Alternative fusion energy approaches

Introduction to Fusion Energy and Plasma Physics
SULI 2020

Derek A. Sutherland
CEO – CTFusion, Inc.

What is an "alternative" configuration, and why do we care about them?

- Historically, this term has been used to refer to non-mainline (e.g. tokamak, ST, stellarator) fusion energy concepts that you've heard about during this course, but sometimes means anything but a conventional aspect ratio tokamak.

- Alternative approaches are quite varied and there is currently quite a bit of R&D in this space being funded by DOE (e.g. ARPA-E) and by private investors.

- The benefits of pursuing alternative fusion energy approaches are extensive, but to summarize:
    - Programmatic risk-reduction of U.S. fusion R&D program by embracing a diverse portfolio approach with orthogonal R&D needs – a potential showstopper for a given concept doesn't halt progress across the entire field.
    - Potentially developing multiple viable approaches to fusion energy, some of which could 1) be lower in cost than others that will translate into more favorable economics on the grid and may 2) offer varied operational characteristics to fulfill different customer needs (e.g power output, LCOE, flexibility, etc…)

Outline

- **Introduction and overview**
- **Toroidal fusion energy concepts**
  - Reversed-Field Pinch (RFP)
  - Spheromaks
  - Field-reversed configuration (FRC)
- **Magnetic mirrors**
  - Gas Dynamic Trap (GDT)
  - Centrifugal mirror (CM)
  - HTS axisymmetric mirror (WHAM)
- **Magneto-Inertial Fusion**
  - Magnetized plasma targets (FRC, spheromak, ST)
  - Drivers (solid liner, liquid metal liner, plasma jet driver)
- **Summary and Resources**

Fusion energy concepts must work towards Lawson conditions to achieve high power gains needed for an eventual fusion power plant

- Lawson "Triple-Product" from power balance - $nT\tau_E >$ (# dependent on fusion fuel cycle)

- For DT fusion, minimum $nT\tau_E > 3\times10^{21}$ keV-s/m^3 at $T \approx 14$ keV.

- Given operation at an optimal temperature T, you can approach Lawson in multiple ways:
  1. Low n, high τ_E - Magnetic Fusion Energy (MFE)
  2. Medium n and τ_E - Magneto-Inertial Fusion (MIF)
  3. High n, low τ_E - Inertial Confinement Fusion (ICF) (you'll also see this expressed in terms of ρr).

- For this talk, we will be focusing on the first two n,τ_E of alternative fusion energy concepts (MFE and MIF). You will hear more about the higher-density (e.g. Z-pinch, MagLIF, ICF) fusion approaches in later talks.

One of the most useful equations when assessing any fusion energy concept is that for volumetric fusion power density P_{fus}

- Fundamentally, plasma ions are undergoing fusion events. Volumetric fusion power density for fusing species A and B

$$P_{fus} = n_A n_B < \sigma v_{A,B} > \mathrm{E_{yield}}\ [\mathrm{MW/m^3}]$$

- Assuming a quasi-neutral DT plasma with $n_D = n_T = \frac{n}{2}$, the volumetric fusion power density is

$$P_{fus} = \frac{n^2}{4} < \sigma v >_{DT} E_{yield,DT} \propto n^2 < \sigma v >_{DT}$$

- Define $\beta = \mathrm{p}/\mathrm{p_{mag}}$ where $p \propto nT$ and $p_{mag} \propto B^2$, solve for n, and then square it to get $n^2 \propto \frac{\beta^2 B^4}{T^2}$. Substitute n^2 expression into P_{fus} to get

$$P_{fus} \propto \beta^2 \quad B^4 \quad \frac{< \sigma v >_{DT}}{T^2}$$

Set by MHD pressure (β) limits for a given confinement configuration

Set by superconducting magnet technology/plasma current magnitude

Usually maximized for a given fusion fuel cycle

We can express Lawson in terms of $\boldsymbol{\beta}$ and $\boldsymbol{B}$ as well using same definition for $\boldsymbol{\beta}$

- Volumetric fusion power density $P_{fus} \propto \beta^2 B^4$
- Lawson “Triple Product” $nT\tau_E = p\tau_E \propto \beta B^2 \tau_E$

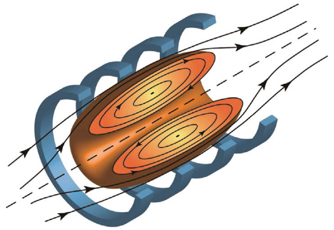
- Thus, it is to our advantage have both high β and B to 1) minimize the required energy confinement time τ_E to reach Lawson conditions and 2) maximize the volumetric fusion power density P_{fus}.

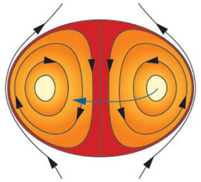
- You increase fusion power density via increasing B faster than with β.

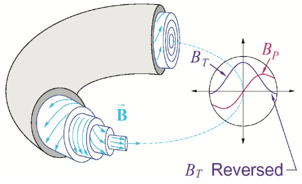
- Of course, there are other considerations (enough to base an entire field on!) besides these two equations that set your preferred operating point, but these are always useful tools when comparing various fusion energy concepts.

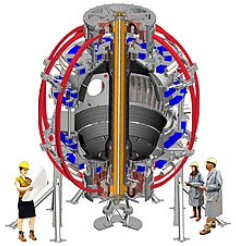
Toroidal fusion energy concepts

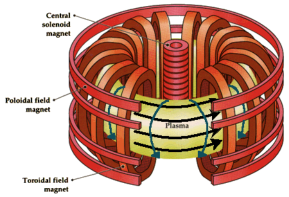
Toroidal confinement concepts can be differentiated by various properties, but one method is based on how magnetic fields are generated

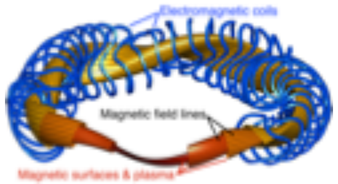


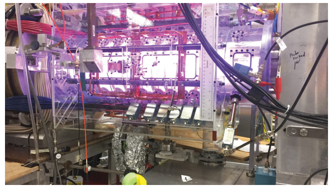


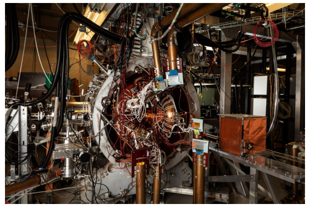


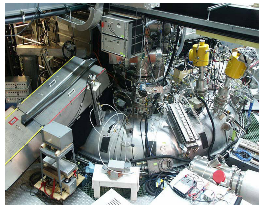


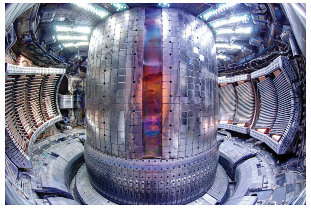


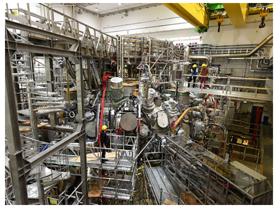












Field-reversed configuration (FRC)

Spheromak

Reversed-Field Pinch (RFP)

