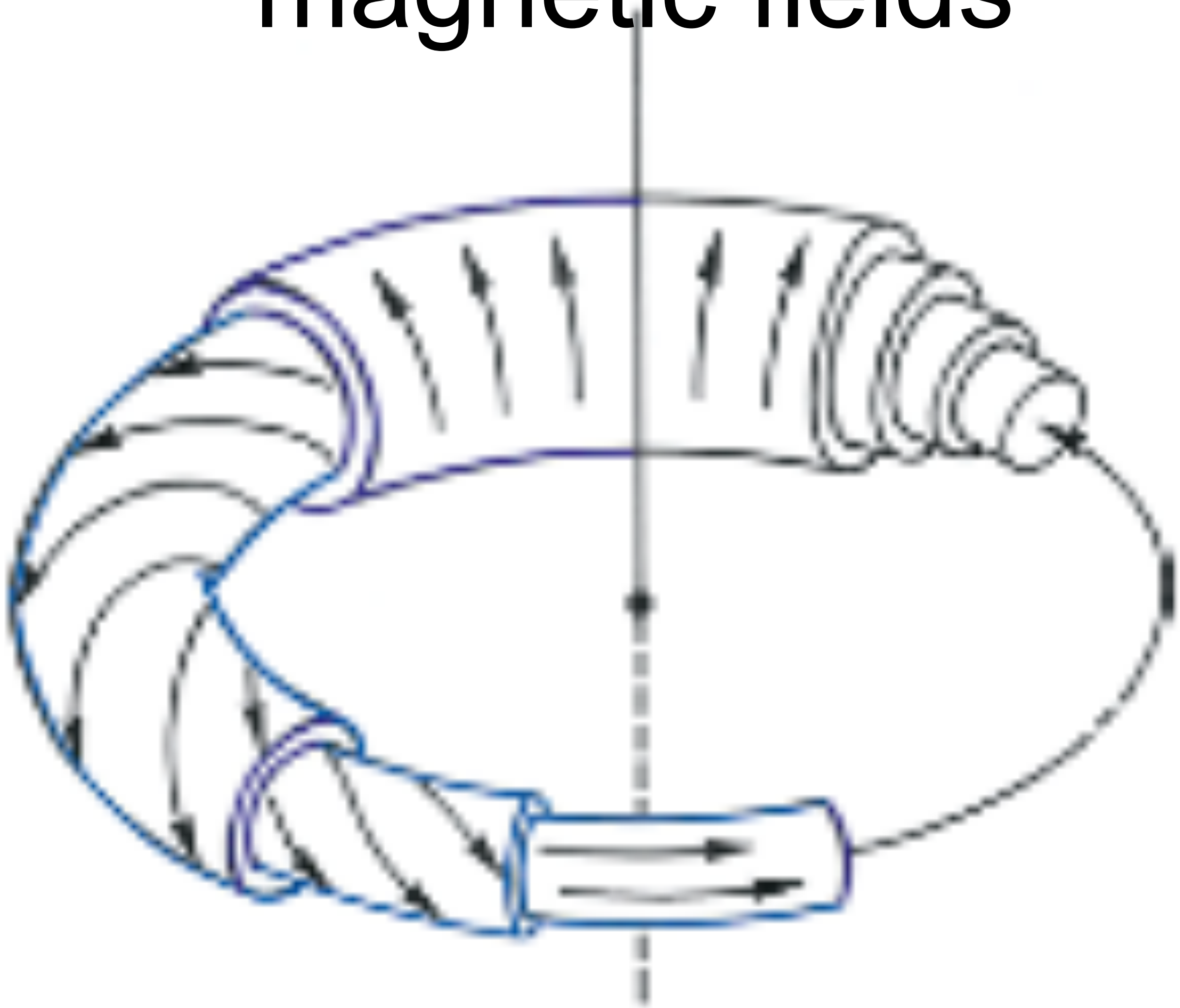
- Right after WWII, there were discussions at LANL of what to do next, including discussions of the possibility of fusion for peaceful energy source. In those discussions, Fermi gave a proof that one can't use a simple torus. One record of this is in classified British reports summarizing those discussions, as Steve Cowley has stated. This is 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.
- Spitzer hired Martin Kruskal in 1951. One of the first things he worked out was the 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 around the plasma without a current in the plasma? Later he thought it was brilliant. He said it seemed intuitively better to rely on magnetic field from coils that are bolted the floor and won't move, as they are in stellarators, instead of relying on currents flowing in a plasma that can move (like in tokamaks), and are thus susceptible 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

- The Model D Stellarator reactor study was called, "The Problems of a Stellarator as a Useful Power Source," was completed in June 1954. http://findingaids.princeton.edu/collections/PPL001/c0015
- 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 electric (in 1954 $, or $1790/kWe in 2013 $), as reported on p. 260 of the report and 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 (or actually p. 47):
  - Copper coils. 75% beta in straight sections and 25% beta in curved sections. "Uncomfortably large---over 500 feet in length" (the length around the figure-8 tube). But she goes on to say "Princeton scientists were not overly concerned with the size and cost of the Model D. They reasoned that fusion reactors were still in the future; by the time they were ready for commercial use, it as likely that 5,000 megawatts would be an acceptable unit size..." (From my perspective, we've made a lot of advances since then and see how to make a much smaller device.)
  - and http://en.wikipedia.org/wiki/Project_Sherwood
- There is an interesting news film made by the AEC about the 1958 Atoms for Peace Conference in Geneva: http://openvault.wgbh.org/catalog/wpna-434-064-atoms-for-peace-geneva-1958-part-2-of-2 There was a working fission reactor exhibited there. Fusion energy is talked about from 4:25 to 6:46. Several fusion concept devices were actually operated. Princeton apparently showed the B-2 stellarator, along with a SIM-8 and a racetrack stellarator, which had helical coils in the u-bend sections to give a rotational transform. (They used an e-beam in these devices to show that electrons were confined when there was a rotational transform, but not without it.) This latter device is on display in the PPPL auditorium. [The narrator in the AEC film above pronounces AEC chairman Lewis Strauss as "Straws", as also stated in his wikipedia page.]

