tae TECHNOLOGIES

A survey of magnetic configurations for plasma confinement

Eli Parke (they/them)

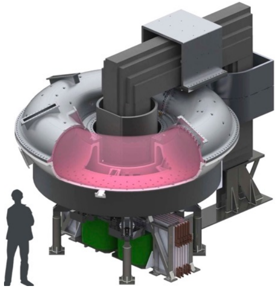
Introduction to Fusion Energy and Plasma Physics, SULI 2024

June 13, 2024

My background

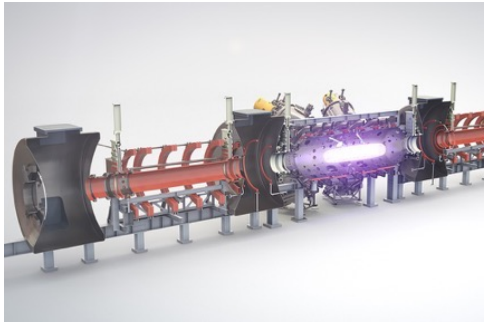
James R. Macdonald Laboratory

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



MST
wippl.wisc.edu

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



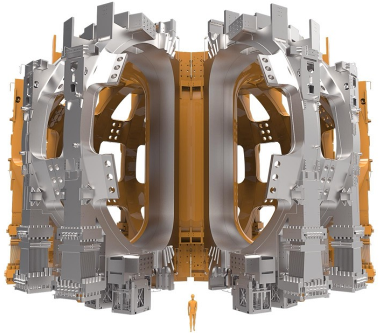
Scientist at TAE Technologies, Inc.
(2018 – present)

Member of APS DPP Pride Committee

engage.aps.org/dpp/programs/plasma-pride

How do researchers confine fusion plasmas?

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



ITER Toroidal Magnetic Field Coils
www.iter.org

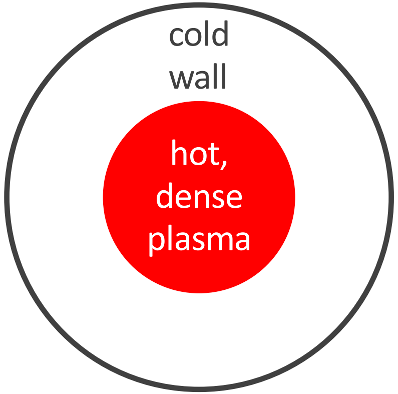
The choice of configuration has important consequences

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

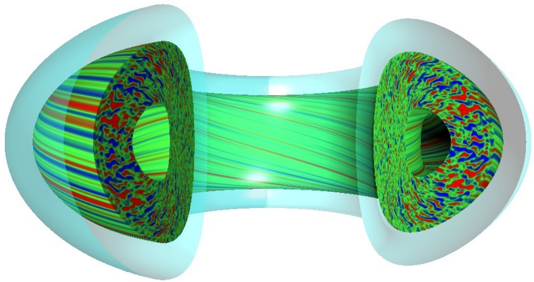
$$nT\tau$$

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

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

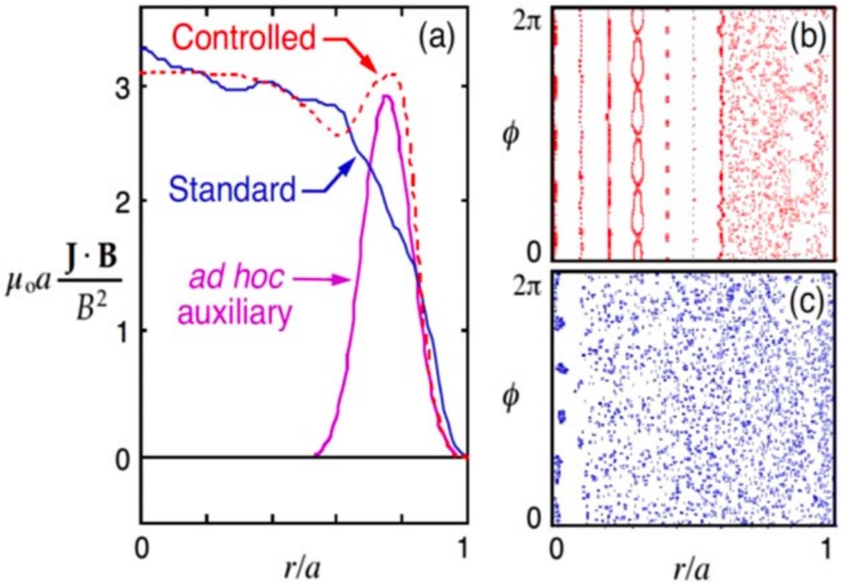


GYRO turbulence simulations
Courtesy of Greg Hammett
w3.pppl.gov/~hammett/viz/viz.html