Spherical Tokamak

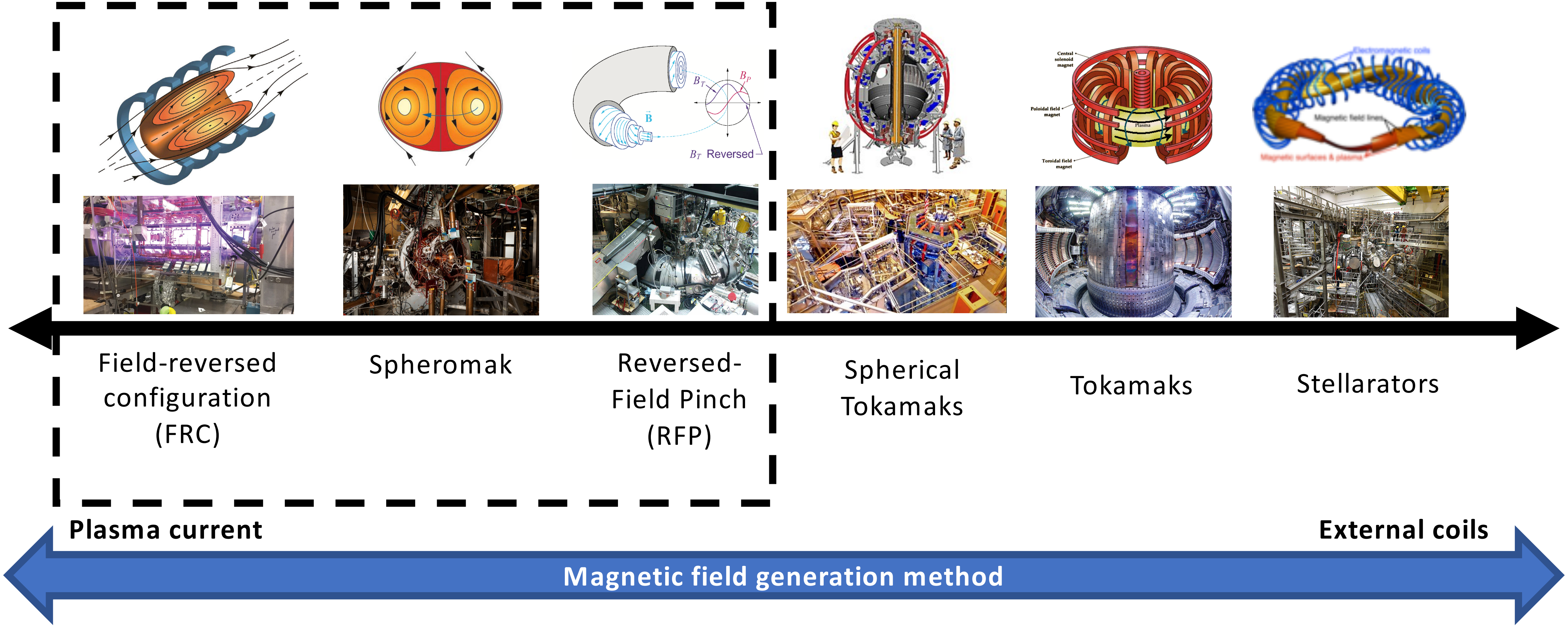
Tokamak

Stellarator

Plasma current | **External coils**

Magnetic field generation method

We're going to focus on the left three in this chart: field-reversed configurations (FRCs), spheromaks and reversed-field pinches (RFP) as alternative toroidal confinement concepts



Reversed-field pinches (RFPs): low applied magnetic field and high plasma current density

- RFPs are doubly connected (like a tokamak) toroidal confinement concepts that have much smaller applied toroidal magnetic fields ($B_T \sim B_P$) and higher plasma current density than a tokamak.
- The RFP gets its name from a reversal of the toroidal magnetic field near the edge of the confinement chamber.
- Due to large plasma currents, Ohmic ignition is possible if confinement τ_E is sufficiently good.
- Very rich and interesting plasma physics:
  - Plasma self-organization (helical states)
  - Advanced current drive (OFCD) and feedback control
  - MHD dynamo activity
  - ….

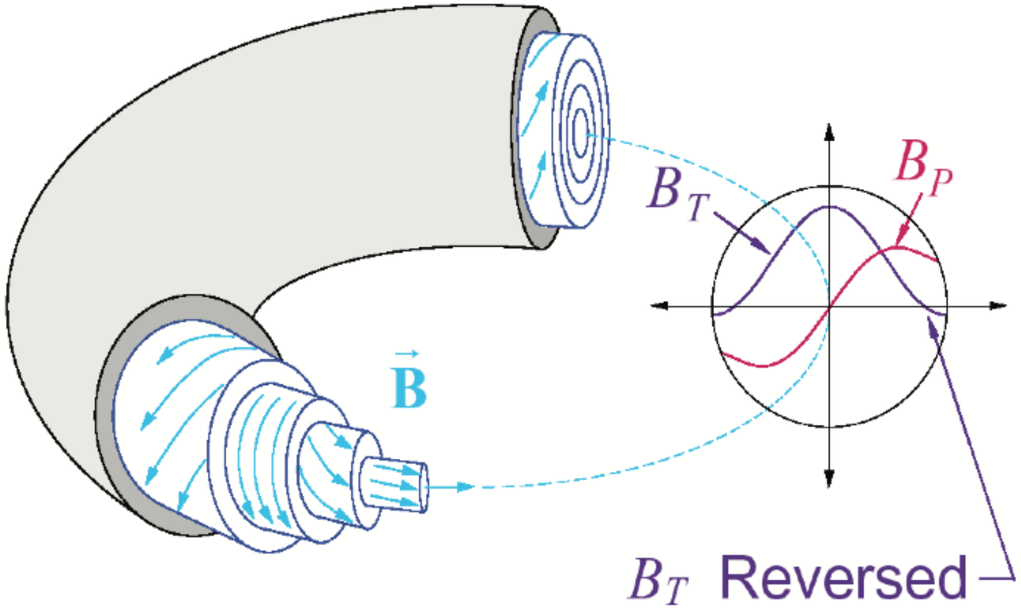


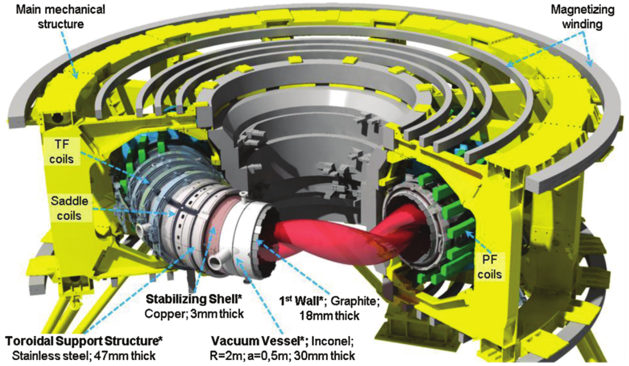
Figure: J. Sarff, Perspectives on Reversed Field Pinch (RFP) Fusion Research, FPA (2011)

Leading RFP experiments are MST at UW-Madison and RFX-Mod in Italy

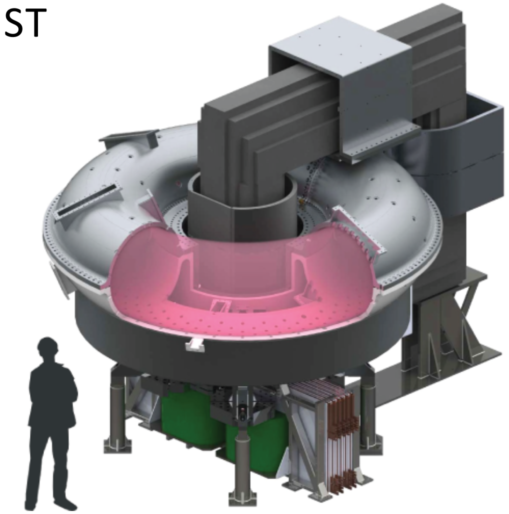
- RFPs produce keV plasma temperatures with high β.
- Plasma current profile control is an active area of research to help reduce instabilities that can degrade confinement quality.
- If scalable towards a fusion reactor, does not require as large applied toroidal magnetic fields (cheaper coil sets).
- Also, possibility of Ohmic ignition could eliminate the need for auxiliary heating systems.
- Recent results and improved understanding motivate continued R&D.

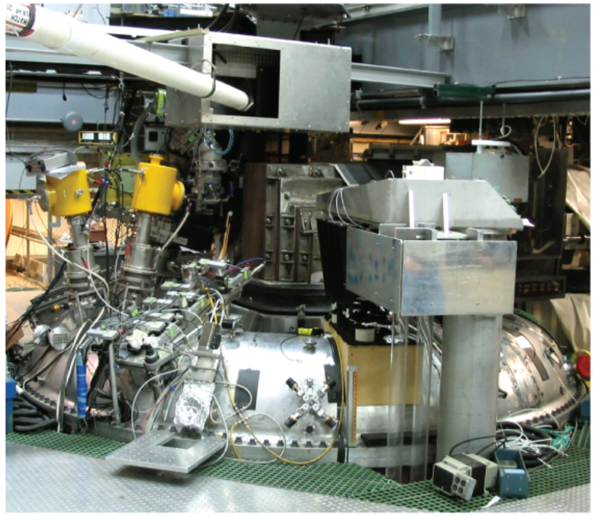
RFX-Mod

Peruzzo et al., FED 123, 59 (2017)



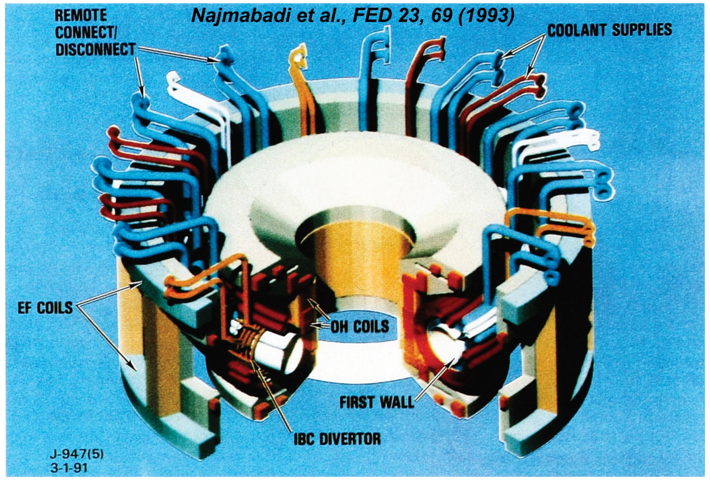
MST

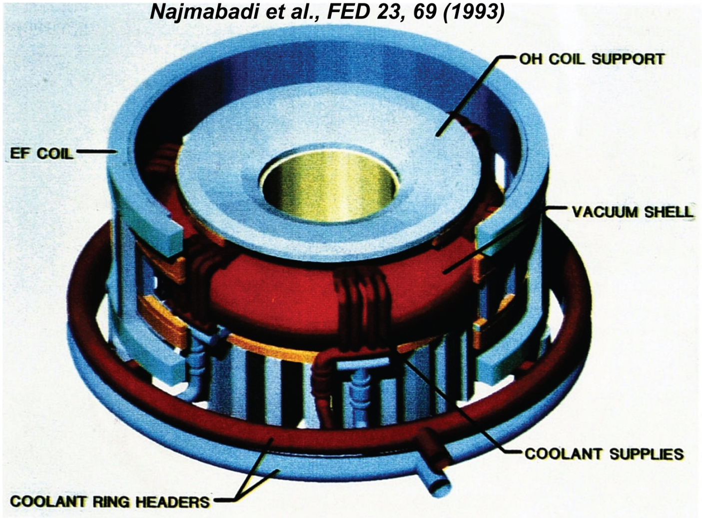




TITAN-I and TITAN-II reactor studies (1990s) provides vision for RFP-based fusion reactors

- Compact design, copper coils, competitive projected cost-of-electricity.
- TITAN had relatively high wall power loading as an aggressive, compact vision – may be relaxed to allow for less demanding physics and engineering requirements.
- New innovations in plasma current profile control and understanding of plasma self-organization in RFPs could improve reactor performance even more.
- Refer to resources in last slides for more information about RFPs (and other approaches in this talk!)





