NOVATRON

A survey of magnetic configurations for plasma confinement

Eli Parke (they/them)

Introduction to Fusion Energy and Plasma Physics
SULI 2026 (June 5)

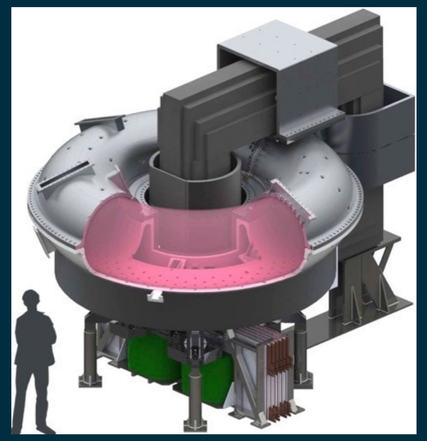
My background

James R. Macdonald Laboratory
Atomic, Molecular & Optical Physics
at Kansas State University

Undergraduate at Kansas State University
Atomic, Molecular, Optics research
(2003 – 2007)

tae

Scientist at TAE Technologies, Inc.
(2018 – 2026)
Laser diagnostics on C-2W



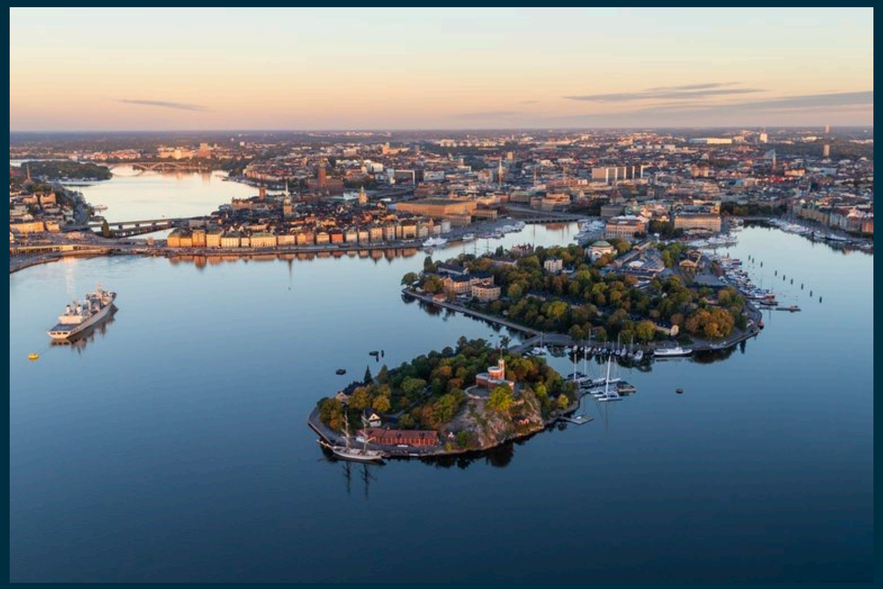
UCLA

Graduate (2007 – 2014) and
postdoc research (2014 – 2017)
on the Madison Symmetric Torus at
University of Wisconsin-Madison

And now…

Scientist at Novatron Fusion Group AB
(May 2026 – present)

Stockholm is an archipelago with over 30,000 islands!



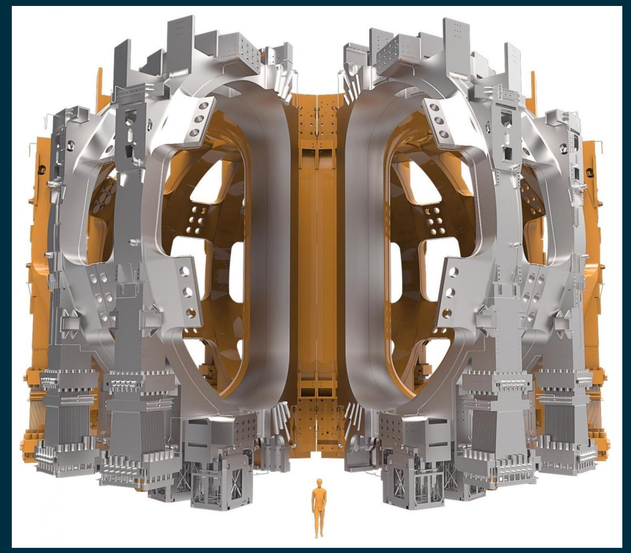
https://www.visitstockholm.com/

https://sweden.se/life/society/key-facts-about-sweden

https://emmasjulblogg.se/kardemummabullar/

How do researchers confine fusion plasmas?

- Magnets
  - You've already heard about magnetic confinement on tokamaks, and you'll hear about stellarators
- Lasers
  - You'll also hear about inertial confinement at facilities like NIF
- Pulsed power
  - You'll hear more about pulsed experiments like the Z-machine
- But there are a wide variety of configurations associated with each of these approaches – historically, many were lumped together under the label "alternate"



ITER Toroidal
Magnetic Field Coils
www.iter.org

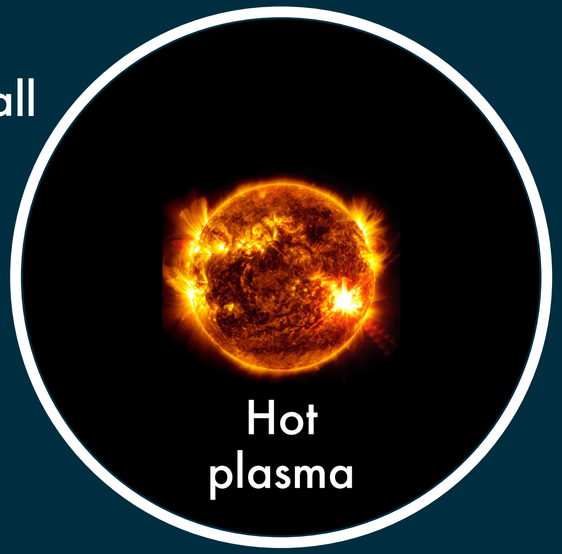
The choice of configuration has important consequences

- Lawson criterion – choice of configuration affects how sufficient power output is achieved

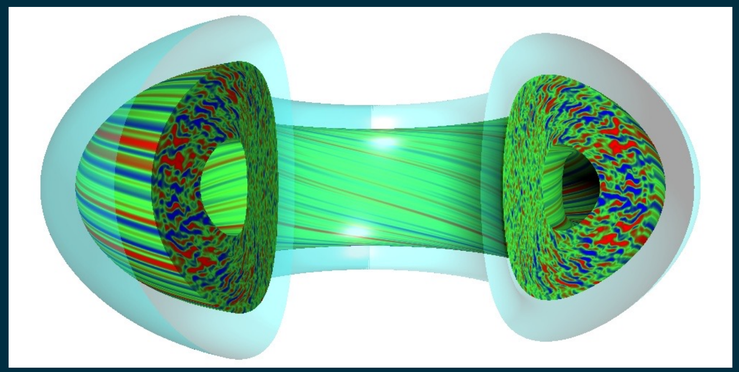
$$nT\tau$$

- Fusion conditions necessitate significant gradients, which are a source of free energy that can drive instabilities
- The structure of the plasma (magnetic fields, pressure, current, etc.) plays a key role in determining the important physics that researchers must address

$$\nabla P, \nabla J, \nabla B$$



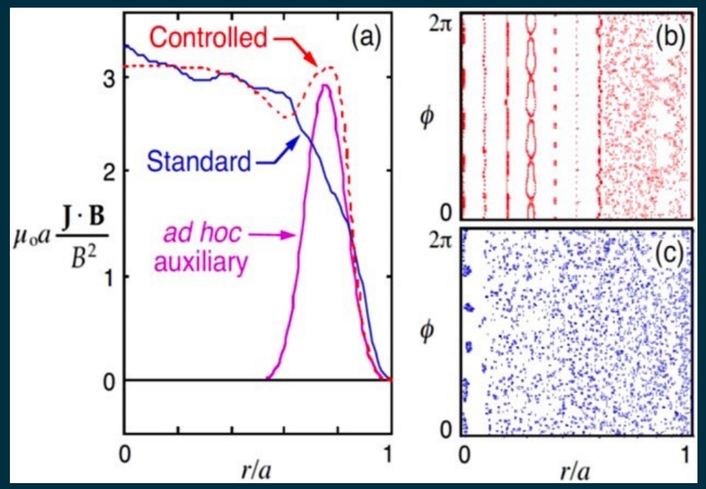
NASA SDO
https://science.nasa.gov/science-research/heliophysics/how-nasa-tracked-the-most-intense-solar-storm-in-decades