There are many approaches to stabilization

- Profile control

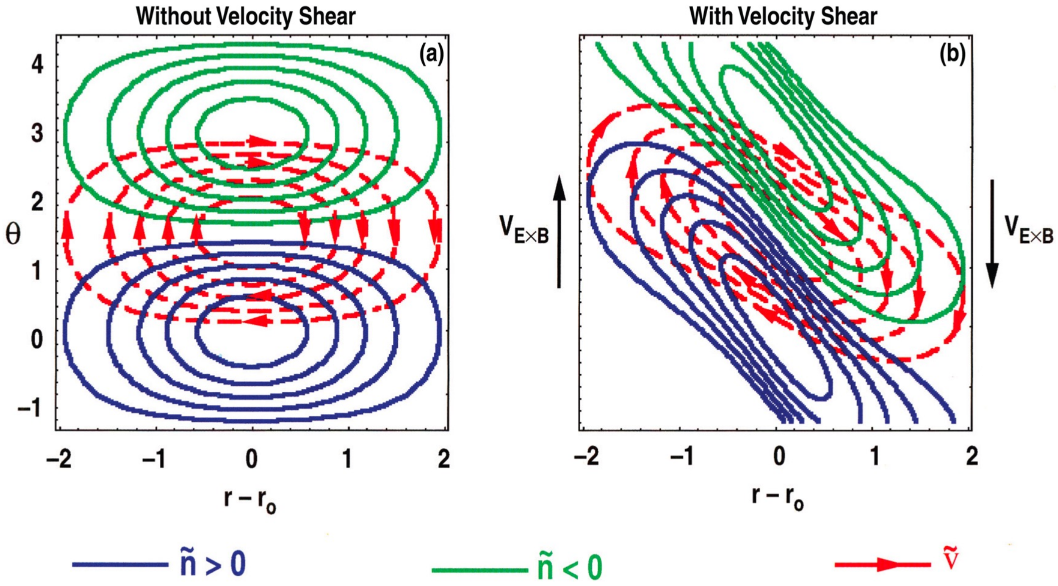


L. Marrelli, Nucl. Fusion 61, 023001 (2021)

There are many approaches to stabilization

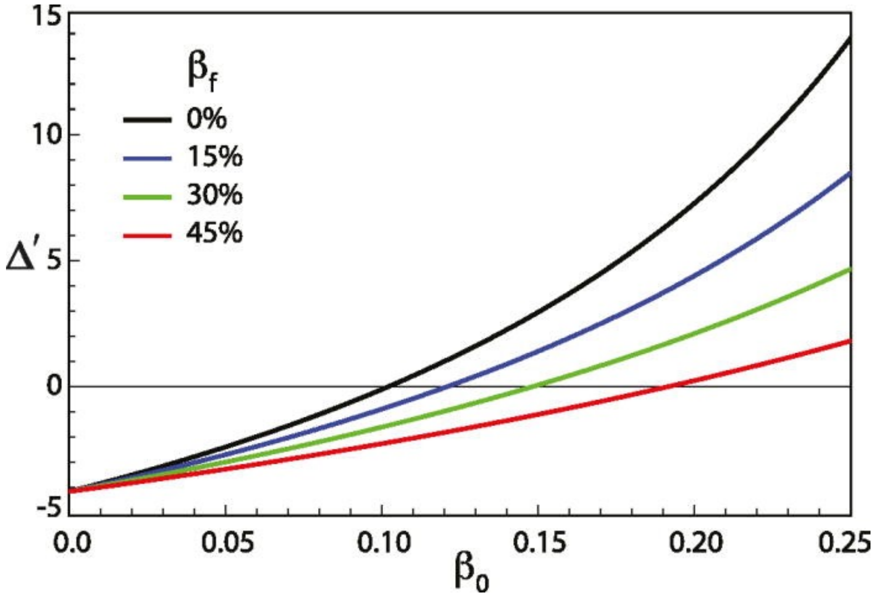
- Profile control
- Flow shear

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



There are many approaches to stabilization

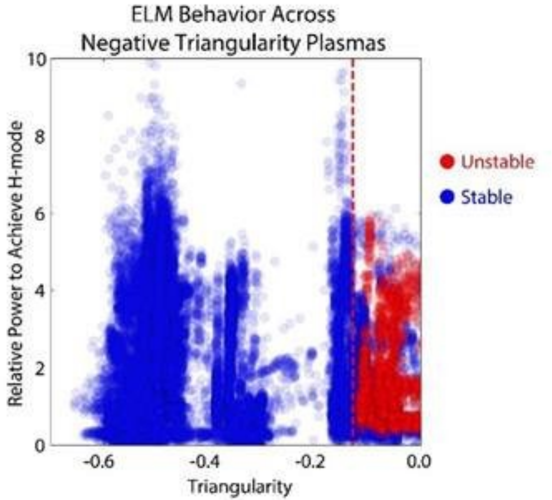
- Profile control
- Flow shear
- Energetic particles



M. R. Halfmoon, Phys. Plasmas 24, 062501 (2017)

There are many approaches to stabilization

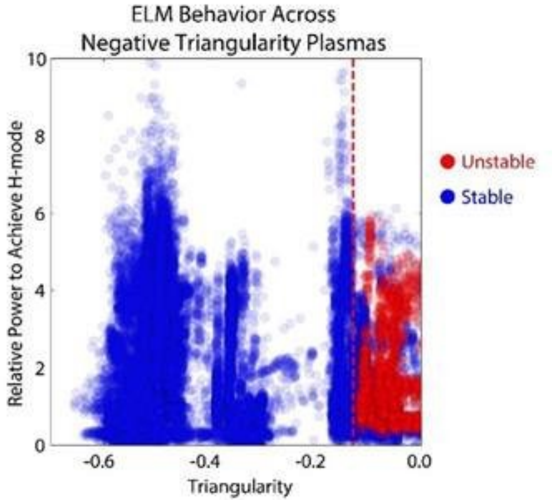
- Profile control
- Flow shear
- Energetic particles
- Field shaping



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

There are many approaches to stabilization

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



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

Outline

- Linear machines
  - Mirrors
  - Pinches
- Toroidal configurations
  - Reversed-field pinches
  - Spheromaks
  - Field-reversed configurations
- Magneto-inertial confinement

Linear machines

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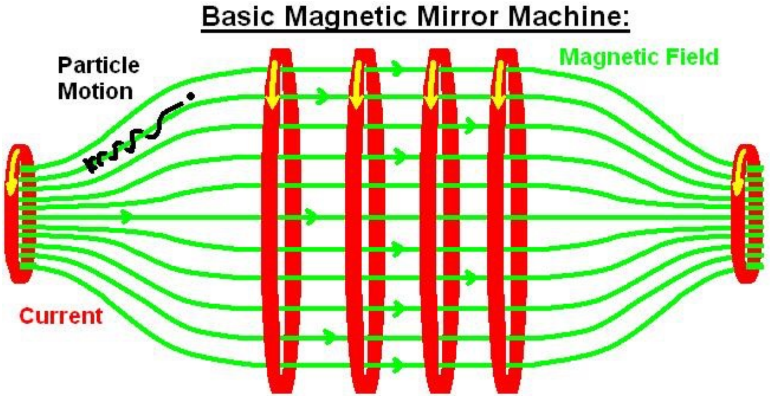
Magnetic mirrors can trap particles