Spheromaks: a simply connected, compact toroidal confinement concept with no externally applied $\boldsymbol{B_T}$

- Spheromaks take the reduction of applied toroidal magnetic field one step further than the RFP and eliminates it – no toroidal field (TF) coil set is used.

- A Spheromak is a simply connected toroidal confinement concept with only plasma generated B_T. (The magnetic field defines a torus, but the confinement chamber is "simply" connected, or spherical in topology).

- Spheromaks belong to a family of "compact torus" (CT) confinement concepts (where "CTFusion" name comes from).

- Just like the RFP, due to larger plasma current densities, there is the possibility of Ohmic ignition if confinement is sufficiently good, eliminating the next for auxiliary heating and current drive systems.

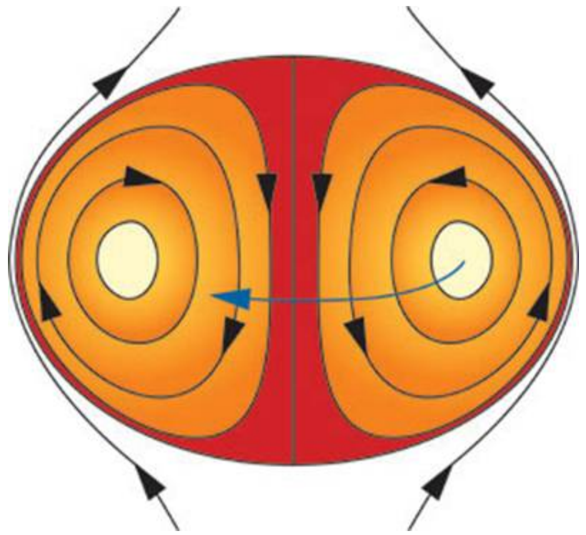


Figure: UW A&A Department, https://www.aa.washington.edu/research/HITsi/research/spheromak

- Toroidal plasma current generated confining poloidal magnetic field B_p.

- Poloidal plasma current creates stabilizing toroidal magnetic field B_T.

- Comparable strengths $B_T \sim B_p$.

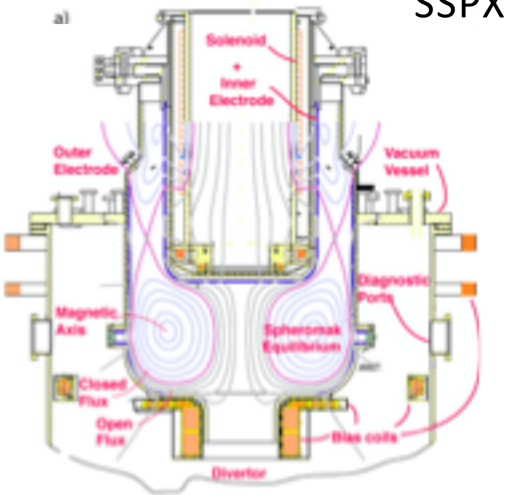
Spheromaks have reached transient plasma temperatures in excess of 500 eV, but sustainment remains an active area of R&D

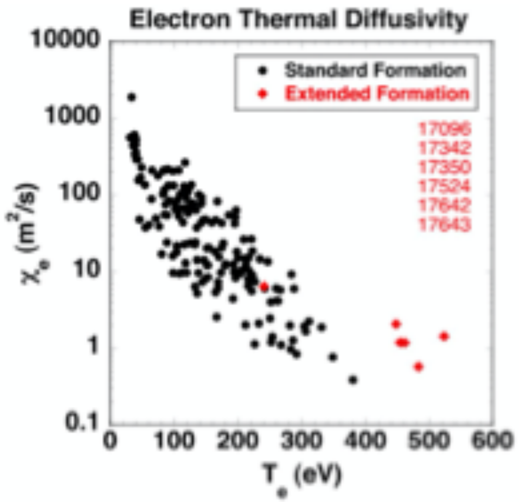
- The plasma currents in spheromaks must be sustained against resistive dissipation to maintain continuous operation.

- The sustained spheromak physics experiment (SSPX) had $T_e > 500$ eV during spheromak decay, but plasma instabilities generated during sustainment degraded confinement.

- Ongoing work at University of Washington and CTFusion funded by ARPA-E is assessing the scalability of this approach to fusion towards reactor-relevant plasma conditions – new HIT-SIU experiment coming online in 2021!

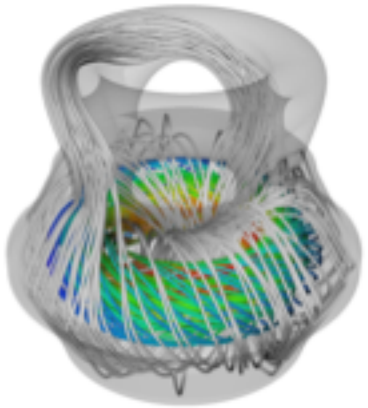
SSPX





Figures: B. Hudson, et al., Physics of Plasmas 15, 056112 (2008).

HIT-SIU Experiment (2021)

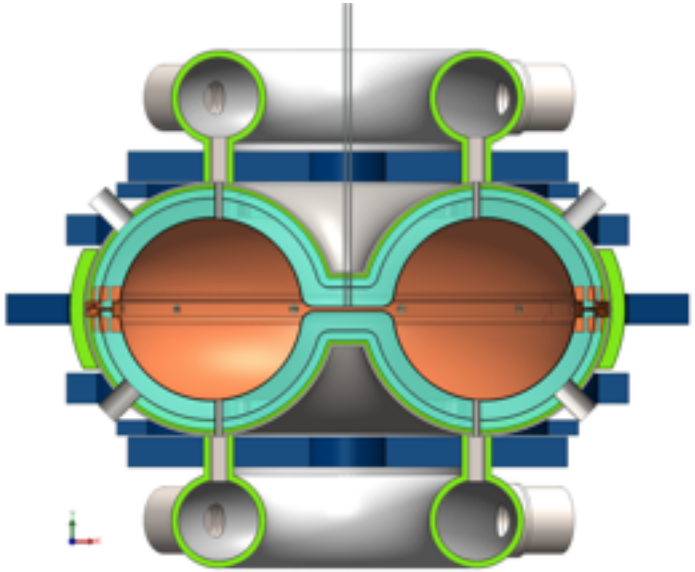


Figures: HIT-SI Research Group, University of Washington (subcontract with CTFusion, Inc.)

Spheromak-based fusion reactor system could be simpler and more compact than other toroidal confinement approaches

- Usage of a sustained spheromak may allow for:
  - Compact, low aspect ratio (A = R_o/a) devices while avoiding inboard real estate issues by eliminating the toroidal field coil set and central solenoid.
  - Full utilization of DT neutron flux for generation of tritium for a closed DT fuel cycle.
  - Possibility of Ohmic ignition if confinement is sufficiently good due to higher plasma current densities $P_{Ohmic} \propto \eta j^2$, eliminating need for auxiliary heating systems (like RFP).
  - And more…

- But sustained spheromak must first demonstrate:
  - Scaling towards keV plasma temperatures with sufficient energy confinement quality.
  - Control of the plasma current profile near the minimum energy state to avoid excess free energy in the system that could drive plasma instabilities.
  - Demonstrate power efficient sustainment of plasma current within the keV plasma temperature regime.



”Dynomak” 1 GWe reactor vision based on sustained spheormak

D.A. Sutherland, et al., Fusion Engineering and Design **89**, 4 (2014).

Field-reversed configurations (FRCs): compact toroidal confinement configurations with little/no B_T

- Compact torus with only poloidal magnetic field B_P generated by toroidal plasma current.
- High-β configurations with field null at magnetic axis (since no toroidal field present).
- Stability issues that must be dealt with (significant progress made on this front).
- Requires sustainment of toroidal plasma current using some method (e.g. neutral beam injection, rotating magnetic field (RMF) current drive) to operate continuously.