CPI = $230 in 2013, $26.9 in 1954 , http://www.bls.gov/cpi/tables.htm, ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt

Torus with sheared helical magnetic fields



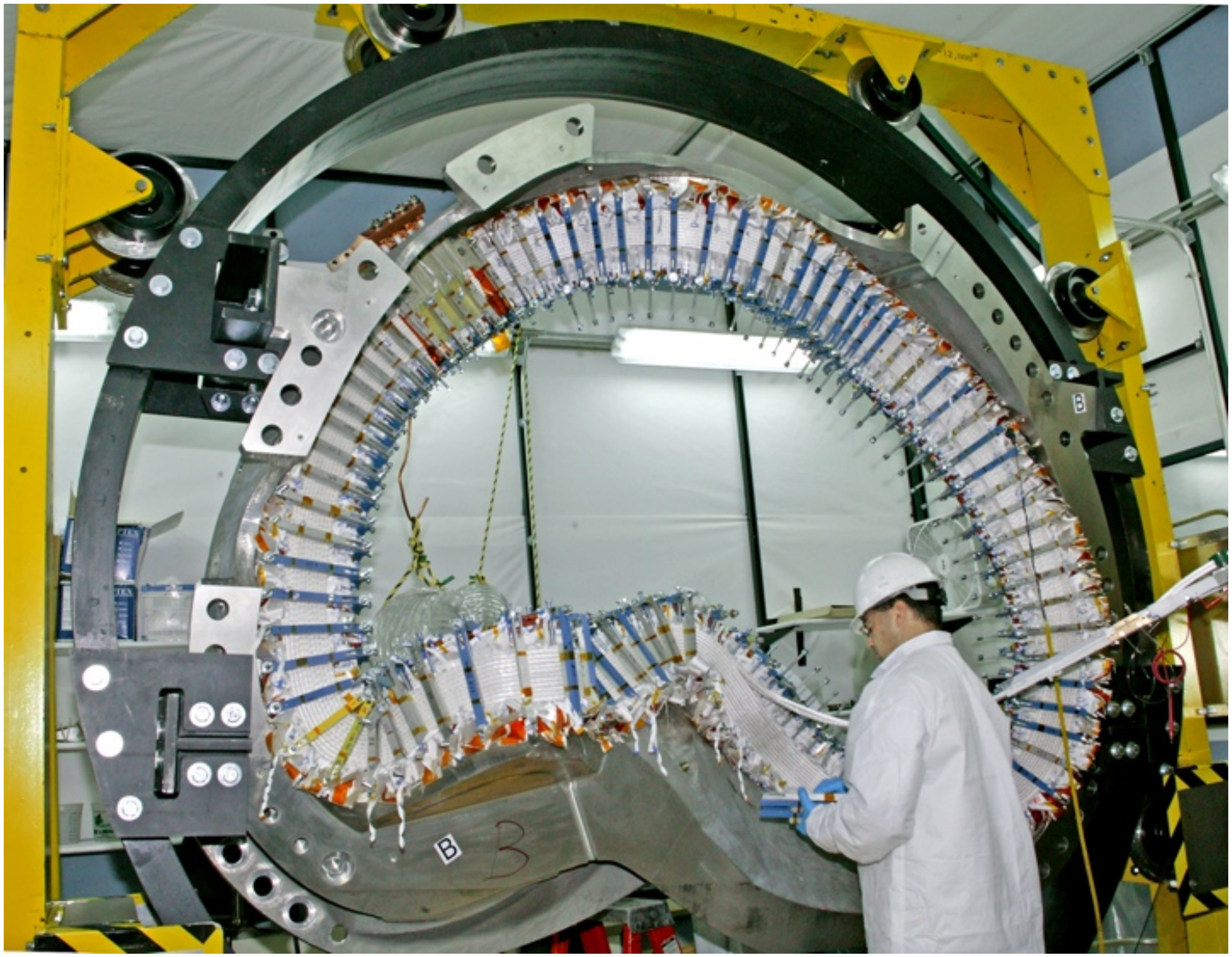
Extreme example, magnetic field is mostly in toroidal direction in standard tokamak.

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

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

Technician hand winding stellarator coils on large rotating metal forms

contact: Jim Chrzanowski or Hutch Neilsen



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)

- 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

To Do:

* Could add figure about Teller's critique at the famous "Gun Club" meeting, about the interchange instability, that trying to confine a plasma with a magnetic field was like trying to confine gas with rubber bands. Could add figures explaining the solution that Spitzer eventually came up with, based on interactions with Kulsrud, Frieman, Kruskal, and Bernstein, of "ell = 3" (l=3) helical coils, which introduce shear in to the magnetic field.

* Steve Cowley's talk at the Spitzer 100th conference had very good slides that could be borrowed from.

• What I learned from multiple comments by speakers at the Spitzer 100th conference in Peyton Hall: Spitzer was a very polite gentleman. He wouldn't directly say that a speaker was wrong, but would say things like: I'm sure you must be right, you've thought about this more than I have, but I would have done the problem this other way.... If he says "that's very interesting", that was his polite way of trying to change the subject or dismiss something if he's not interested (i.e., thinks it unimportant or incorrect).

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