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

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



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

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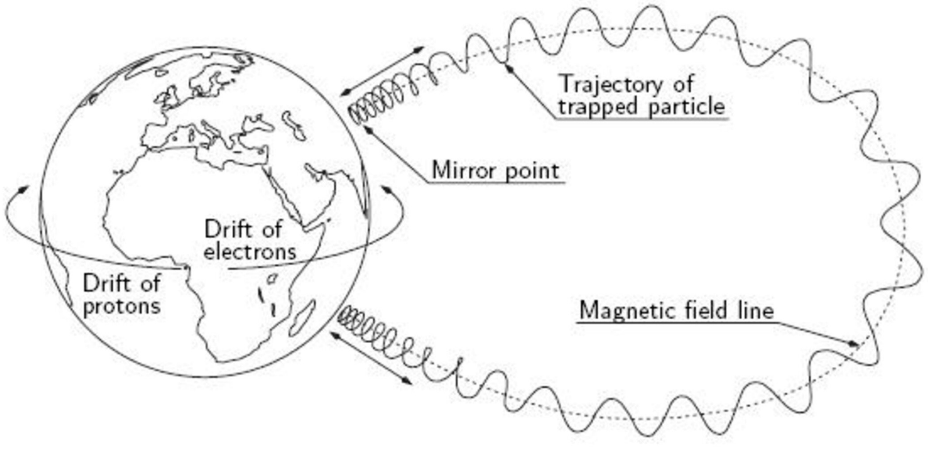

Magnetic mirrors can trap particles

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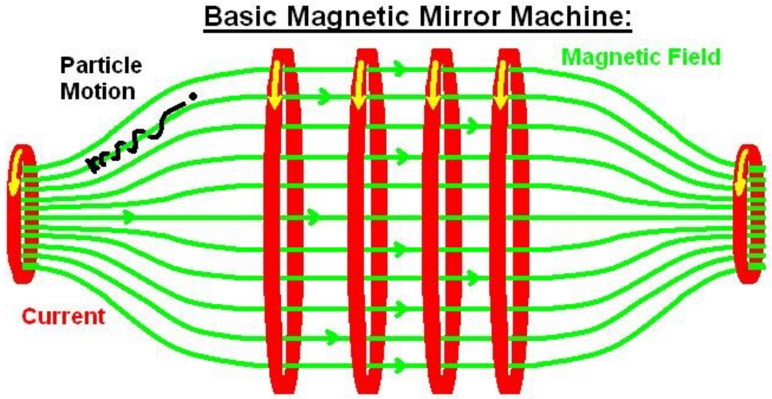
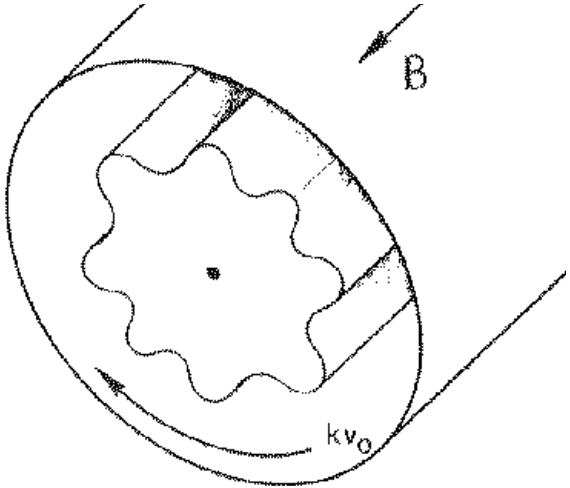
- Magnetic bottle – varying the magnetic field strength axially produces a radial field component that reflects particles
- Conservation of energy and the magnetic moment of the particle leads to mirroring
- Mirror phenomena occur in many plasmas
- Magnetic bottle is leaky – particles can escape through the ends



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

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, also observed in other devices and astrophysical plasmas



Francis Chen
Introduction to Plasma Physics and Controlled Fusion, 1974

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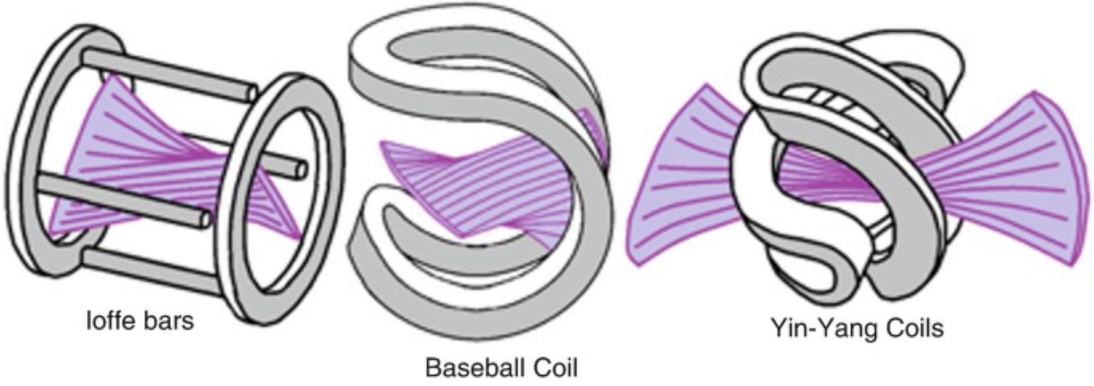
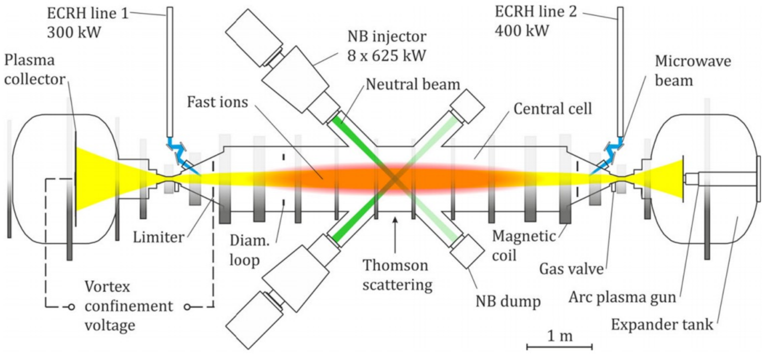
- In the mirror machine these are known as flute instabilities, also observed in other devices and astrophysical plasmas
- Could be stabilized by complicated magnet configurations in mirror machines

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



Mirror machines have seen renewed interest

- More recent advances in mirror research have provided alternative methods for improving mirror performance
- Maxwellian distributions, density-weighted curvature, neutral beams, end-biasing



Gas Dynamic Trap
Courtesy of Peter Bagryansky
en.wikipedia.org/wiki/Gas_Dynamic_Trap