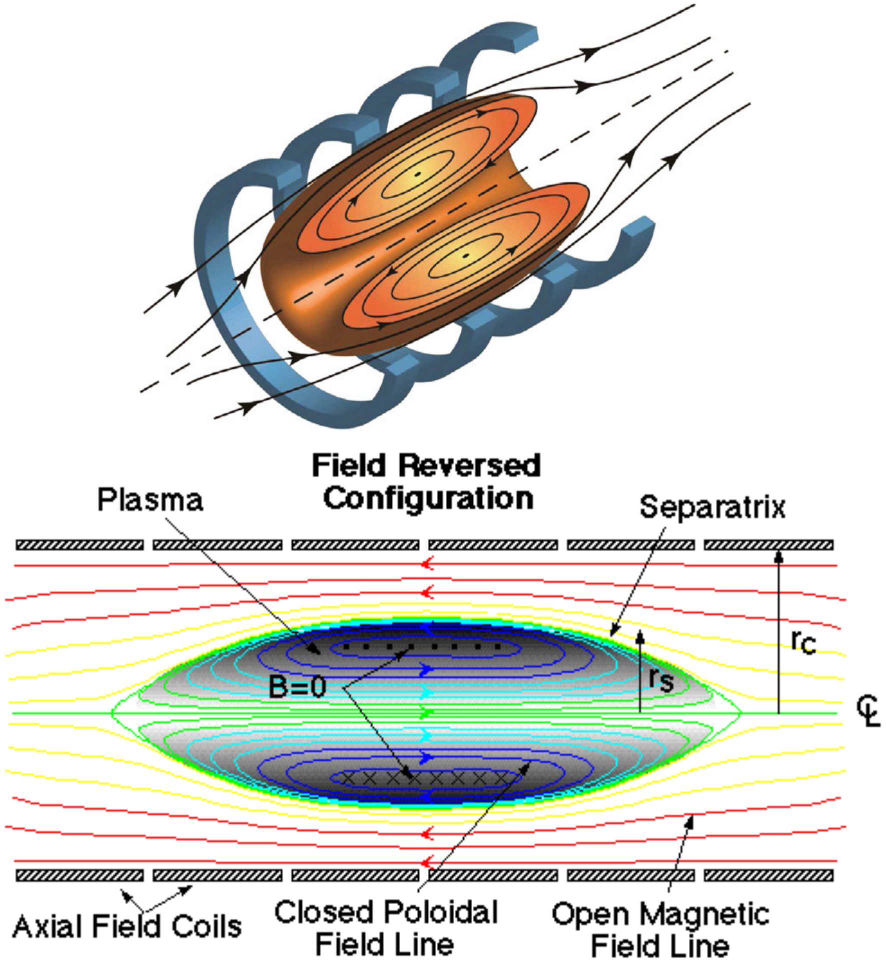
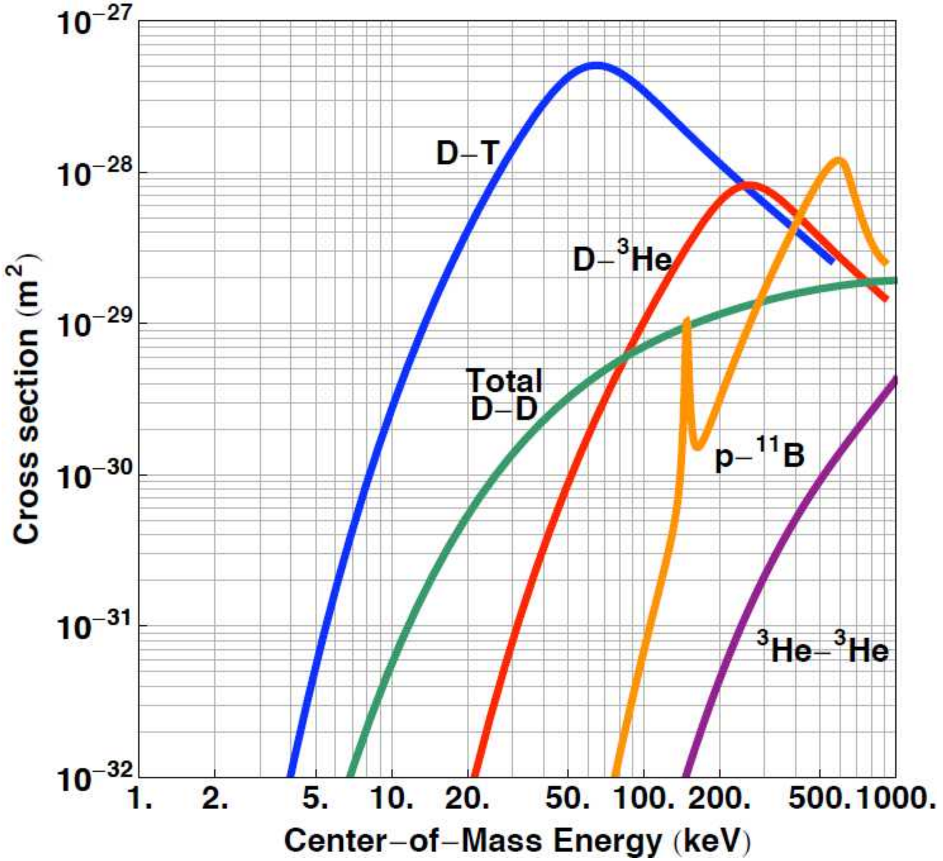


Figure: PPPL, FESAC Toroidal Alternates Panel (2008).

Higher-β (> 0.50) configurations like the FRC allows for the consideration of advanced fusion fuel cycles

- Advanced fuel cycles (D-D, D-^{3}He, p-^{11}B) require higher temperatures than D-T but produce less neutrons and eliminates the need to breed tritium (p-^{11}B is the least ”neutronic”).
- Neutrons can have negative impacts on reactor materials and lead to activation of reactor materials.
- But, having more fusion yield come in the form of charged fusion products can make other issues harder (e.g. heat exhaust) depending on the specifics of your approach.
- Also, at higher temperatures required for these fuel cycles, radiation losses (e.g. synchrotron) become more of a concern, which strongly favors high-β approaches by reducing required magnetic field B.
- FRC projects underway today are primarily looking at the target fuel cycles of D-^{3}He and p-^{11}B.



C-2W at TAE Technologies and PFRC2 at PPPL are currently operating sustained FRC experiments using different sustainment methods

Neutral-beam driven FRC

tae TECHNOLOGIES

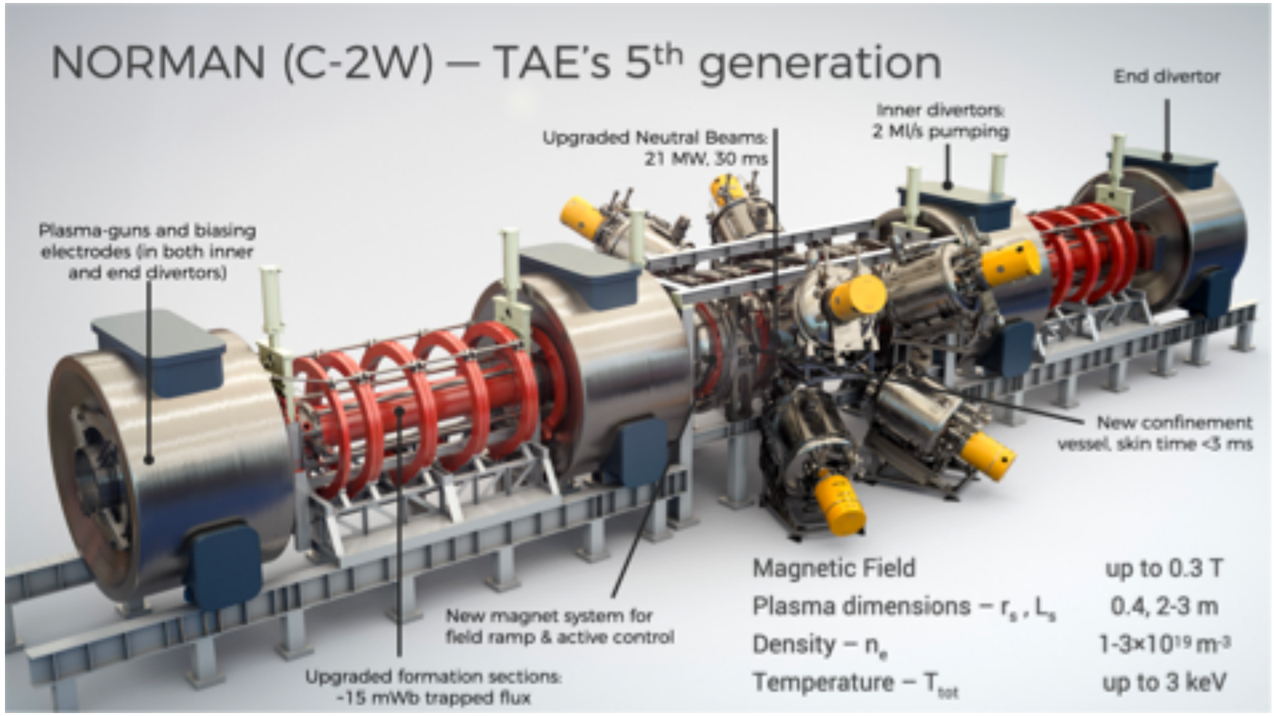
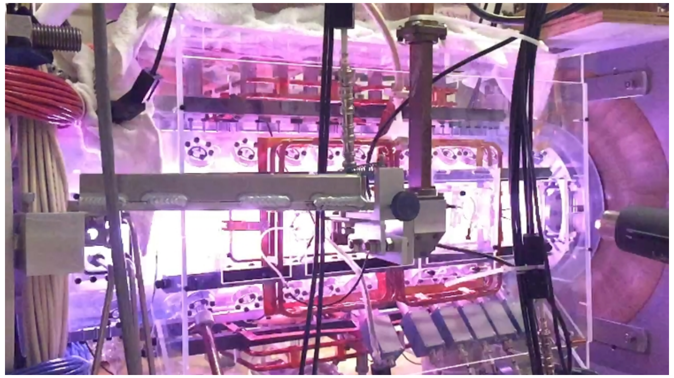


Figure: “Progress and Next Steps at TAE” Michl Binderbauer, 40th FPA Annual Meeting (2019).