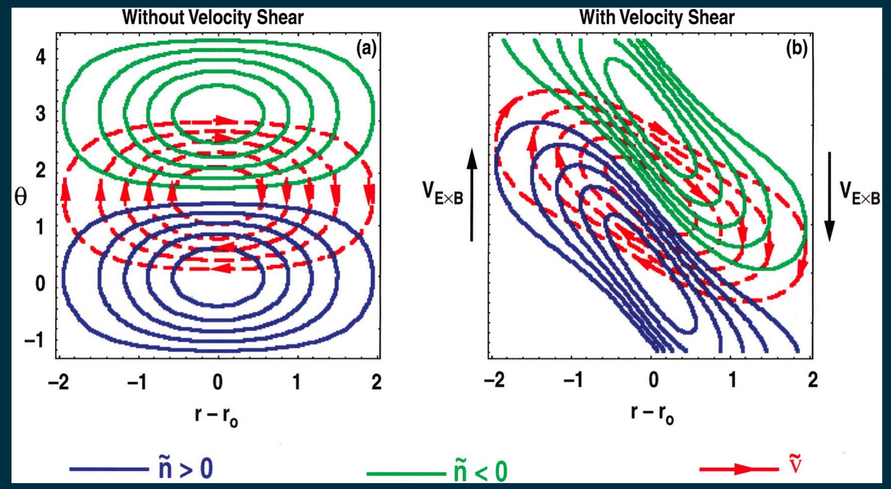
GRYO turbulence simulations
Courtesy of Greg Hammett
w3.pppl.gov/~hammett/viz/viz.html

There are many approaches to stabilization

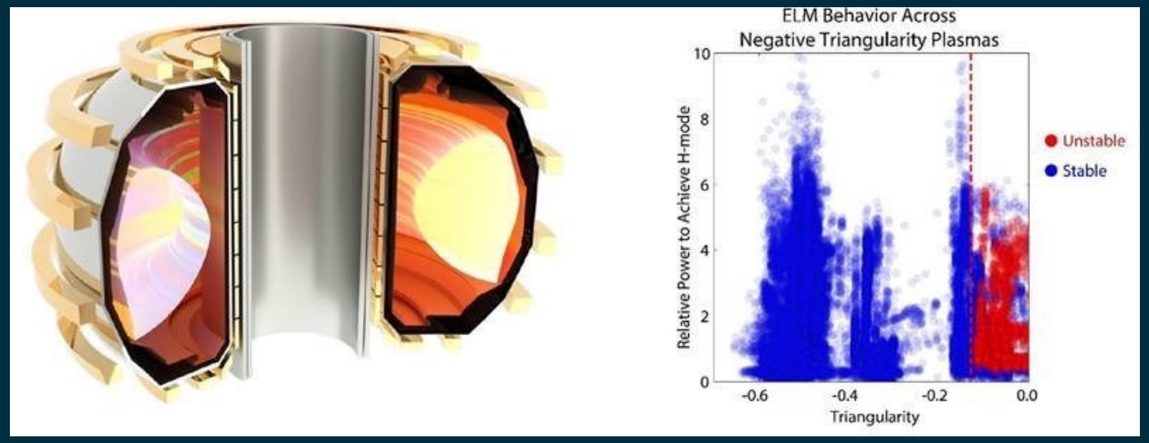
- Profile control
- Flow shear
- Energetic particles
- Field shaping
- Many more:
  Other instabilities
  Conducting shell
  Etc.



L. Marrelli, Nucl. Fusion 61, 023001 (2021)



K. H. Burrell, Phys. Plasmas 4, 1499 (1997)



A. O. Nelson, Phys. Rev. Lett. 131, 195101 (2023)

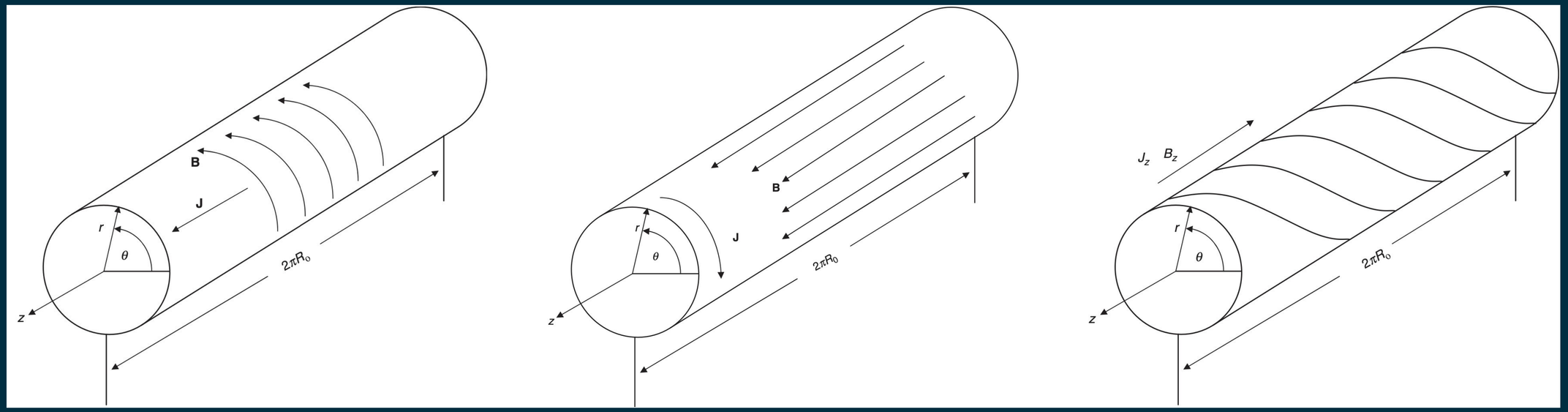
Outline

- Linear machines
  - Pinches
  - Mirrors
  - Field-reversed mirrors / FRCs
- Toroidal configurations
  - Reversed-field pinches
  - Spheromaks
  - Levitated dipoles

Pinches were an early pulsed power approach

- Several configurations of linear pinches – names are derived from direction of current flow
- Current and magnetic field are perpendicular: JxB force causes radial “pinch” effect
- Axial field lines of the theta and screw pinches provide stability but lead to higher end-losses

Jeffrey Freidberg
Ideal MHD
(2007)



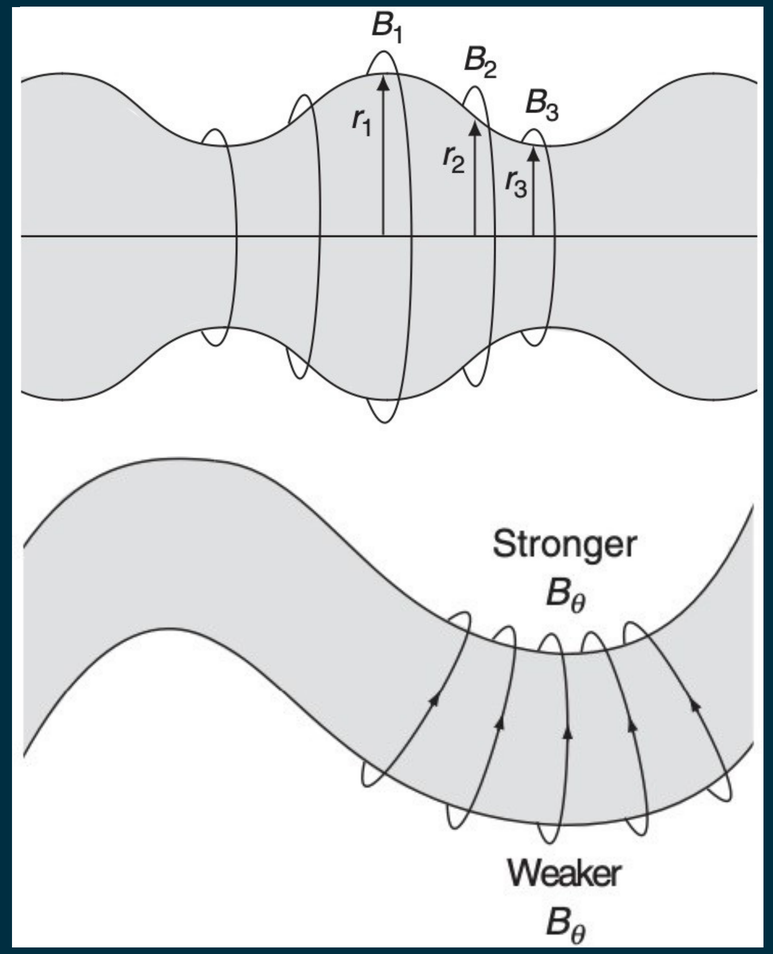
Z-pinch

Theta-pinch

Screw pinch

Z-pinches are susceptible to MHD instabilities

- Interchange Modes (also sausage or m=0)
  Perturbation in radius of plasma column
  Pressure driven
- Kink Modes (also m=1)
  Perturbation in displacement from axis
  Current driven
- Perturbations grow rapidly and degrade the plasma