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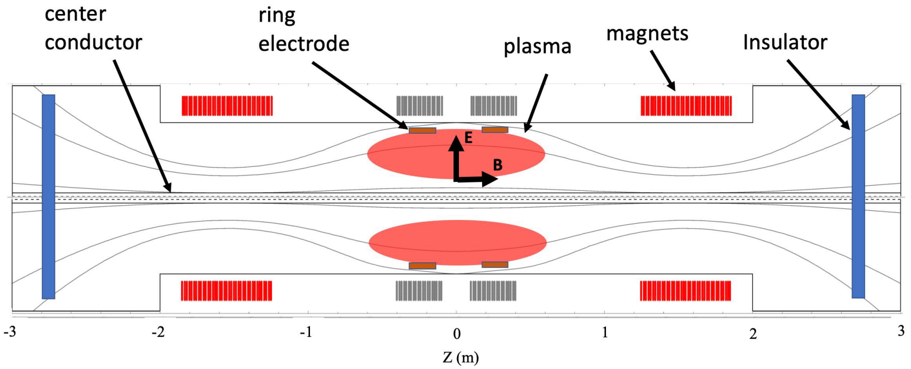

Centrifugal Mirror Fusion Experiment
Courtesy of C. A. Romero-Talamás

Mirror machines have seen renewed interest

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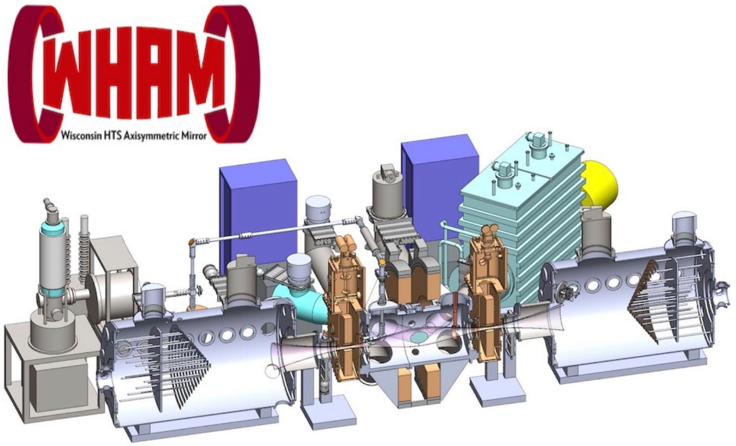
- High temperature superconducting magnets



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

Mirror machines have seen renewed interest

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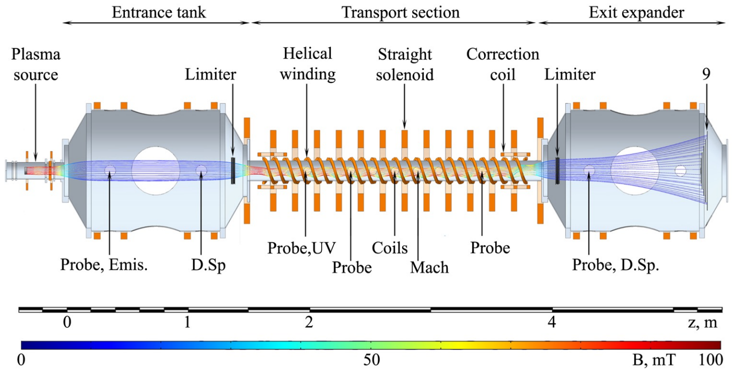
- Maxwellian distributions, density-weighted curvature, neutral beams, end-biasing
- Supersonic plasma rotation with high voltage biasing
- High temperature superconducting magnets
- Helical windings with biasing

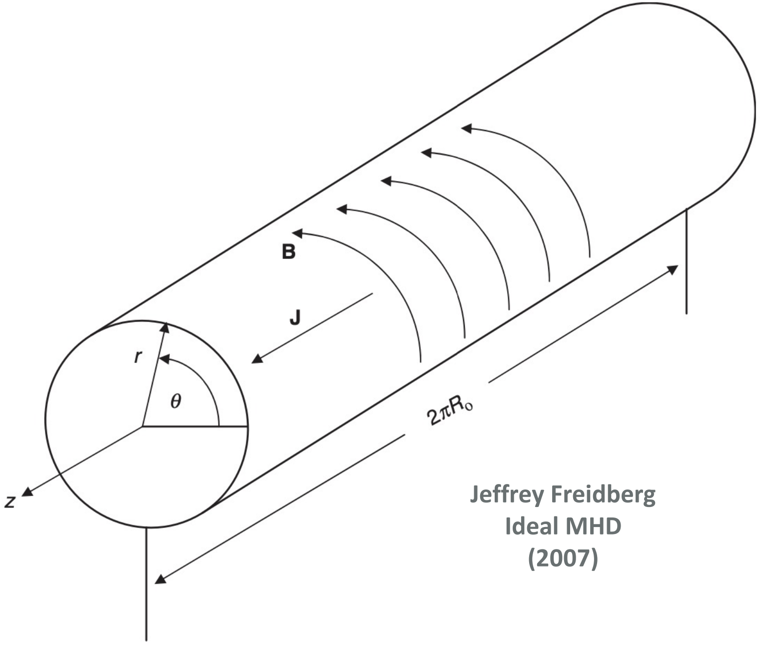


SMOLA Helical Mirror
A. V. Sudnikov, J. Plasma Physics 88, 905880102 (2022)

Pinches were an early pulsed power approach

- Several configurations of linear pinches – names are derived from direction of current flow

Z-Pinch



Jeffrey Freidberg
Ideal MHD
(2007)

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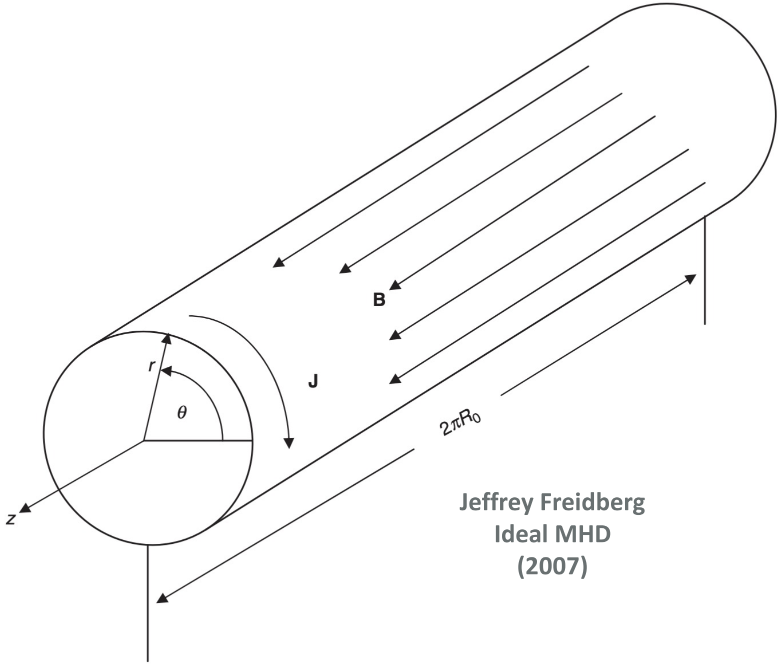
Theta-Pinch