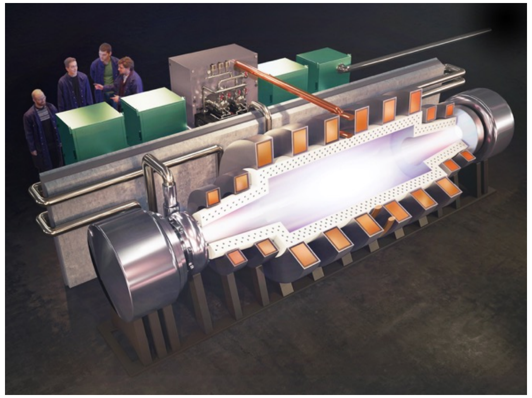
Rotating magnetic field (RMF)-driven FRC

PPPL PRINCETON PLASMA PHYSICS LABORATORY



Princeton Fusion Systems

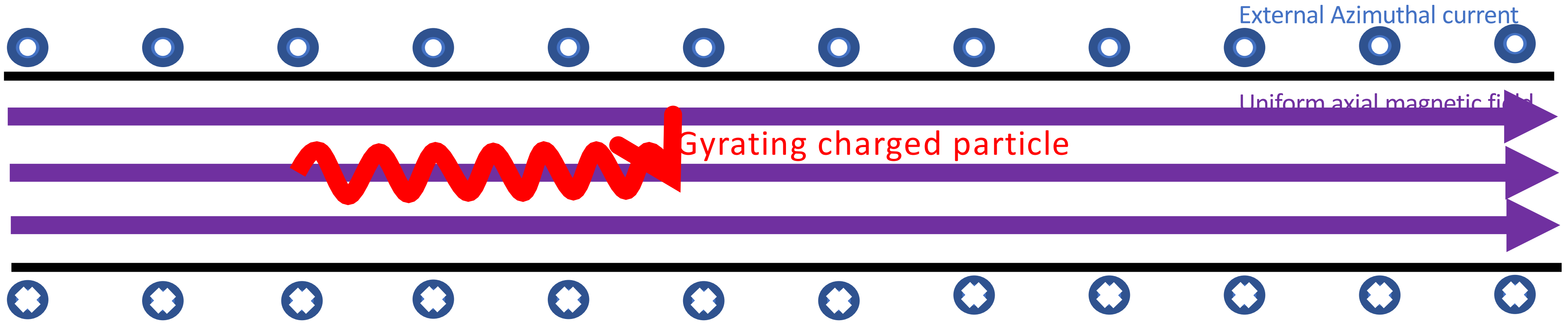
PrincetonSATELLITE SYSTEMS



Figures: Dr. S. Cohen, Princeton Plasma Physics Lab

Magnetic mirrors

Consider a linear confinement concept with only axial field to start



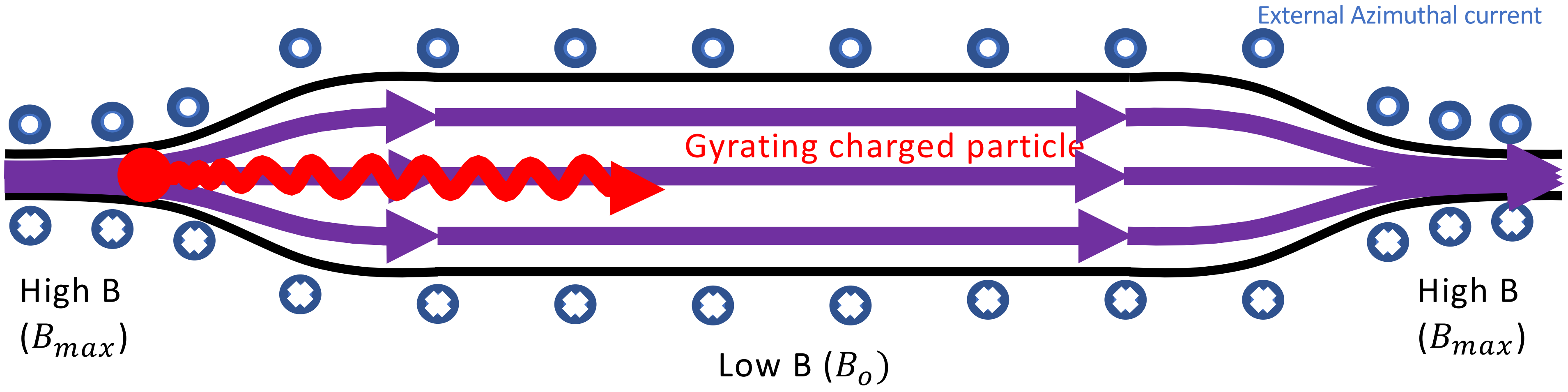
Basic principle of magnetic confinement from Lorentz force is confinement perpendicular to magnetic field but free stream along magnetic field direction.

Parallel thermal conduction would require unreasonably long (~100 km) linear device to be able to reach fusion temperatures in this type of machine (running steady-state).

Need a method to ”plug” the ends of this concept to shorten the total length of device required to reach fusion conditions.

Fun extra: When this type of concept is used in a pulsed fashion, it’s commonly referred to as a theta-pinch (azimuthal current direction θ, θ-pinch) and can be used to generate field-reversed configurations (FRCs) as well.

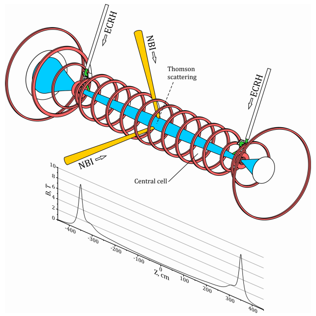
Plug the ends of this linear device with bigger magnetic fields to create a magnetic mirror machine

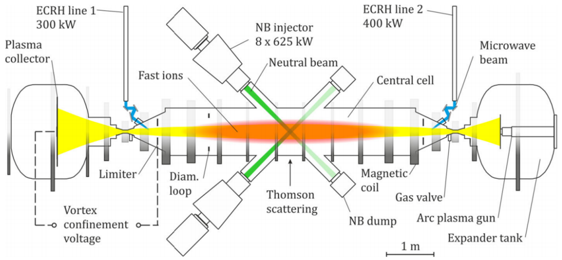


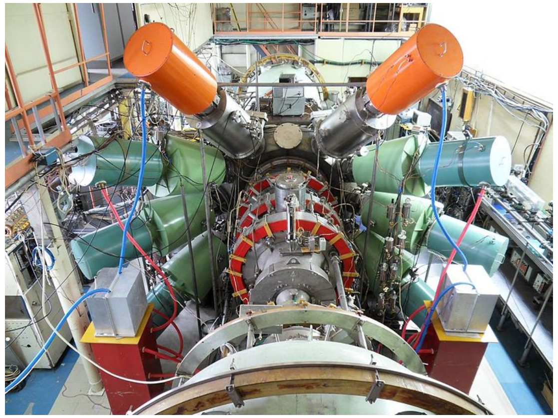
- By creating regions of higher B and lower B, a magnetic field gradient is introduced to the confinement region.
- Derive magnetic mirror effect using: the conservation of magnetic moment $\mu = \frac{m v_\perp^2}{2B}$, the force on a magnetic moment due to a gradient in the magnetic field, and conservation of kinetic energy.
- If parallel (to magnetic field) velocities are sufficiently low, particles are reflected at a magnetic mirror point back into the lower B region.
- Particles with sufficient energy to escape along field lines through the region of high B are lost from the system (and are part of the so-called "loss cone" in velocity space (smallest confined $\theta, \sin^2(\theta) = \frac{B_0}{B_{max}} = \frac{1}{R_m}$ where R_m is mirror ratio and $\sin(\theta) = v_\perp / v_\parallel$)

Magnetic mirrors are attractive due to their simplicity and their ability to run steady-state but methods of reducing losses and maintaining MHD stability is an active area of research

- Gas Dynamic Trap (GDT) in Russia
  - $R_m \sim 100$
  - NBI and ECRH heating
  - $T_e \sim 1$ keV, $n_i \sim 1 \times 10^{20}$ m^{-3}







Figures: GDT Wikipedia page, https://en.wikipedia.org/wiki/Gas_Dynamic_Trap

- Two ongoing ARPA-E projects:
  - Centrifugal Mirror Experiment (University of Maryland)
    - Using supersonic rotation of mirror to help close loss cone to reduce parallel end losses.
    - Velocity shear to help stabilize interchange instability modes.
  - Wisconsin High-field Axisymmetric Mirror (University of Wisconsin-Madison)
    - Use high-temperature superconductors capable of much higher steady-state magnetic fields than previously possible – increase mirror field strength $B \sim 17 - 20 +$ T.
- Interest in these devices for fusion but also as potential, relatively low-cost volumetric neutron source (VNS) to test materials/components in DT fusion neutron environment.
- Lastly, magnetic mirroring occurs in fusion energy concepts, such as in tokamaks with banana orbits due to the 1/R toroidal magnetic field variation from the toroidal field coil set.