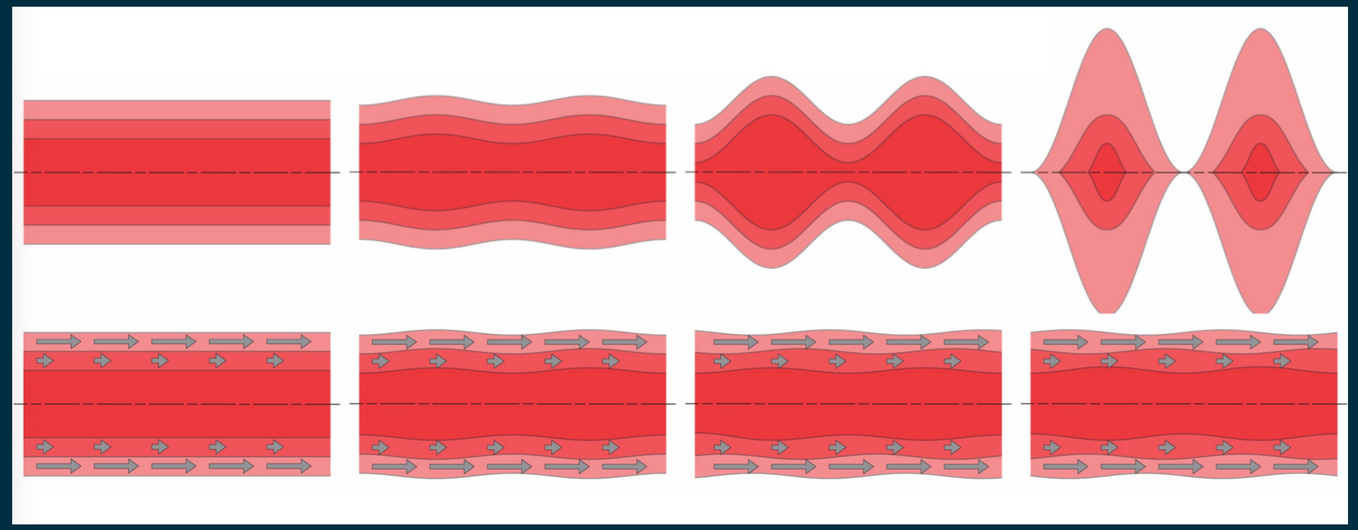
Interchange mode

Kink mode

Jeffrey Freidberg, Ideal MHD (2007)

A variety of techniques are used for stabilization

- Axial field lines stabilize against interchange and kink modes but sacrifice confinement
- Close conducting boundary/wall can stabilize these modes
- Pressure profile control stabilizes interchange modes but not kink modes
- Flow shear stabilization is a newer technique for z-pinches $\frac{dv_z}{dr} \neq 0$



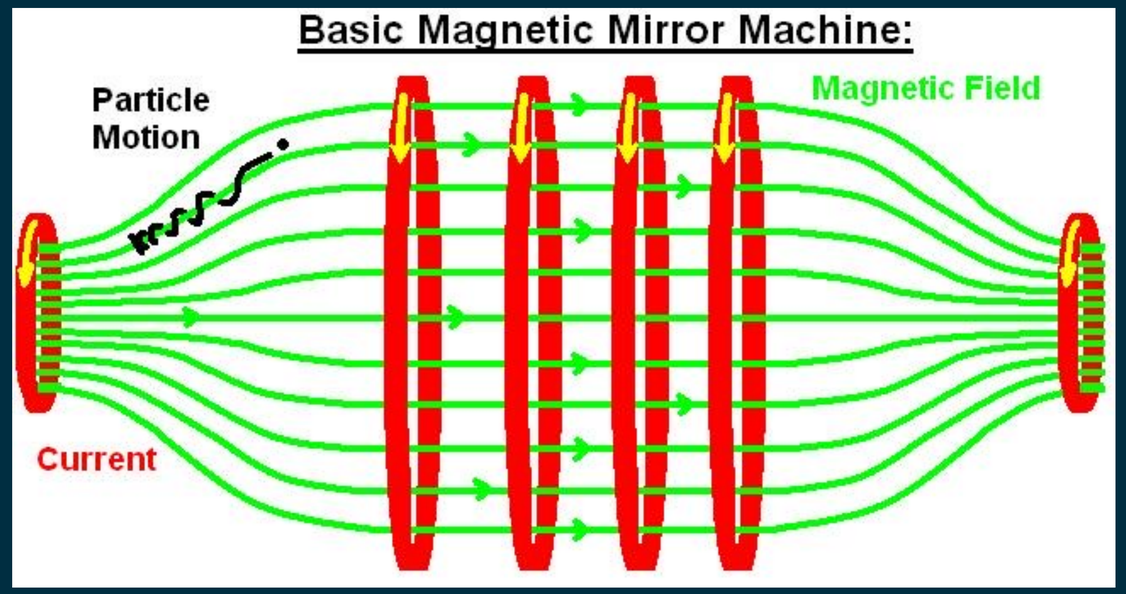
Courtesy of Derek Sutherland
SULI 2023
suli.pppl.gov/2023/course

Magnetic mirrors can trap particles

- Charged particles in a uniform magnetic field have helical trajectories
- Magnetic bottle – varying the strength of the magnetic field axially produces a radial field component that reflects particles
- Conservation of energy and the magnetic moment of the particle leads to mirroring

$$E = \frac{1}{2}mv_{\parallel}^2 + \frac{1}{2}mv_{\perp}^2 \qquad \mu = \frac{mv_{\perp}^2}{2B}$$

- Magnetic bottle is leaky – particles can escape through the ends



Courtesy of Matthew Moynihan
en.wikipedia.org/wiki/Magnetic_mirror

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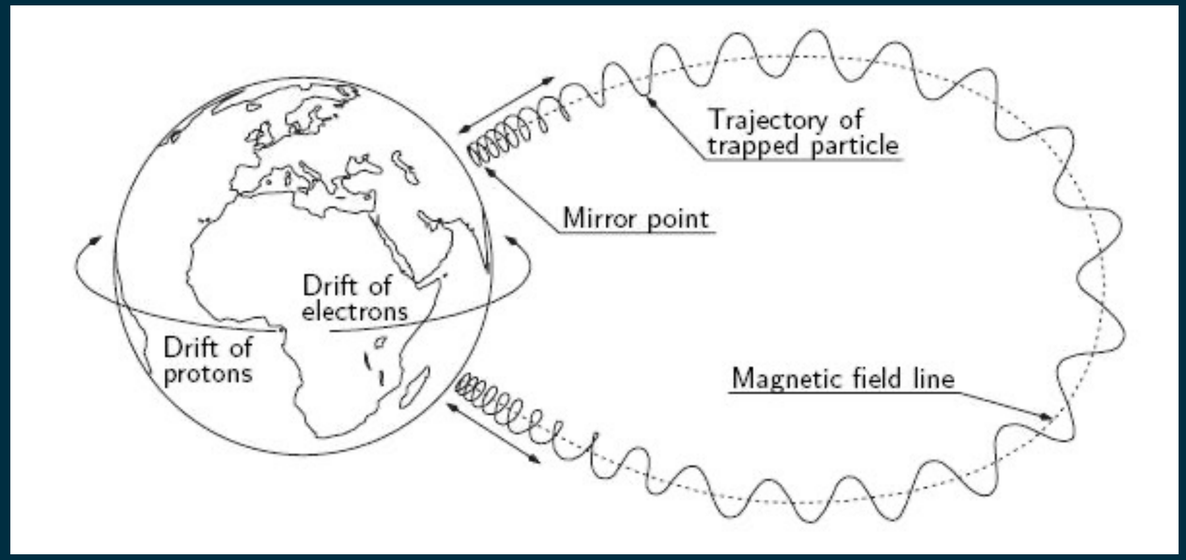
Mirror phenomena can occur in many plasmas!



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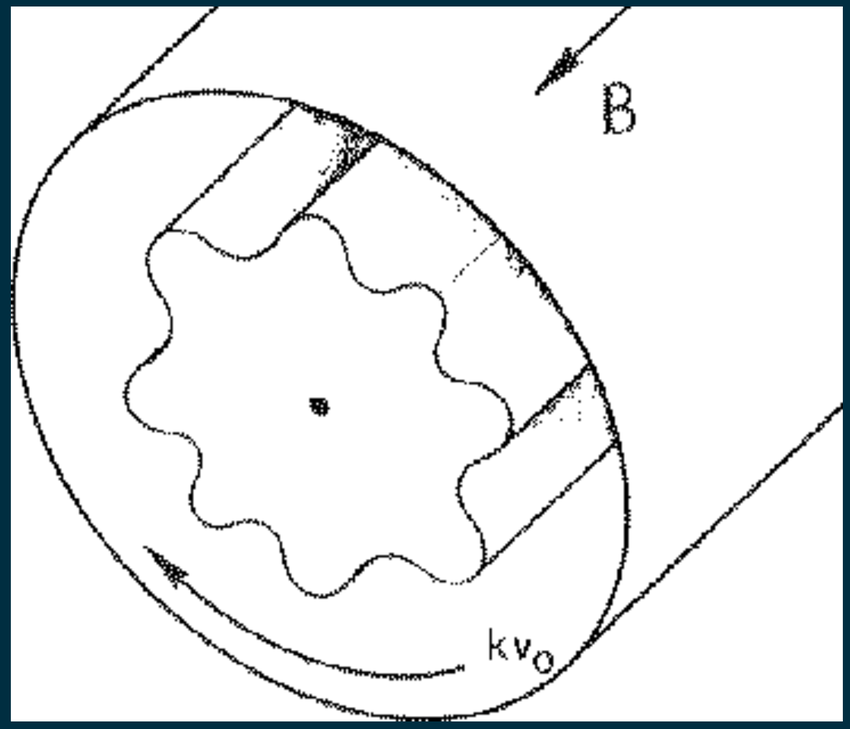
Flute instabilities plagued early mirror machines

- Instabilities can be driven by pressure gradients in regions with unfavorable magnetic field curvature
- In the mirror machine these are known as flute instabilities – they are interchange modes like the instabilities seen earlier on Z-pinches and are observed in many devices and astrophysical plasmas
- Analogous to hydrodynamic instability associated with a denser fluid on top of a less dense fluid



Francis Chen
Introduction to Plasma Physics and Controlled Fusion (1974)

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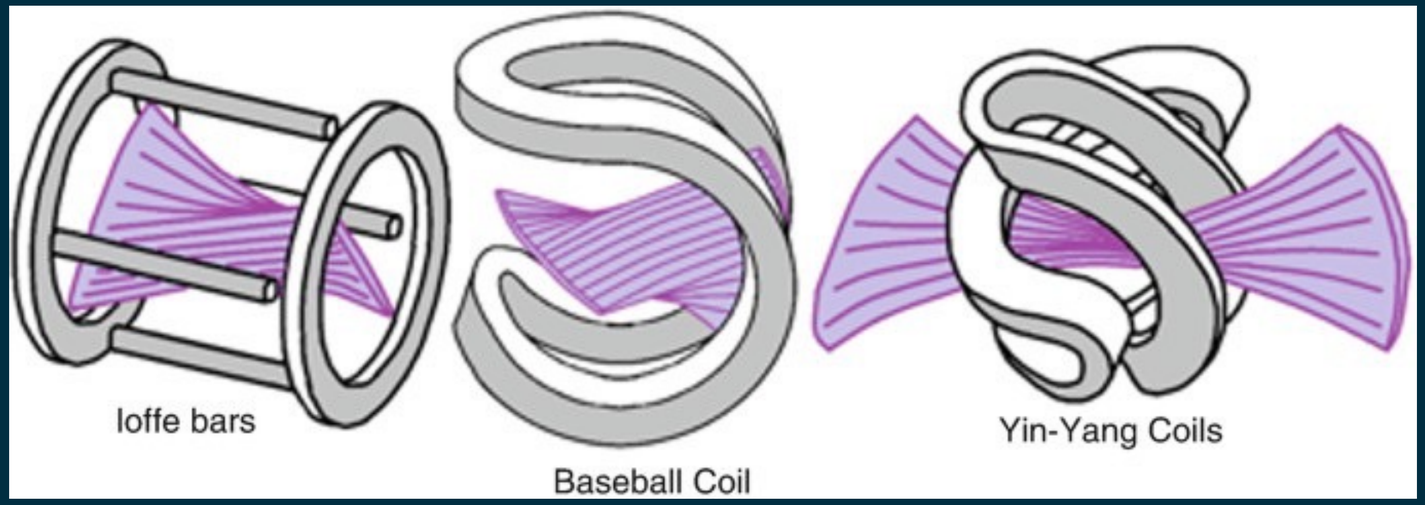
- Analogous to hydrodynamic instability associated with a denser fluid on top of a less dense fluid
- Could be stabilized by complicated magnet configurations

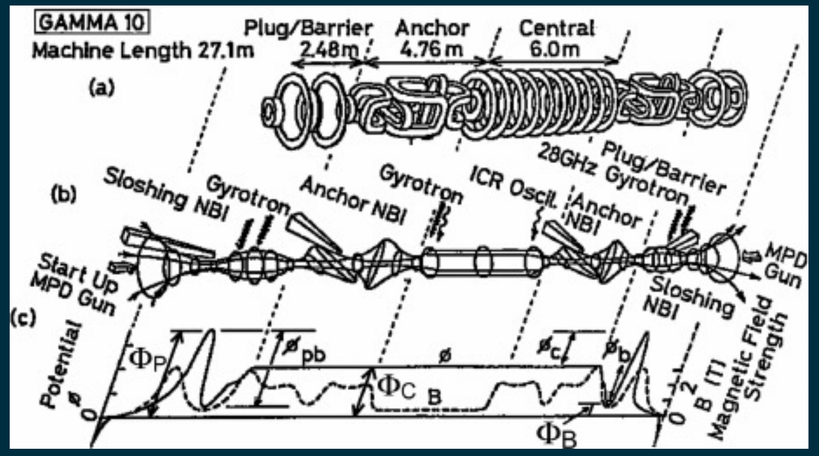
Matthew Moynihan and Alfred B. Bortz
Fusion's Promise, 2023



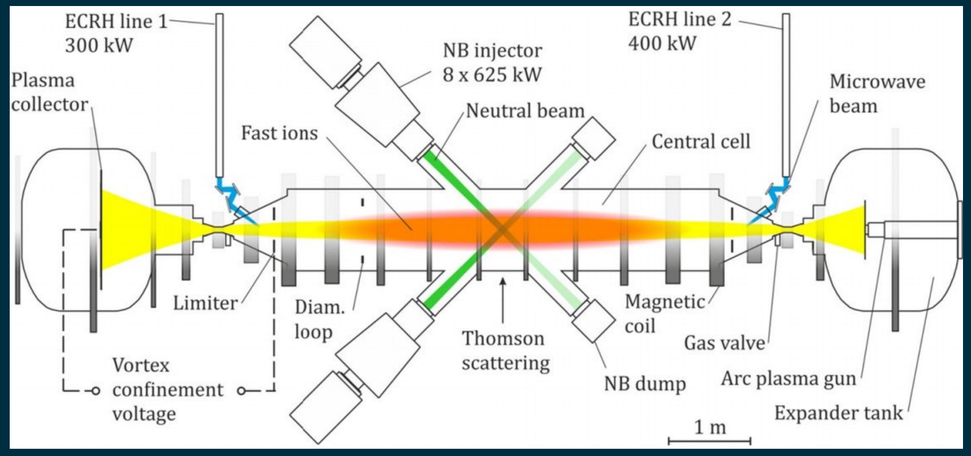
Mirror research never stopped

- With the cancellation of MFTF-B in 1986, the US mirror program was decimated but research continued, mainly in Russia and Japan
- The GAMMA 10 device in Japan continued to demonstrate tandem mirror techniques
- The Gas Dynamic Trap in Russia explored a novel approach with isotropic, Maxwellian mirror plasmas

GAMMA 10



T. Imai, Fusion Sci. Technol. 59, 1 (2011)

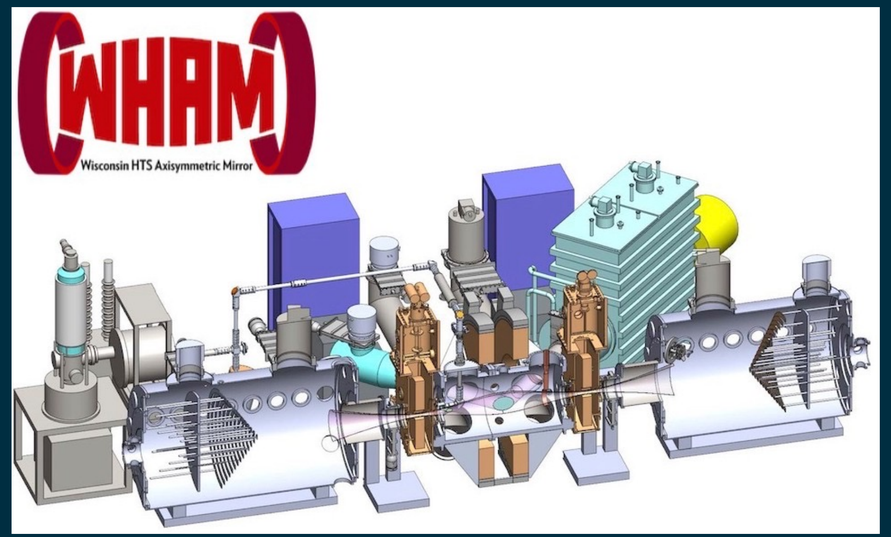


Courtesy of Peter Bagryansky
en.wikipedia.org/wiki/Gas_Dynamic_Trap

Gas Dynamic Trap

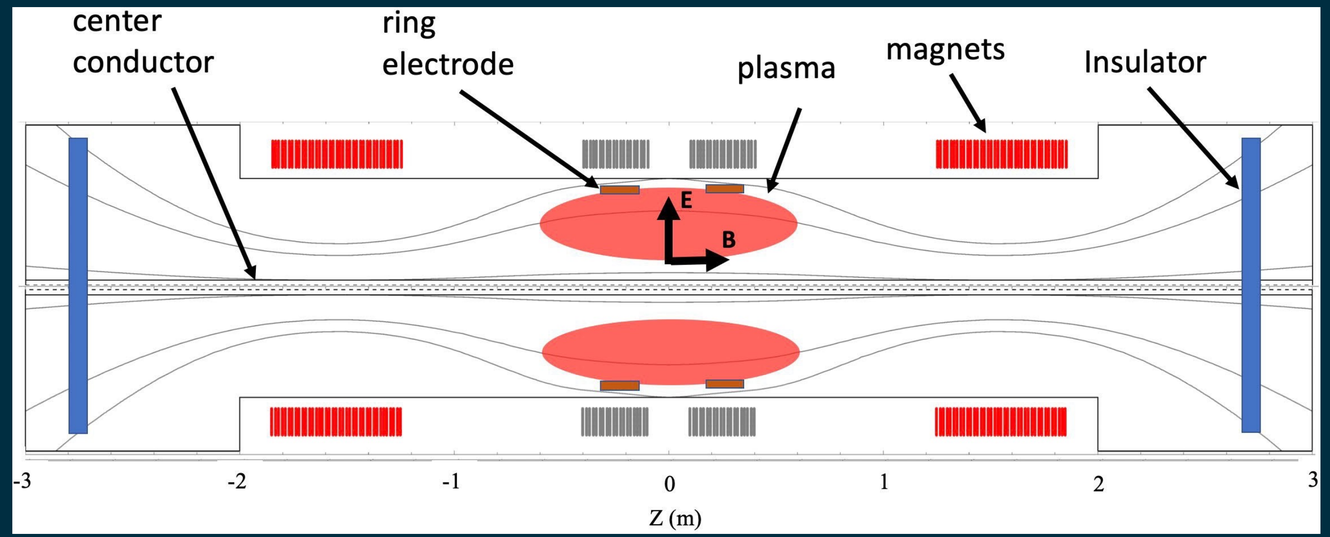
Mirror machines have seen renewed interest

- More recent advances have provided alternative methods for improving mirror performance
- Supersonic plasma rotation with high-voltage biasing
- High temperature superconducting magnets



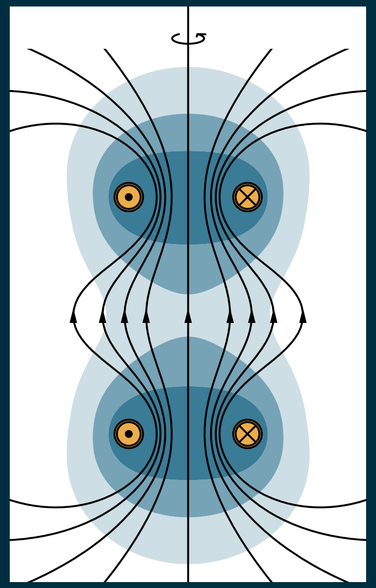
Wisconsin HTS Axisymmetric Mirror
wippl.wisc.edu/wisconsin-hts-axisymmetric-mirror/

Centrifugal Mirror Fusion Experiment
Courtesy of C. A. Romero-Talamás

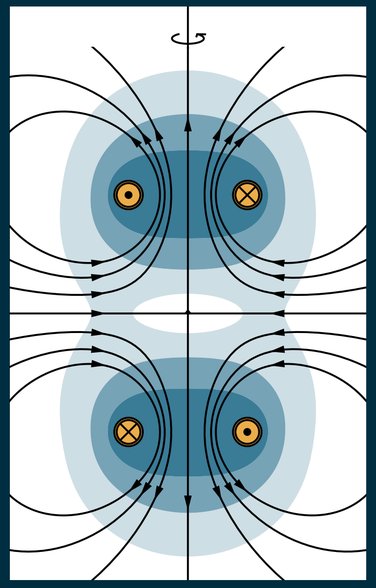


The Novatron combines mirror and cusp designs

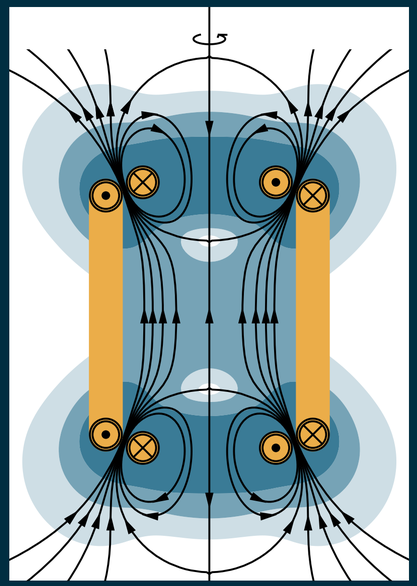
- Classical mirror – good single particle confinement, poor interchange stability
- Biconic cusp – good MHD stability, poor particle confinement
- Novatron – combines stability of cusp with confinement of classical mirror



Mirror



Cusp



Novatron

Novatrons show improved stability in simulations

- Classical mirror configuration for N1 device quickly exhibits interchange instability in simulations
- Simulations of Novatron field configuration demonstrate stability to interchange, density profiles are wider and hollow

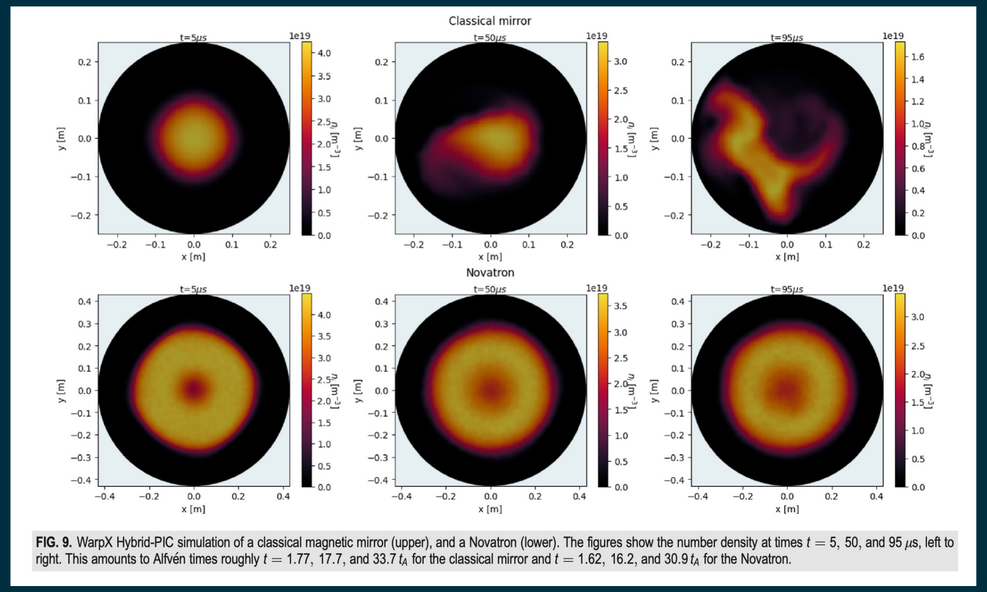


FIG. 9. WarpX Hybrid-PIC simulation of a classical magnetic mirror (upper), and a Novatron (lower). The figures show the number density at times $t = 5$, 50, and 95 μs, left to right. This amounts to Alfvén times roughly $t = 1.77$, 17.7, and 33.7 t_A for the classical mirror and $t = 1.62$, 16.2, and 30.9 t_A for the Novatron.

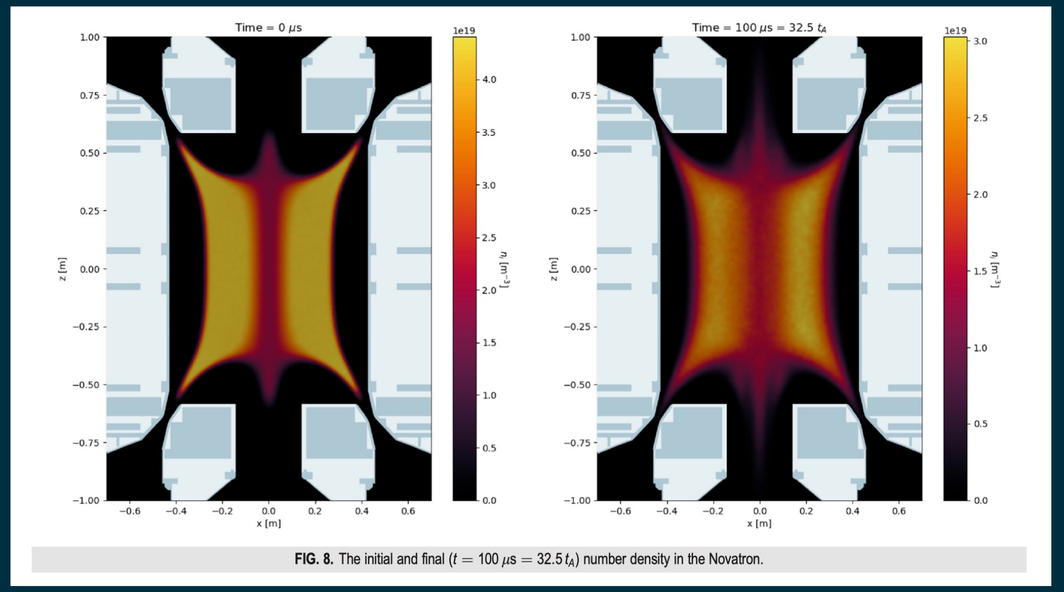
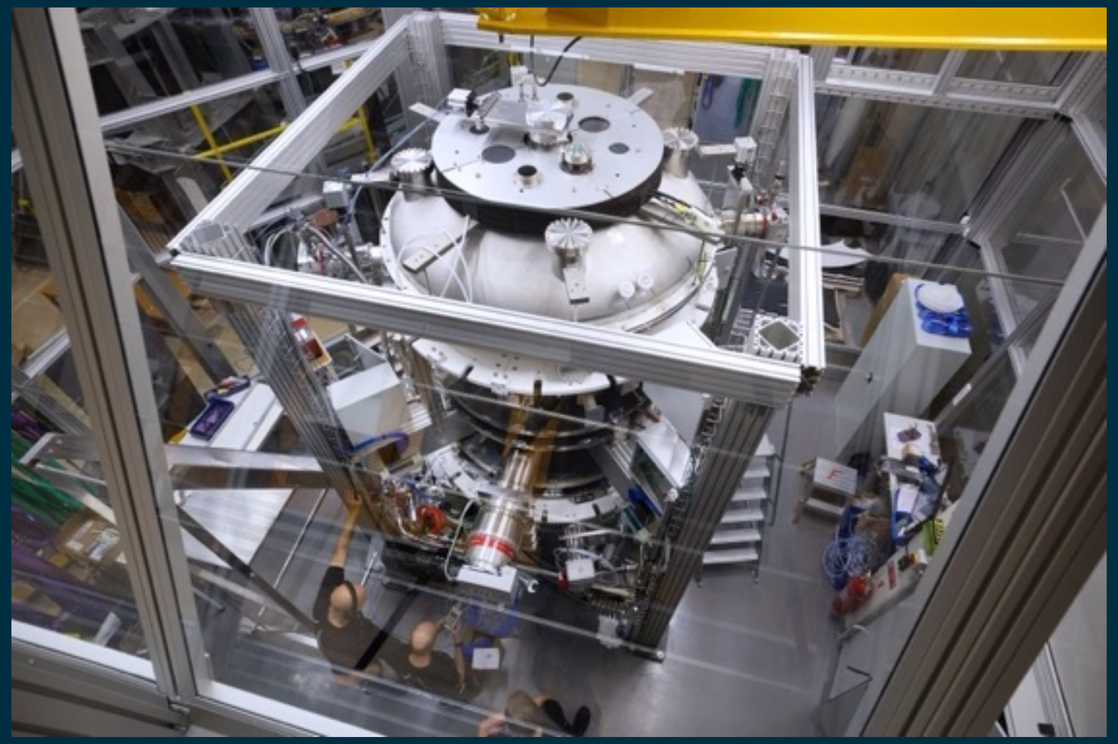


FIG. 8. The initial and final ($t = 100\ \mu s = 32.5\, t_A$) number density in the Novatron.

K. Lindvall, Phys. Plasmas 32, 072509 (2025)

N1 experiment aims to validate stability predictions

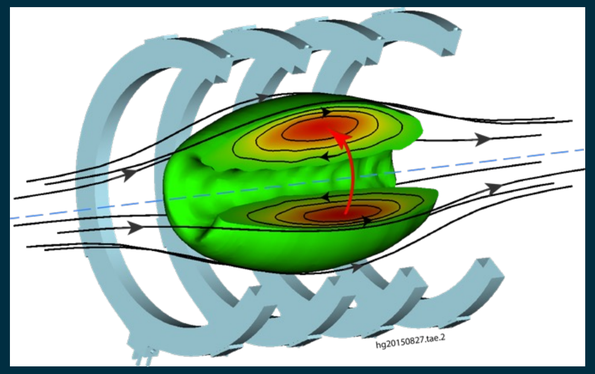
- Machine can be run in both classical mirror and Novatron configurations (B up to 0.4 T)
- Heating:
  - ECRH: 36 kW @ 2.45 GHz installed
  - ICRH: currently being installed
    - 1 MHz, half-strap antenna
- Diagnostics include interferometer, spectroscopy, and probes to measure interchange modes
- Target plasma parameters:
  - $n_e \cong 1e17\ m^{-3}$
  - $T_e \cong 30$ eV
  - $T_i \cong 100$ eV

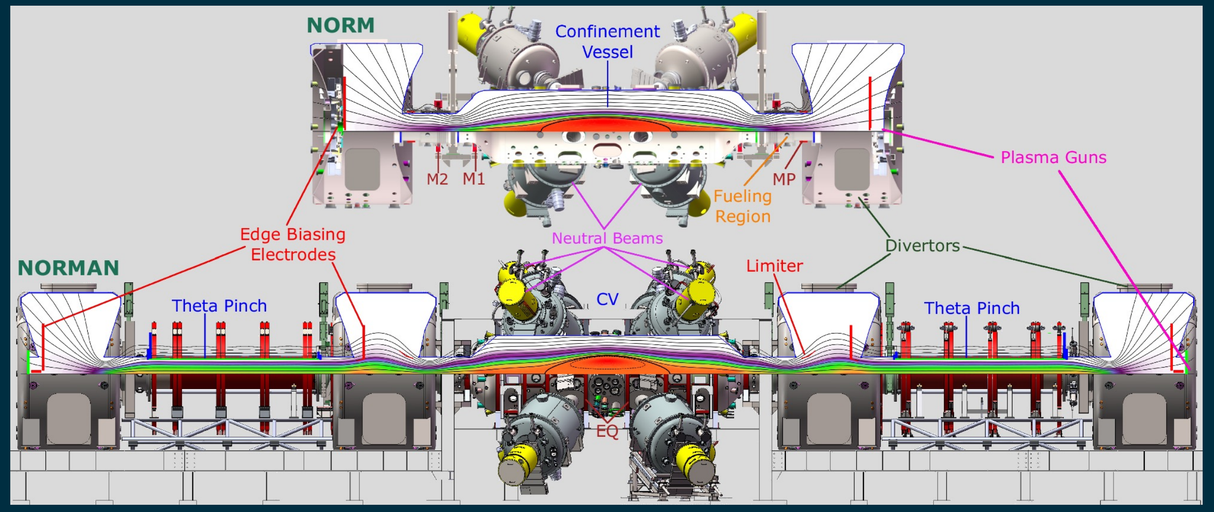


Field-reversed mirrors can be generated with neutral beams

- A long-standing goal of the mirror program to use neutral beams to reverse magnetic field has been achieved on C-2W
- Substantial current driven by injection of energetic particles causes field on-axis to change sign, leading to magnetic reconnection and the formation of a closed, toroidal, high-beta plasma

Also known as a field-reversed configuration (FRC)

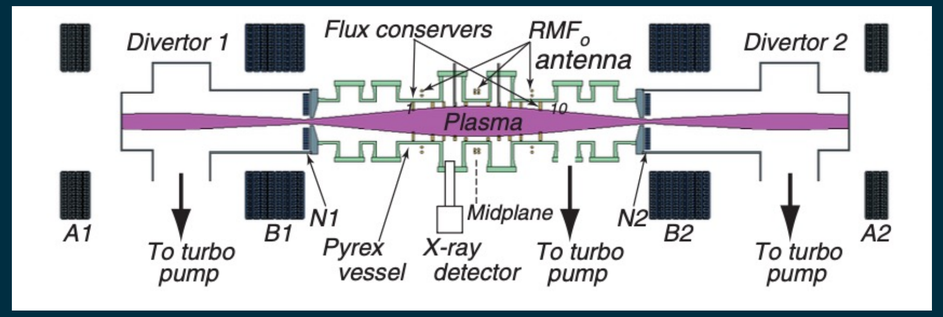




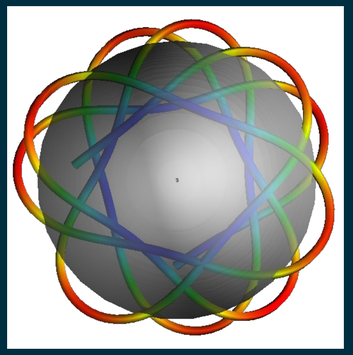
T. Roche, Nat Commun 16, 3487 (2025)

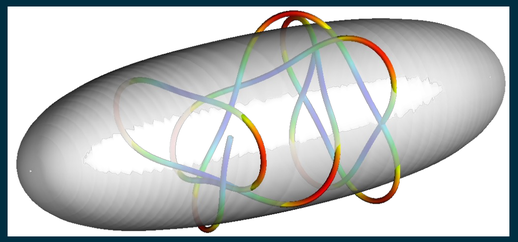
FRC current can be sustained with beams or RMF

- Field-reversed configurations have been studied for decades with other formation techniques: theta-pinch, collision-merger, and rotating magnetic fields (RMF)
- Dominant instabilities are tilt and wobble modes
- Current sustainment achieved through two main approaches: RMF or neutral beams (NBI), both of which demonstrate stable, long-lived plasmas
- Aneutronic fuel cycles require high-beta plasmas, favoring FRCs



PFRC
S. A. Cohen, Phys. Rev. Lett. 98, 145002 (2007)





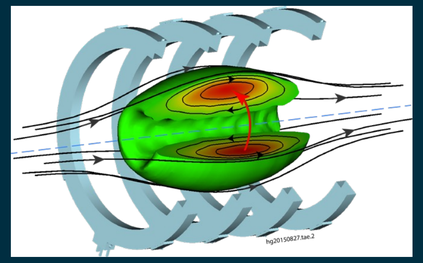
Large fast ion orbits in the FRC decouple from small scale turbulence

Figures courtesy of TAE

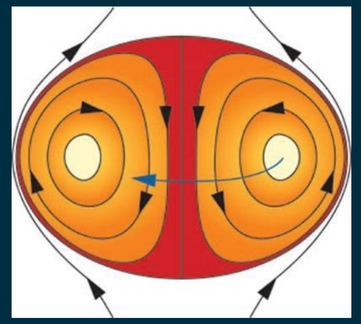
Outline

- Linear machines
  - Pinches
  - Mirrors
  - Field-reversed mirrors / FRCs
- Toroidal configurations
  - Reversed-field pinches
  - Spheromaks
  - Levitated dipoles

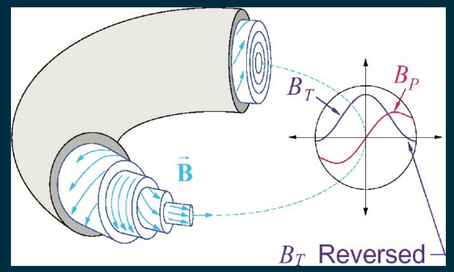
Toroidal configurations can be distinguished by degree of self organization



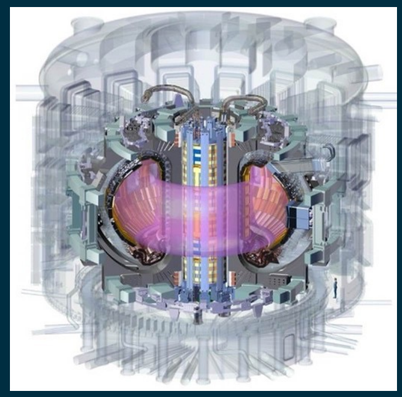
FRC



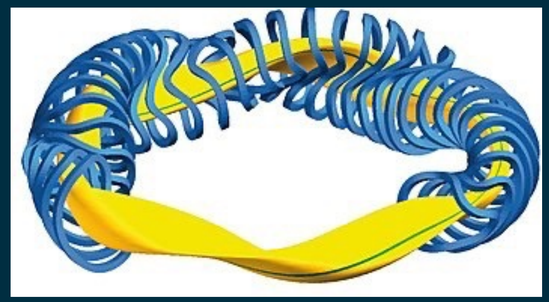
Spheromak



Reversed-field Pinch



Tokamak



Stellarator

Plasma Currents

Magnetic Field Generation

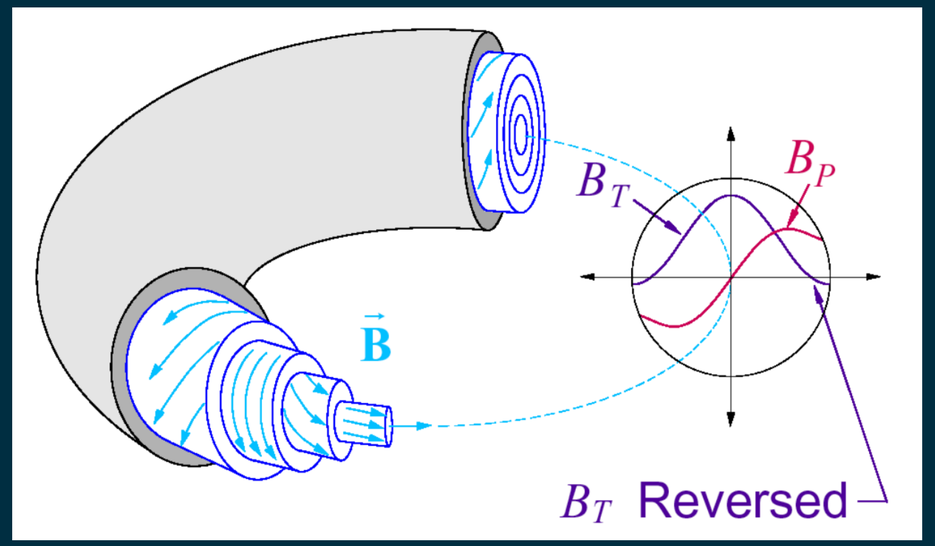
External Coils

Levitated Dipole

OpenStar's "Junior" experiment

Reversed-field pinches (RFPs) have low external magnetic field

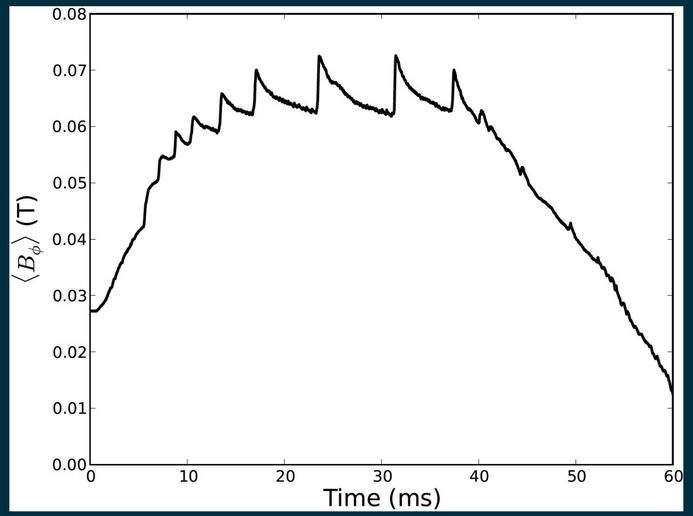
- Toroidal field is applied externally but lower than would be used for a tokamak
- Poloidal field is generated by plasma currents, typically $B_t \sim B_p$
- Plasma currents cause toroidal field at edge of plasma to reverse direction, giving the configuration its name
- High plasma beta, high magnetic shear

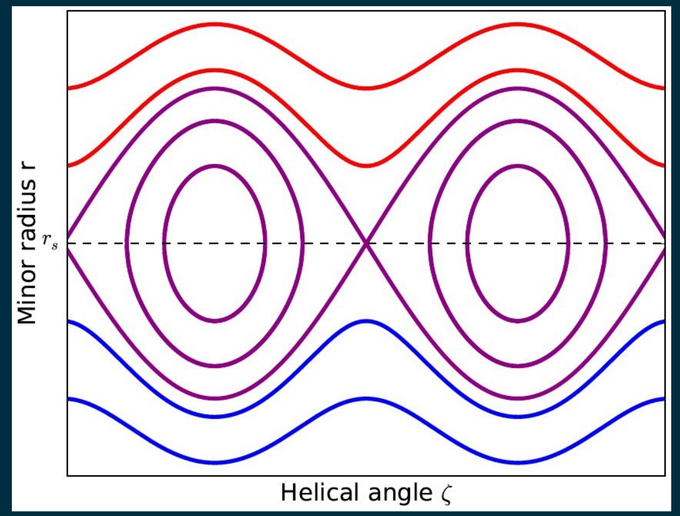


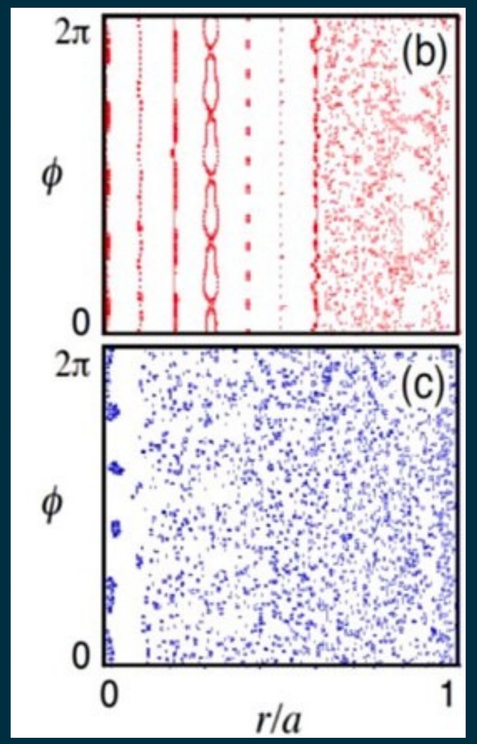
J. Sarff, Opportunities and Context for Reversed Field Pinch Research, FESAC Strategic Planning Meeting (2014) fire.pppl.gov

Current gradients drive sawtooth cycle in RFPs

- Self-organization is important for RFP physics – magnetic relaxation and reconnection lead to RFP "dynamo"
- Current density gradients drive instabilities known as tearing modes
- Many overlapping tearing modes produce stochastic magnetic fields and increased particle/energy transport



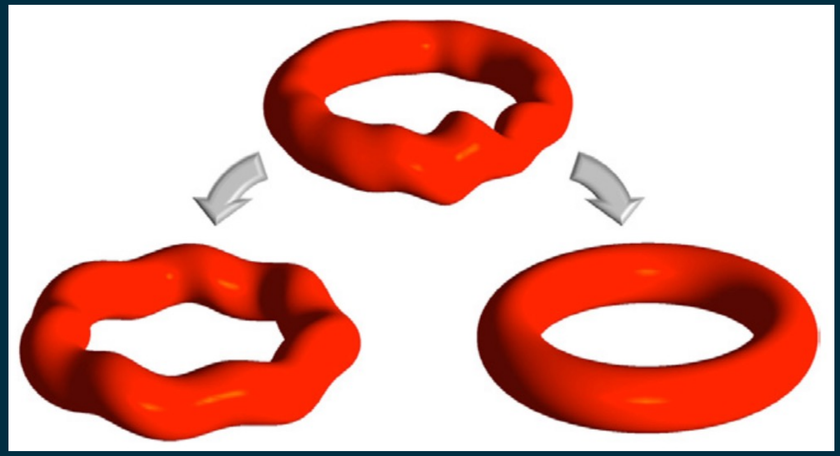




L. Marrelli, Nucl. Fusion 61, 023001 (2021)

Different approaches to current drive in RFPs: control instability or adapt to it

- Oscillating field current drive
  DC plasma current can be driven with AC applied loop voltages – helicity injection
- Helical states
  With sufficient toroidal current, dominant tearing mode alters equilibrium to become more stellarator like
- Current profile control
  Altering plasma current profile reduces the drive for tearing modes and improves confinement

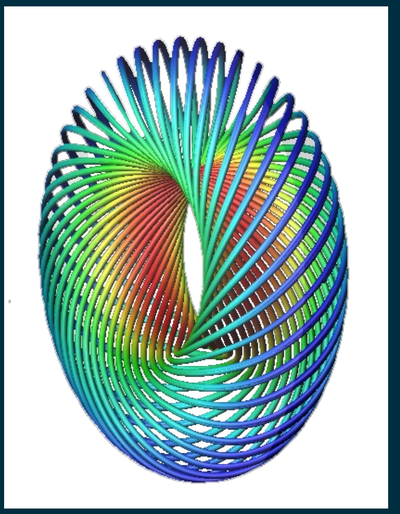


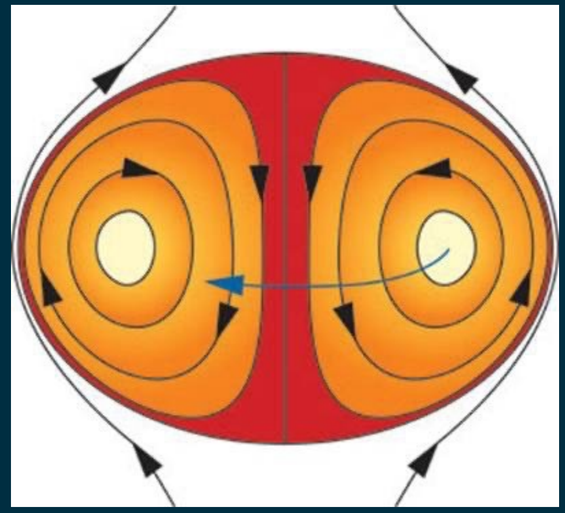
J. S. Sarff, Nucl. Fusion 53, 104017 (2013)

Spheromaks have no externally applied toroidal field

- No external coils are needed to generate the toroidal field for a spheromak, internal plasma currents generate B_t
- Like the RFP, B_t and B_p are comparable and plasma beta is also high
- Any configuration with sufficient energy and helicity will spontaneously relax into a spheromak given sufficient boundary conditions – another good example of magnetic relaxation

Courtesy of Manjit Kaur
SSX, Swarthmore College

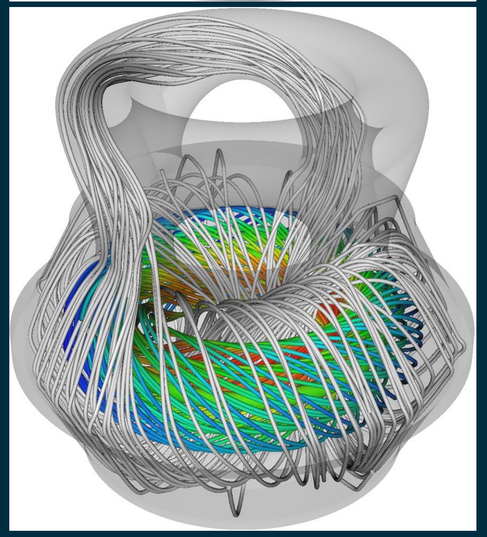




Courtesy of Derek Sutherland
SULI 2020
suli.pppl.gov/2020/course

Spheromaks can be sustained using helicity injection

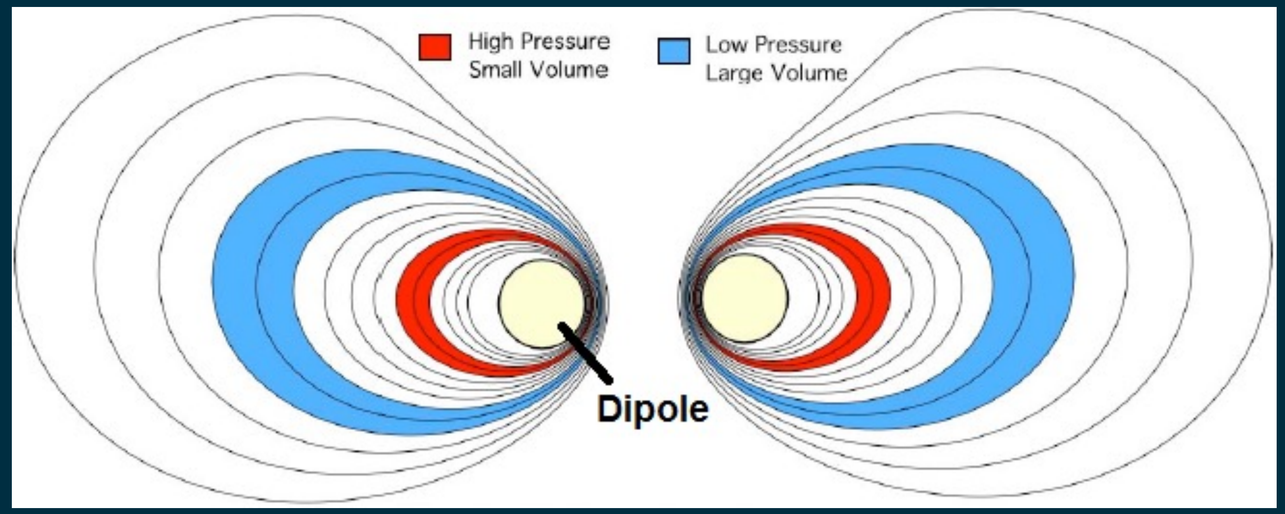
- Spheromaks are important for laboratory astronomy research, for example – coronal loops and magnetic reconnection
- Spheromaks can be used to inject plasma into other magnetic configurations for fueling, flux injection, and start up
- Helicity injection can be used to sustain currents against resistive dissipation, but instabilities driven during this process must be addressed



HIT-SIU, University of Washington / CTFusion Inc.
Courtesy of Derek Sutherland, SULI 2020
suli.pppl.gov/2020/course

Levitated dipoles draw inspiration from space plasmas

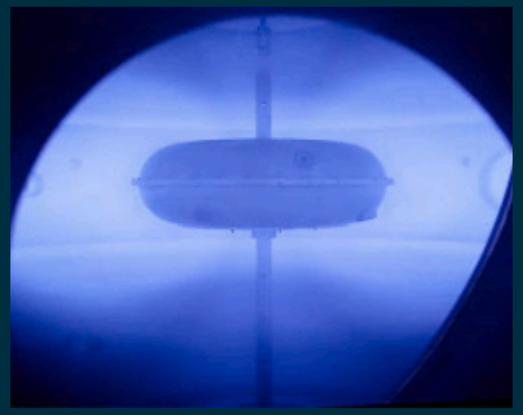
- First proposed following observations of planetary magnetosphere (Voyager 2 flyby of Uranus)
- Fluctuations due to the solar wind cause a “turbulent pinch” that transports particles inward
- Process is driven by interchange modes and the conservation of number of particles in flux tubes
- But magnetic field lines pass through the planet, causing aurora and loss of particles



en.wikipedia.org/wiki/Levitated_dipole

Turbulent pinch has been demonstrated in the lab

- Levitated dipoles in the lab have successfully demonstrated the turbulent pinch by using superconducting coils
- Instead of the solar wind, fluctuations are driven by RF heating
- Reactor concepts typically avoid deuterium-tritium fuel cycle to reduce neutron load on the levitating coil

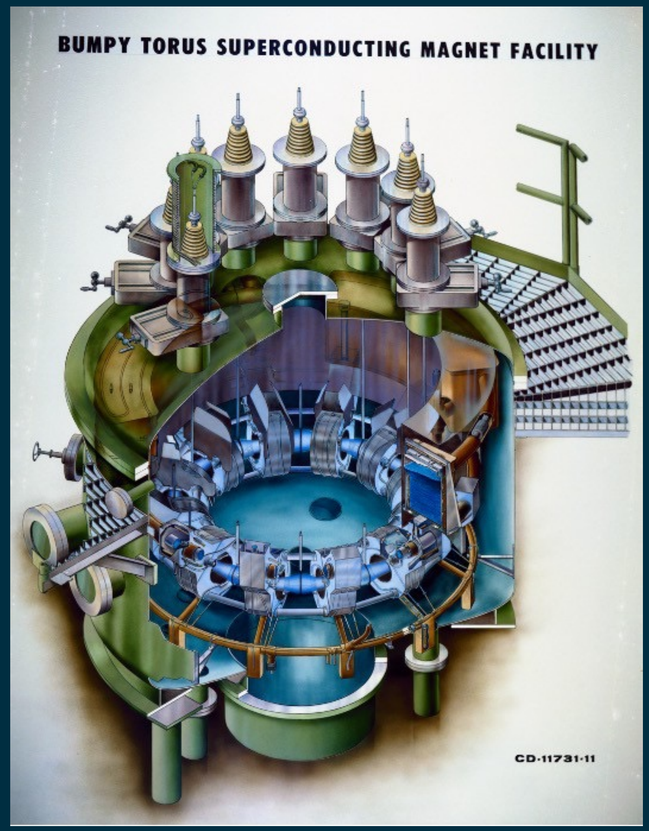


C.S. Chisholm, Fusion Eng. Des. 223, 115551 (2026)

J. Kesner and M. Mauel, Final Report: Levitated Dipole Experiment (2013) www.osti.gov/servlets/purl/1067488

Many other configurations exist

- The toroidal configurations discussed so far are not an exhaustive list
- Some examples of configurations include:
  Many varieties of cusps
  Quadrupoles/Octupoles/etc
  Bumpy Torus



Bumpy torus
NASA
en.wikipedia.org/wiki/Bumpy_torus

This is an exciting time to be doing fusion energy research

- Fusion Industry Association
  https://www.fusionindustryassociation.org
- US Fusion Energy
  https://usfusionenergy.org