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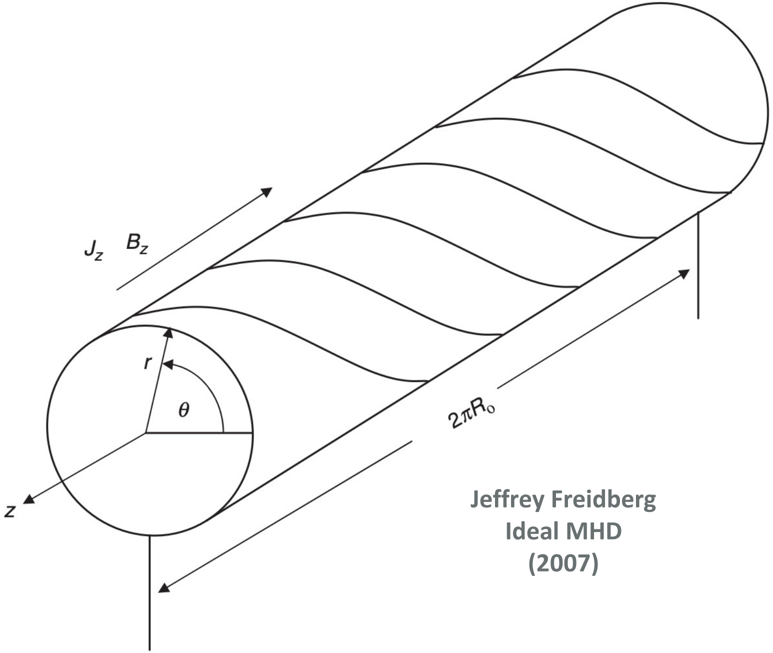
Screw Pinch



Jeffrey Freidberg
Ideal MHD
(2007)

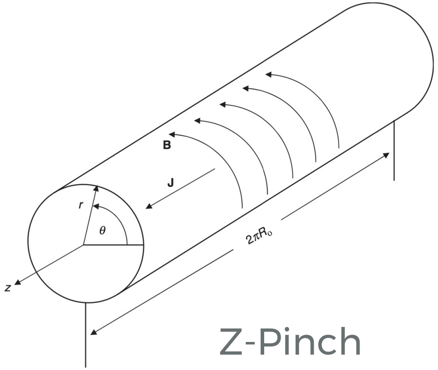
Pinches were an early pulsed power approach

- 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

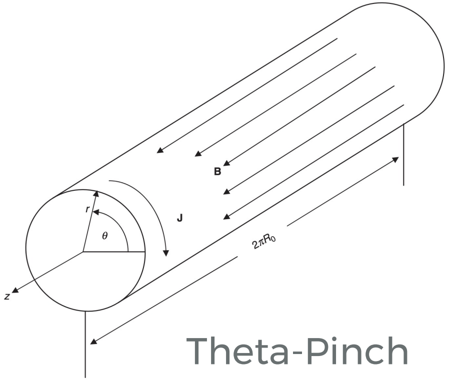
Courtesy of Bert Hickman
en.wikipedia.org/wiki/Pinch_(plasma_physics)

Pinches were an early pulsed power approach

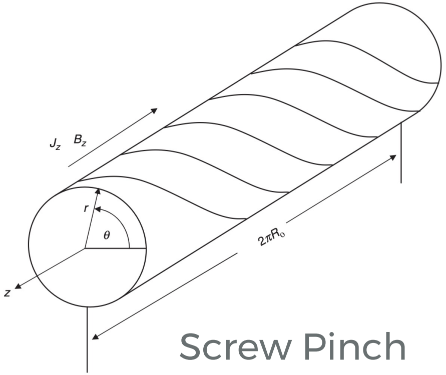
- Several configurations of linear pinches – names are derived from direction of current flow
- Current and magnetic field are perpendicular: JxB force causes radial “pinch” effect
- Axial field lines of the theta and screw pinches provide stability but lead to higher end-losses



Z-Pinch



Theta-Pinch



Screw Pinch

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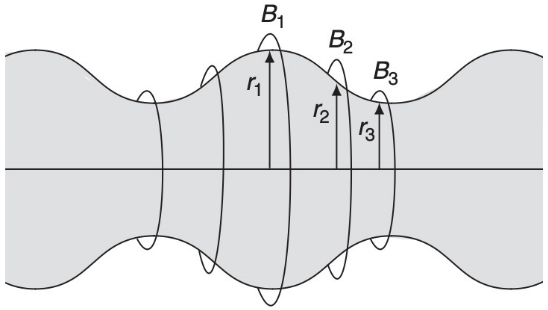
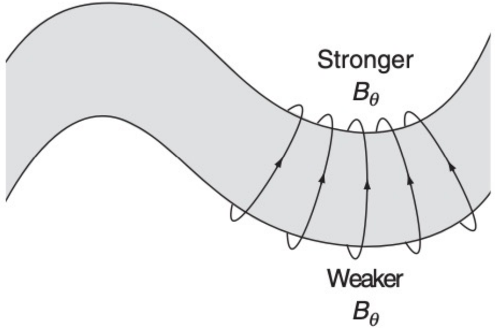
Z-pinches are susceptible to MHD instabilities

- Sausage modes
  - Perturbation in radius of plasma column
  - Analogous to flute modes described earlier
- Kink modes
  - Perturbation in displacement from axis
  - Current driven
- Perturbations grow rapidly and degrade plasma



Sausage mode



Kink mode

Jeffrey Freidberg
Ideal MHD
(2007)

A variety of techniques are available for stabilization

- Axial field lines stabilize against sausage and kink modes but sacrifice confinement
- Close conducting boundary/wall stabilizes these modes
- Pressure profile control stabilizes sausage modes but not kink modes
- Flow shear stabilization is a newer technique for z-pinches

$$\frac{dv_z}{dr} \neq 0$$

Toroidal configurations

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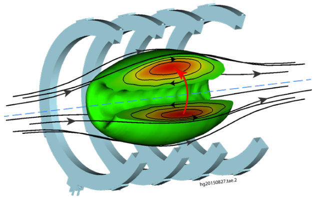
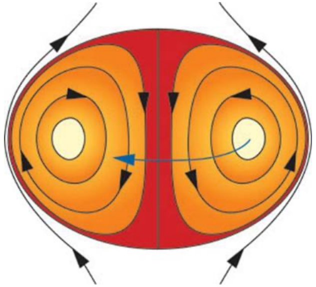
Toroidal configurations can be distinguished by degree of self-organization