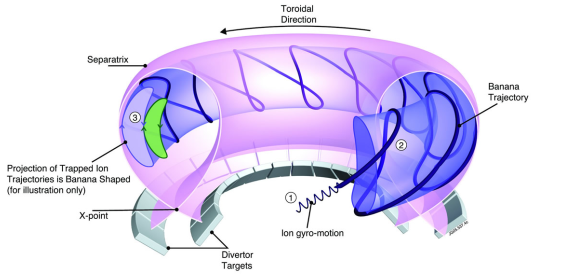


Figure: EUROfusion, https://www.euro-fusion.org/news/detail/detail/News/from-doughnuts-to-bananas/

Magneto-Inertial Fusion

So far, we have focused the conversation on relatively low plasma density, continuous (or long-pulse) alternative magnetic fusion energy (MFE) concepts

- The types of approaches discussed so far: RFPs, spheromaks, FRCs, and mirrors are being developed with the intent to use as the basis of a steady-state (or very long pulse) fusion power plant.
- However, some of these concepts (e.g. spheromak and FRC in particular) also are of interest for pulsed fusion approaches that instead target medium-density plasma regimes (remember Lawson).
- In fact, there is an entire field of fusion R&D characterized by an intermediate density regime called magneto-inertial fusion (or sometimes called magnetized target fusion (MTF)) that is between MFE and ICF.
- In short, this approach to fusion is based on compressing a magnetized plasma target toward fusion conditions.
- Depending on the target type and compression method, a given MIF fusion energy concept maximum density can span many orders of magnitude between MFE ($\sim 10^{20}$ m^{-3}) and ICF ($\sim 10^{31}$ m^{-3}).

A recent U.S. DOE ARPA-E program called ALPHA focused on the development of intermediate-density fusion energy concepts and supporting technologies

- The ALPHA program postulated that a lower cost approach to fusion may be possible in the intermediate density regime.
- However, this ALPHA program builds upon decades of R&D of this type of approach to fusion.
- This approach can naturally be separated into a discussion regarding:
  - Plasma drivers
  - Plasma targets
  - Supporting technology
- Note: You'll hear about Z-pinches, MagLIF, and pulsed power in a later talk.

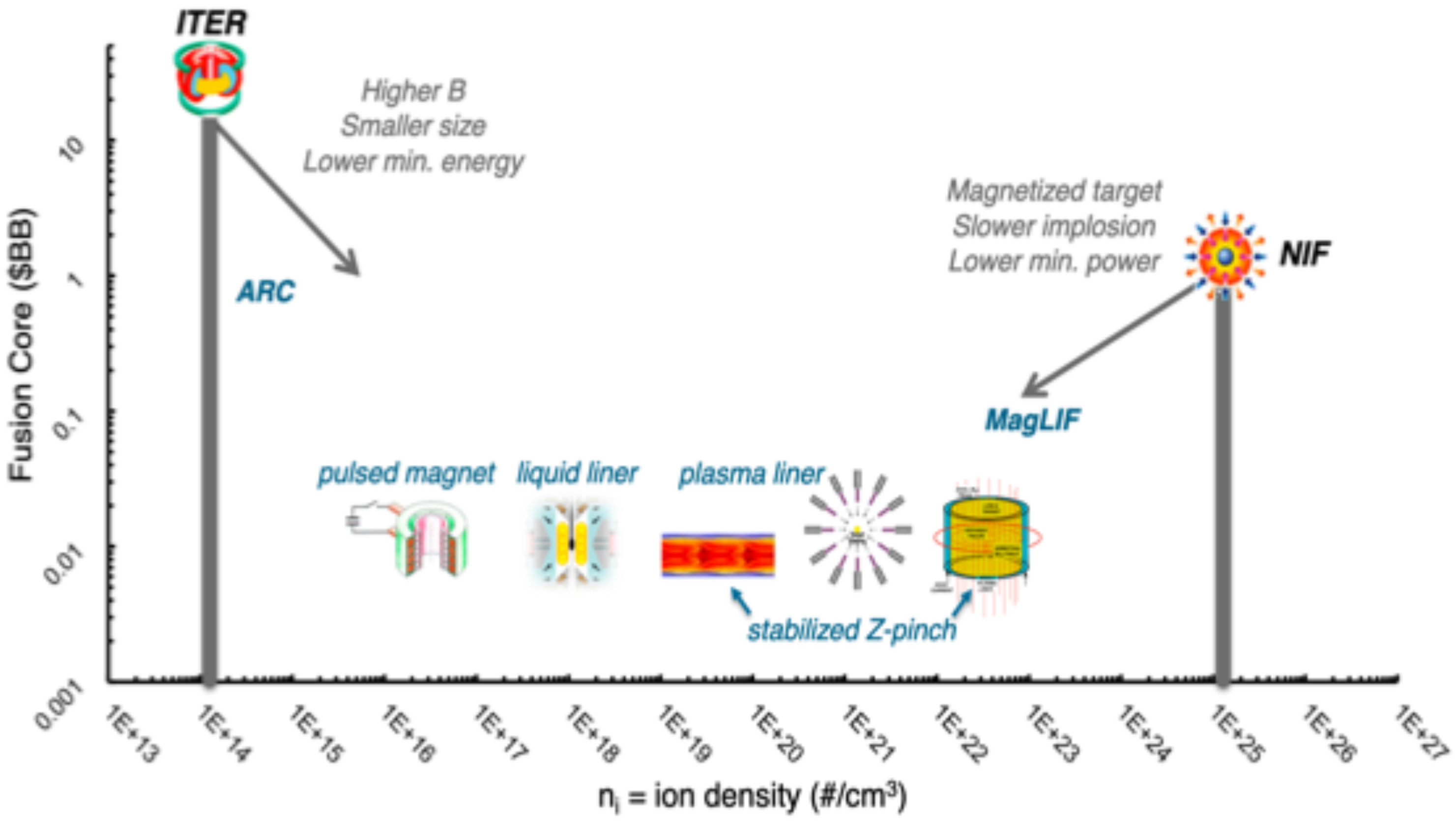
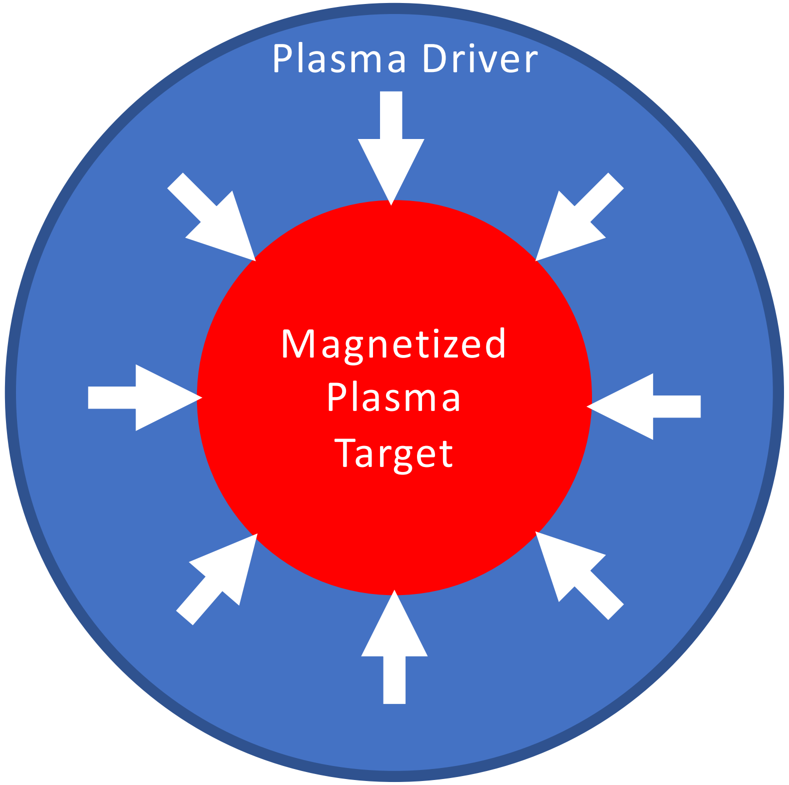


Figure: ALPHA: Seeking Faster and Cheaper Fusion Development, P. McGrath and R. Umstattd, ARPA-E.

Plasma targets, drivers, and supporting systems makeup a MIF concept

- Plasma target is magnetized to reduce thermal transport and enhance fusion product energy deposition in plasma (self-heated).
- Plasma driver is used to compress plasma target to increase plasma density (and usually magnetic field as well).
- Shares characteristics from both magnetic fusion (e.g. overlap with types of plasma targets) and inertial confinement (e.g. compressing target to reach higher density plasma conditions).
- But MIF relaxes both the stored power requirement (primarily in magnetic fields) and large plasma size of MFE and the very high required implosion velocity and heating power of ICF.
- Power supply system usually requires large scale pulsed power system or some other method of compression (e.g. pneumatic driven liquid metal at General Fusion).



Potential plasma targets for MIF: FRCs and spheromaks just to name a few

- **Field-reversed configurations (FRCs):**
  - Compact, translatable plasma configurations – allows for formation in one area and translation to compression region.
  - High-β with only poloidal magnetic field B_p – maximizes compressional energy going into density and confining field.
  - Plasma geometry lends itself towards cylindrical compression.

- **Spheromaks:**
  - Compact, translatable plasma configurations (like an FRC).
  - Relatively low-β compared to FRC but with stabilizing B_T.
  - Plasma geometry lends itself more towards spherical compression but can still be compressed cylindrically so long as plasma stability is maintained.

- **Key challenge:** making a starting plasma target that has sufficiently high plasma temperatures and density and maintain stability and confinement during translation and compression to fusion conditions.

Plasma drivers: many choices for the method of compression

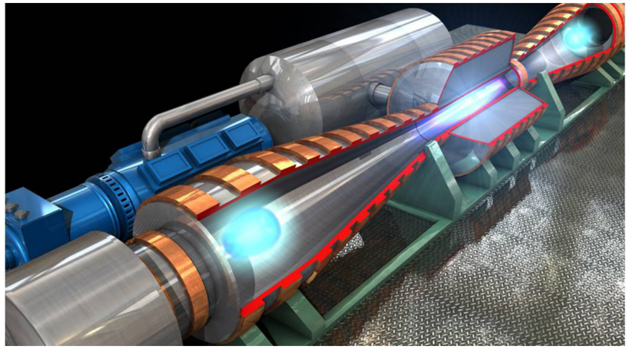
- Provided with your favorite choice for a plasma target, now you must decide how to compress it.

- There are quite a few different approaches being consider as plasma drivers for MIF, but a few are:
  - **Magnetic compression:** Quickly ramping external magnetic fields to compress confinement fields (usually the slowest, lower peak density MIF approach).
  - **Liquid liner compression:** Using the conductive nature of a liquid metal to compress a magnetized plasma target (avoids replacement of solid materials that are destroyed during implosion process).
  - **Solid liner compression:** Using a solid liner to compress a magnetic plasma target (usually is destroyed during implosion process and must be replaced between pulses).
  - **Plasma liner compression:** Using plasma to compress a magnetized plasma target (similar to liquid metal as far as nondestructive nature but avoid using higher density liquid plasma-material interface that can pollute plasma).

- We will explore a few approaches that make use of these various types of plasma target and driver techniques for MIF.

FRCs with magnetic, liquid metal, and solid liner compression for MIF at Helion Energy, Compact Fusion Systems and FRCHX at LANL/AFRL

Helion Energy – Fusion Engine



Helion Energy

Figure: Website, helionenergy.com

- Two FRCs are formed, translated and merge into plasma target.
- FRC is magnetically compressed to fusion conditions.
- Part of ARPA-E ALPHA program.

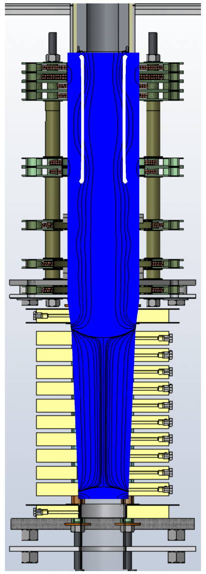
Compact Fusion Systems

Figure: S. Woodruff, ARPA-E meeting poster

- Liquid metal compression of FRCs.
- Pneumatic (pistons and compressed gas) compression, pulsed-power injectors for plasma target.
- Actively funded work by ARPA-E.

Solid liner compression in FRCHX – LANL/AFRL

Figures: Courtesy of G.A. Wurden, LANL.



- FRC is formed and translated into compression region.
- 10 MA-scale current flows axially through solid metal liner which causes it to pinch radially inward.
- Compression of FRC to fields on the order of 100s of T and high density.
- Concluded that a higher quality initial plasma target and improved FRC position control was required for concept to reach desired fusion conditions.
- Also for undergrads** this was my first lab experience in the fusion field during a summer internship after my freshman year at MIT, lots of fun!

Spheromaks and spherical tokamak pneumatic compression with liquid metal (and high explosives!!) at General Fusion

- General Fusion has explored pneumatic piston driven liquid metal compression of both spheromaks and spherical tokamaks.
- Originally, used coaxial helicity injection to form spheromaks, and then accelerate them towards the compression region.
- However, it proved difficult to maintain a high quality (high T) spheromak plasma target during the formation and acceleration stages.
- Uses high explosives to simulate compression stage prior to building full scale compression system for power plant demonstration.
- Modifying the specifics of this approach a bit, General Fusion is now exploring coaxial formation of spherical tokamak plasmas that is then compressed by a liquid metal liner.
- CHI for the formation and startup of spherical tokamaks was done in HIT-II at the University of Washington and on NSTX to aid in non-inductive startup (knowledge and skills developed researching a particular fusion approach can apply to other approaches as well!)

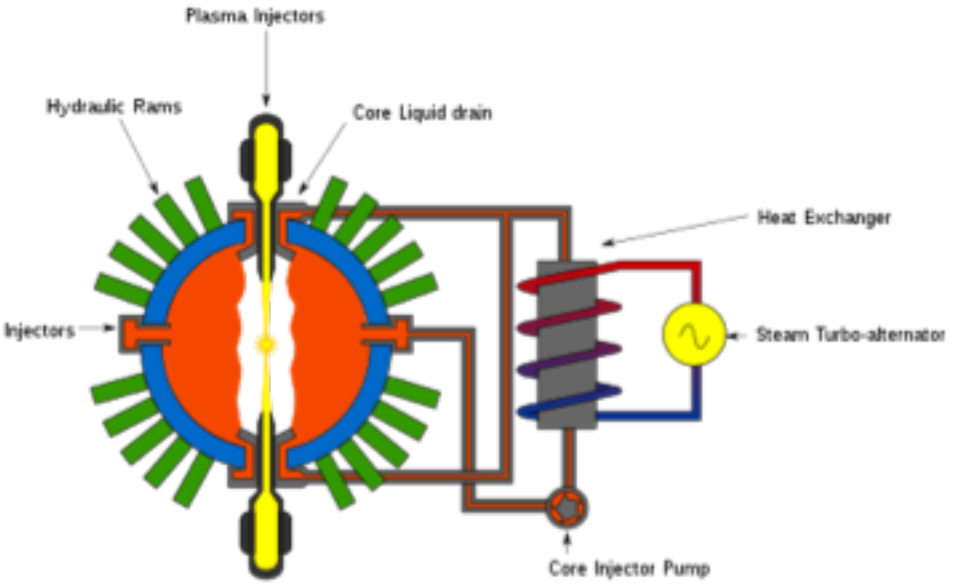


Figure: General Fusion Wikipedia Page, https://en.wikipedia.org/wiki/General_Fusion

- Also for undergrads** this was my second lab experience in the fusion field during a summer internship. Lots of fun!

generalfusion®

ST plasma formed by coaxial helicity injection into liquid metal cavity

- Temperature: ~500 eV
- Density: ~1E20 m^{-3}
- Cavity diameter: ~4 m

Piston array compression

- ~7:1 radial compression
- 20 ms compression time

Liquid Metal Liner serves as:

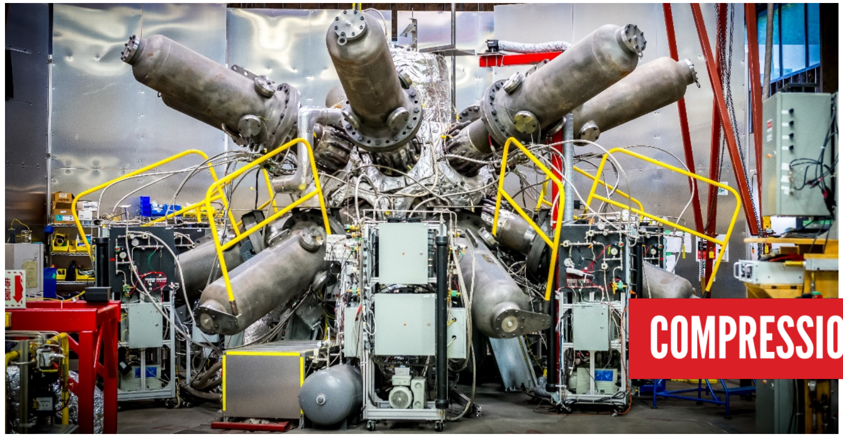
- First Wall
- Neutron Blanket
- Tritium Breeding
- System Coolant
- Radiation Shielding

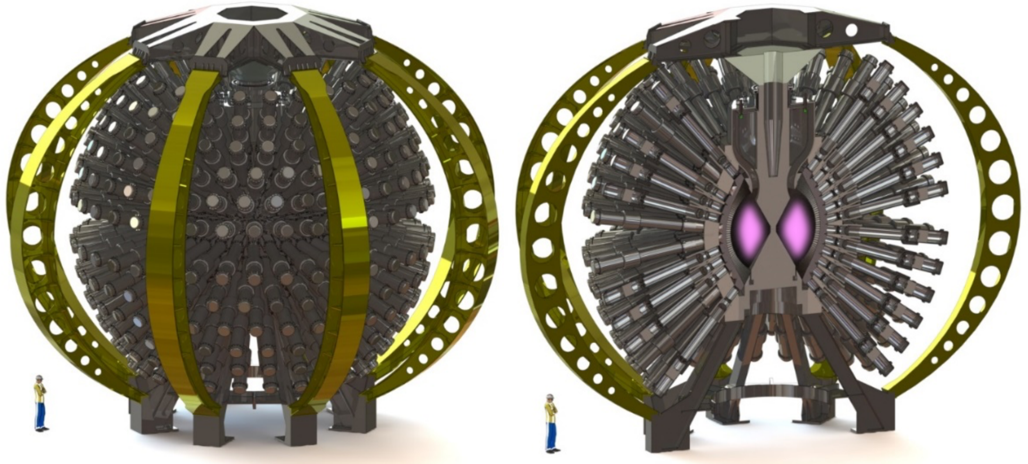
Slides contributed by Michael Delage, *General Fusion*, Burnaby, BC, Canada

generalfusion

generalfusion

General Fusion Development Activities





Slide contributed by Michael Delage, *General Fusion,* Burnaby, BC, Canada

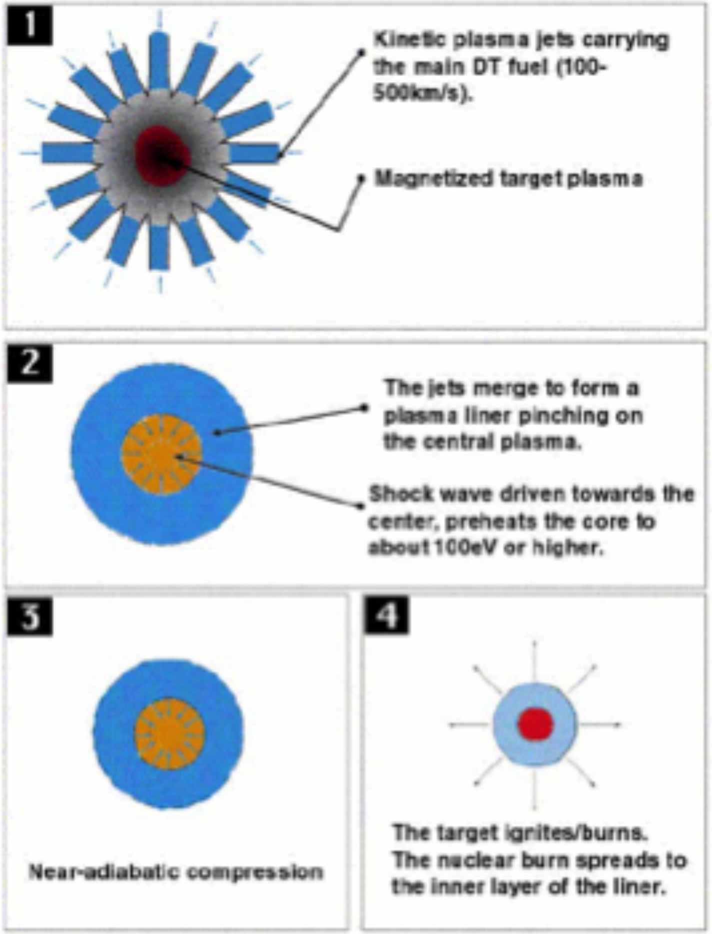
Another MIF approach is to use plasma jets to compress a plasma target to fusion conditions – Plasma Jet Magneto Inertial Fusion (PJMIF)

- Spherical implosion of a magnetized fusion target with standoff drivers was conceived in the late 1990s.*

- Approach is generally referred to as PJMIF.

This approach generally has the following features:
- A magnetized plasma target with very high β
- Low-cost, high-efficiency, standoff plasma-gun drivers
- Uses high-Z (e.g. Xenon) plasma jets to compress target
- High implosion speeds (> 50 km/s)
- High final compression densities for potentially high energy gain (> 20)

*Y. C. F. Thio et al., in Current Trends in International Fusion Research – 2nd International Symposium, ed. E. Panarella (NRC Canada, Ottawa, 1999), p. 113.

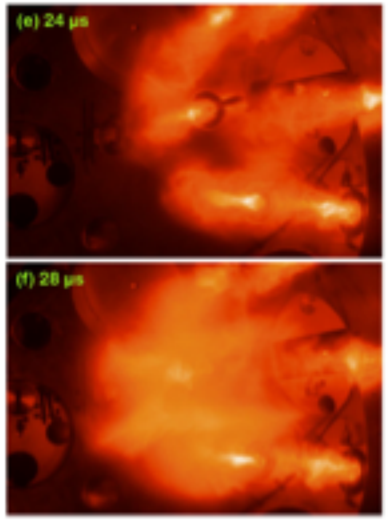


On-going research and development activities of PJMIF with Plasma Liner Experiment (PLX)-α project

- Advanced plasma guns being developed by HyperJet Fusion Corporation and testing in PLX-α experiment at LANL.
- Gun development and testing in PLX-α during ARPA-E ALPHA program with six plasma guns.
- Good results motivated continuation of project and ramping up number of plasma guns to demonstrate liner compression of a plasma target up to keV, Mbar temperatures and pressures.
- Ongoing development at LANL and HyperJet as part of ARPA-E BETHE program.

Los Alamos NATIONAL LABORATORY EST. 1943

HYPERJET FUSION CORPORATION



STRONG ATOMICS

arpa·e CHANGING WHAT'S POSSIBLE

S. C. Hsu at al., "Experiment to Form and Characterize a Section of a Spherically Imploding Plasma Liner," IEEE Trans. Plasma Sci. **46**, 1951 (2018).

A video concept of a PJMIF-based fusion reactor

Video courtesy of HyperJet Fusion Corporation

HYPERJET FUSION
CORPORATION

Summary

- Alternative fusion concepts are generally regarded as non-tokamak and non-stellarator approaches to fusion energy.

- Various fusion energy approaches that all approach Lawson with different combinations of plasma density and confinement time.

- This talk focused on the follow alternative concepts:
  - **Toroidal magnetic fusion energy:** RFPs, Spheromaks, and FRCs
  - **Magnetic mirrors:** GDT, centrifugal mirror, HTS mirror.
  - **Magneto-inertial fusion:** FRC, spheromak, and ST targets with solid, liquid metal and plasma jet drivers.

Recommendations

- In this talk, we have discussed a series of alternative fusion energy approaches, but this is by no means an exhaustive list.

- Other concepts you will hear about are Z-pinches, MagLIF, and ICF which are towards higher plasma densities.

- Other concepts you may want to investigate for more information:
  - Magnetic cusps
  - Levitated dipoles
  - …

Additional resources – General overview and RFPs

Introductory Textbook:

J. Freidberg, Plasma Physics and Fusion Energy, *Cambridge University Press* (2007)

RFPs

- H.A.B Bodin & A.A. Newton, "Reversed-field pinch research," *Nucl. Fusion* **20**, 10 (1980), https://doi.org/10.1088/0029-5515/20/10/006
- H.A.B. Bodin, "The Reversed Field Pinch," *Nucl. Fusion* **30**, 9 (1990), https://doi.org/10.1088/0029-5515/30/9/005.
- J.S. Sarff, et al., "Fluctuation and transport reduction in a reversed field pinch by inductive poloidal current drive," *Phys. Rev. Lett.* **72**, 3670 (1994), https://doi.org/10.1103/PhysRevLett.72.3670
- J.S. Sarff, et al., "Increase Confinement and β by Inductive Poloidal Current Drive in the Reversed Field Pinch," *Phys. Rev. Lett.* **78**, 62 (1997), https://doi.org/10.1103/PhysRevLett.78.62
- D.F. Escande, et al., "Quasi-Single-Helicity Reversed-Field-Pinch Plasmas," *Phys. Rev. Lett*. **85**, 1662 (2000), https://doi.org/10.1103/PhysRevLett.85.1662
- B.E. Chapman, et al., "High confinement plasmas in the Madison Symmetric Torus reversed-field pinch," *Phys. Plasmas* 9, 2061 (2002), https://doi.org/10.1063/1.1456930
- S.C. Prager, et al., "Overview of results in the MST reversed field pinch experiment," *Nucl. Fusion* **45**, 10 (2005), https://doi.org/10.1088/0029-5515/45/10/S23
- K.J. McCollam, et al., "Oscillating-Field Current-Drive Experiments in a Reversed Field Pinch," *Phys. Rev. