A survey of magnetic configurations for plasma confinement

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My background

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

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Scientist at TAE Technologies, Inc.
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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’ve also heard about inertial confinement at facilities like NIF

• Pulsed power
  You’ll hear about pulsed power and Z-pinches, etc. later this week

• 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”
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

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

- Mirror machines
- Toroidal configurations
- Magneto-inertial confinement
Mirror machines
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
- Consider conservation of energy and the magnetic moment of the particle
- Mirror phenomena occur in many plasmas
- Magnetic bottle is leaky – particles can escape through the ends
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
- Could be stabilized by complicated magnet configurations in mirror machines
Mirror machines have seen renewed interest

• More recent advances in mirror research have provided alternative methods for improving mirror performance
• Electrode biasing and neutral beam heating
• Supersonic plasma rotation with high voltage biasing
• High temperature superconducting magnets

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

Wisconsin HTS Axisymmetric Mirror
wippl.wisc.edu/wisconsin.hts-axisymmetric-mirror/
Toroidal configurations
Toroidal configurations can be distinguished by degree of self-organization.

- **FRC**
- **Spheromak**
- **RFP**
- **Tokamak**
- **Stellarator**

Plasma currents

Magnetic field generation

External coils

**Courtesy of Max Planck Institute for Plasma Physics**


[ ITER Tokamak](http://www.iter.org)
Reversed-field pinches 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 $B_p \sim B_t$
- 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

- 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

J. Sarff, Opportunities and Context for Reversed Field Pinch Research, FESAC Strategic Planning Meeting (2014) fire.pppl.gov
Different approaches to current drive in RFPs: control instability or adapt to it

- 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

- 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
Spheromaks can be sustained using helicity injection

- 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-pin, fast reversal
- Toroidal plasma can easily be accelerated, translated
- Current can be sustained with rotating magnetic fields or neutral beams, for example
Instabilities can be controlled by energetic particles and biasing

- 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

- Possibility of fuel cycles that do not produce neutrons, like $p^{11}\text{B}$, 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](en.wikipedia.org/wiki/Bumpy_torus)

[Bumpy torus](en.wikipedia.org/wiki/Bumpy_torus)

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/