ITER Tokamak
www.iter.org

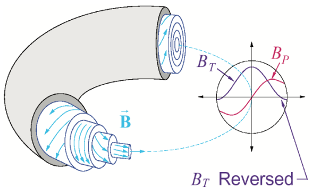
W7-X Stellarator
Courtesy of Max Planck Institute for Plasma Physics
en.wikipedia.org/wiki/Stellarator



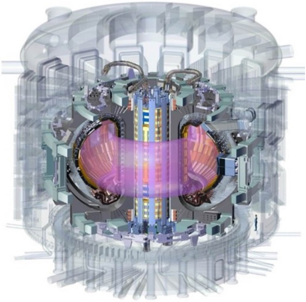
FRC



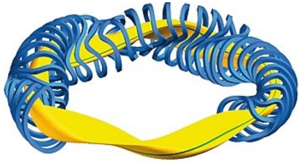
Spheromak



RFP



Tokamak



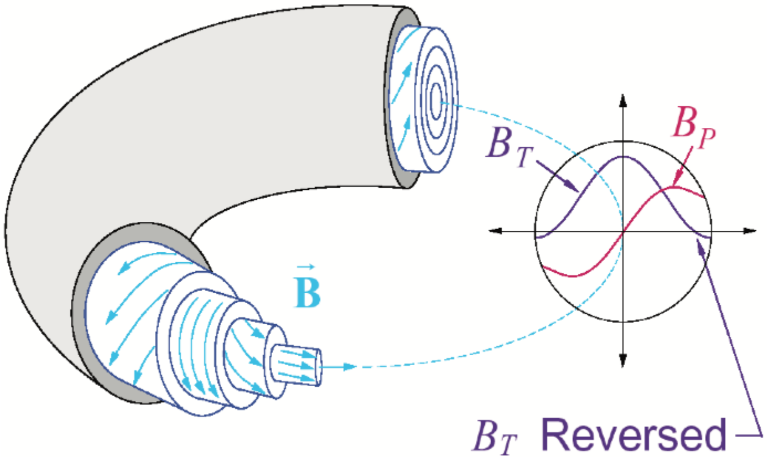
Stellarator

Plasma currents — Magnetic field generation — External coils

Reversed-field pinches have low external magnetic field

RFP

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

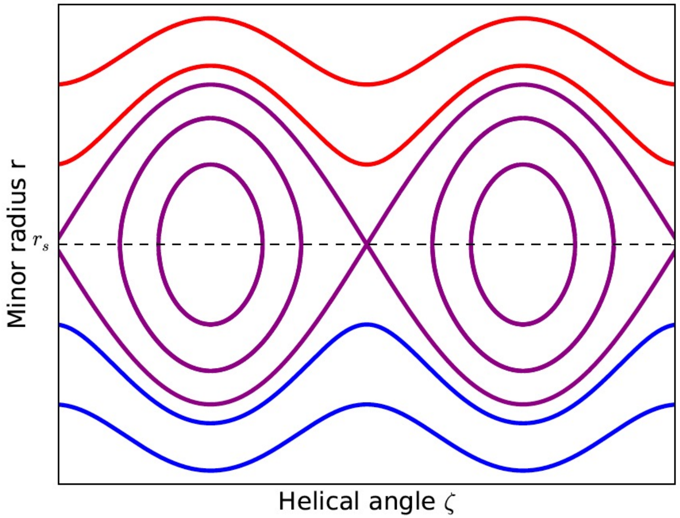


J. Sarff, Opportunities and Context for Reversed Field Pinch Research, FESAC Strategic Planning Meeting (2014) fire.pppl.gov

Current gradients drive sawtooth cycle in RFPs

RFP

- 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



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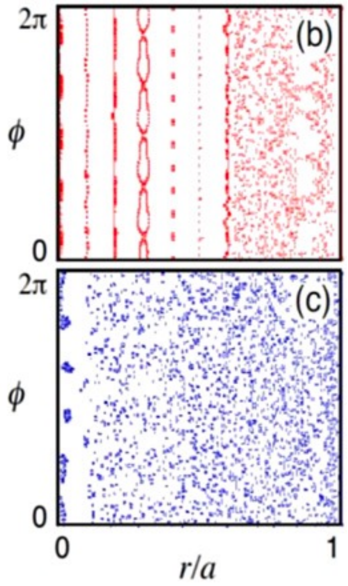

L. Marrelli, Nucl. Fusion 61, 023001 (2021)

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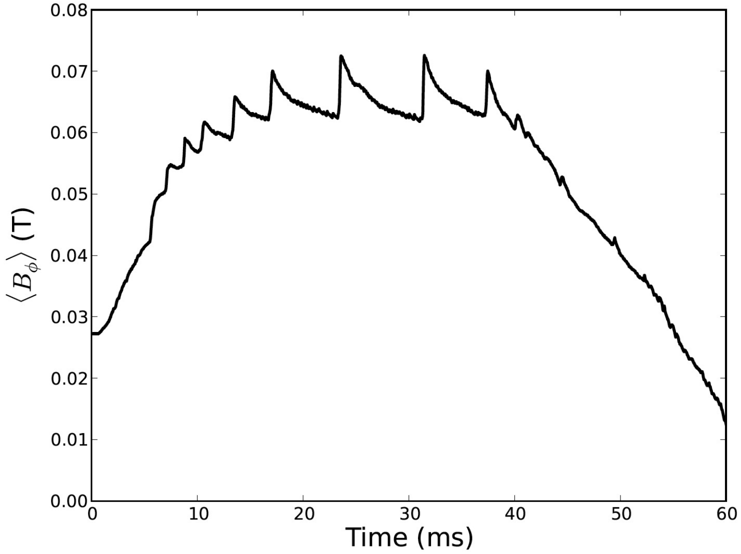


Different approaches to current drive in RFPs: control instability or adapt to it

RFP

- Oscillating field current drive

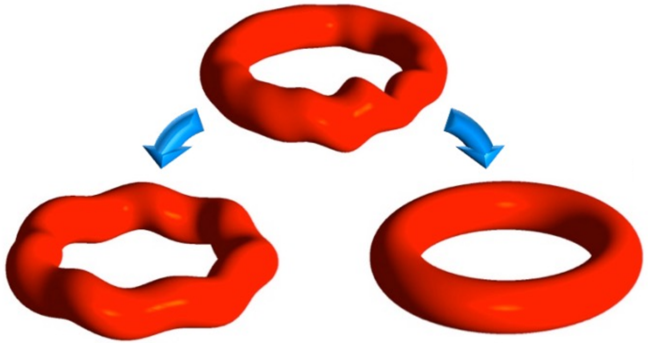
  DC current can be driven with AC applied loop voltages – helicity injection

- 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

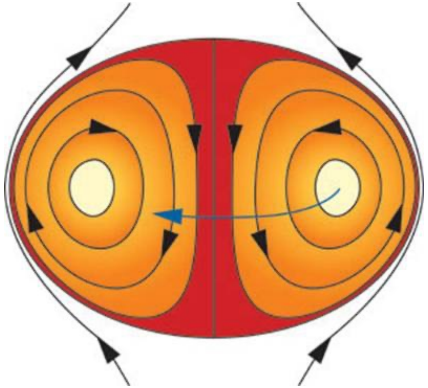


J. Sarff, Opportunities and Context for Reversed Field Pinch Research, FESAC Strategic Planning Meeting (2014) fire.pppl.gov

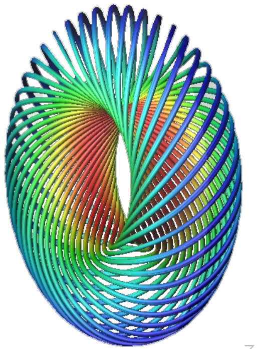
Spheromaks have no externally applied toroidal field

Spheromak

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



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

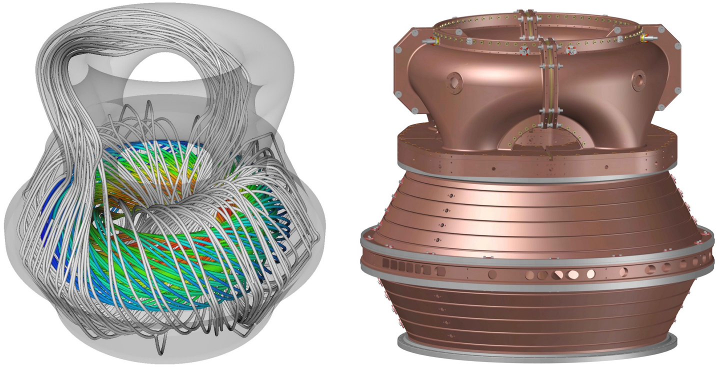


SSX, Swarthmore College
Courtesy of Manjit Kaur

Spheromaks can be sustained using helicity injection

Spheromak

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

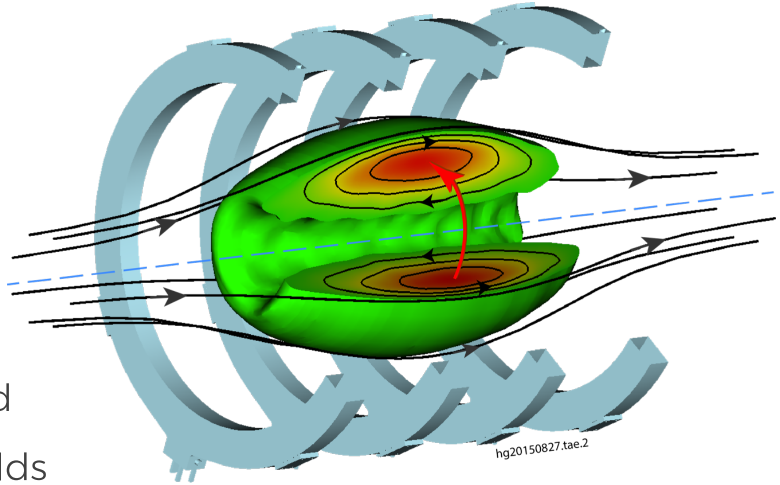


HIT-SIU, University of Washington / CTFusion, Inc.
Courtesy of Derek Sutherland, SULI 2020
suli.pppl.gov/2020/course/

Field-reversed configurations have no toroidal field

- Unlike the other toroidal configurations, FRCs have no (or very small) toroidal field
- Compact toroidal plasma has closed poloidal field sustained by plasma current, high plasma beta
- Frequently made using theta-pinch, fast reversal
- Toroidal plasma can easily be accelerated, translated
- Current can be sustained with rotating magnetic fields or neutral beams, for example

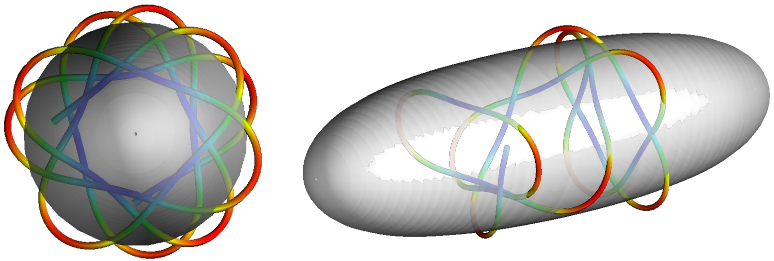
FRC

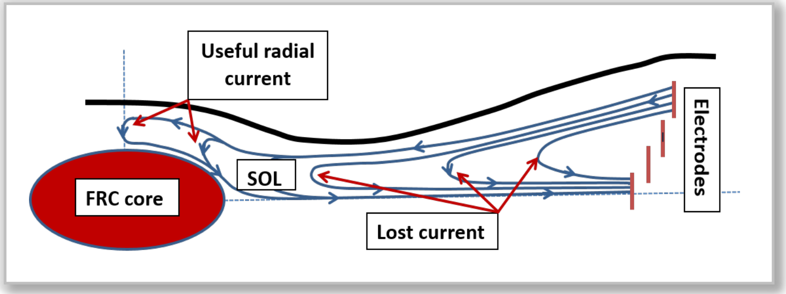


Instabilities can be controlled by energetic particles and biasing

FRC

- Dominant instabilities are tilt/wobble modes
- Stabilizing effects of fast ions
  - Large orbit ions can decouple from microturbulence, leading to improved stability/transport
- Electrodes can drive rotation in FRC plasmas
  - Generating radial electric field creates torque on plasma
- Real-time control systems can correct for instabilities and maintain equilibrium

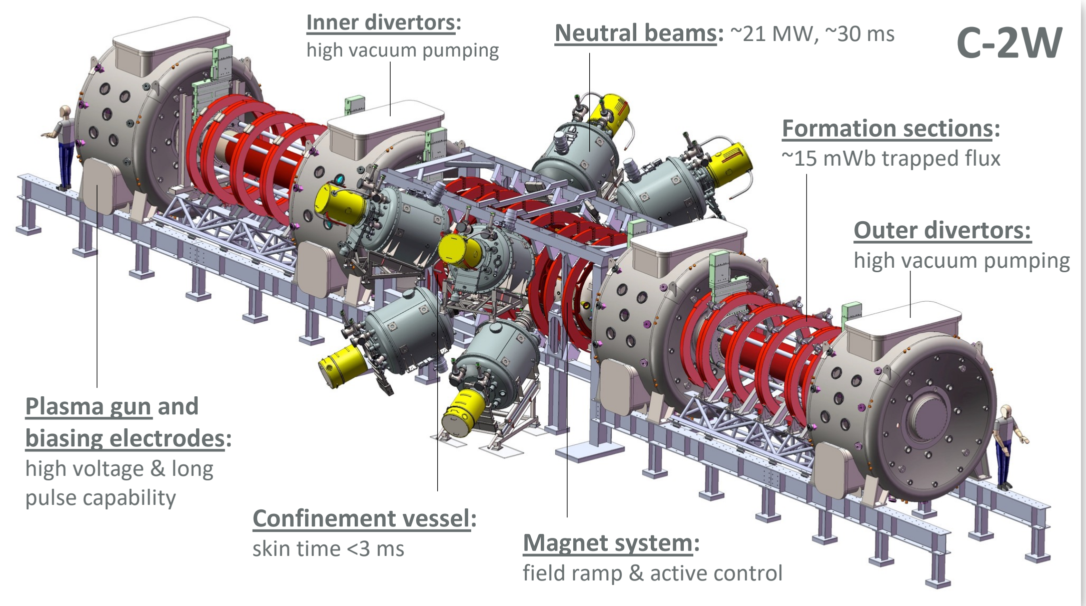




Field-reversed configurations facilitate pursuit of aneutronic fuel cycles

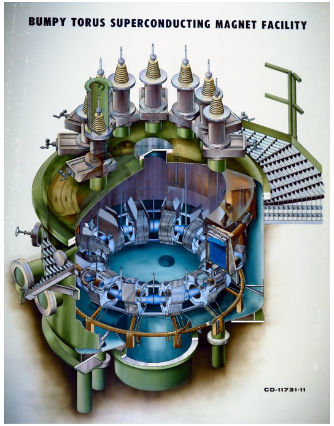
FRC

- Possibility of fuel cycles that do not produce neutrons, like p-^{11}B, due to high plasma beta
- Tritium supply is constrained, requires breeder reactors
- Neutrons can damage reactor and induce radioactivity
- Aneutronic fuel cycles require higher temperatures, but avoid these problems
- Linear configuration facilitates impurity/ash removal and direct extraction of energy

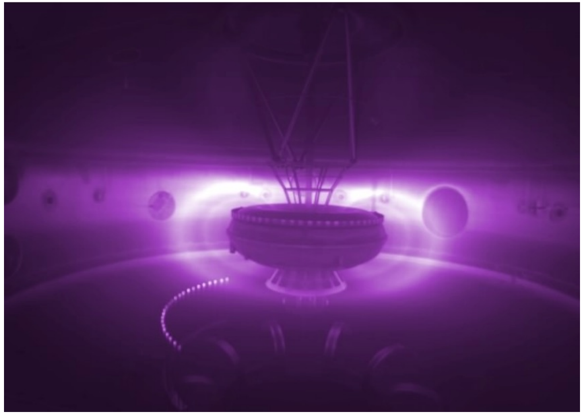


Many other configurations exist

- The toroidal configurations discussed so far are not an exhaustive list
- Some examples of other plasma experiments include:
  - Cusps
  - Dipoles/Quadrupoles/etc.
  - Bumpy torus



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

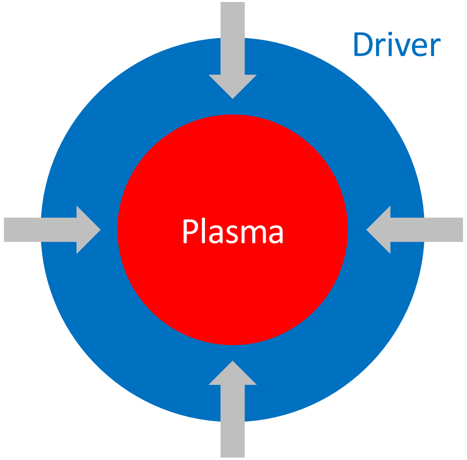


Levitated dipole
J. Kesner and M. Mauel, Final Report: Levitated Dipole Experiment (2013)
www.osti.gov/servlets/purl/1067488

Magneto-inertial confinement

Magneto-inertial confinement is a pulsed power approach

- Concepts discussed previously are generally considered for steady state operation, but some could be applied to pulsed systems
- Magneto-inertial confinement is a hybrid approach that compresses a magnetized plasma
- Plasma density can span the range between magnetic and inertial confinement schemes, and some approaches can generate extreme magnetic fields
- High yields potentially allow a lower repetition rate than inertial confinement schemes



Magnetized targets offer advantages

- Compared to inertial confinement, the magnetized target can reduce transport and improve heating
- Magnetic configurations are generally chosen to be FRCs or spheromaks, but spherical tokamaks are also used
- Compact toroids allow for translation of plasma from formation region to compression region
- The initial target plasma needs to have sufficiently high temperature, density, and stability, with a robust lifetime longer than time required to translate/compress

Many choices are available for driving compression

- Solid liners – liner implodes and is destroyed during compression
- Liquid metal liners – liner is compressed, can be used repetitively
- Plasma liners – similar advantages to liquid metal, can also reduce impurity contamination
- Magnetic compression – external magnetic fields are used to compress plasma
- Time scales for compression with magneto-inertial confinement are slower than inertial confinement

Additional resources

This is an exciting time to be doing fusion energy research

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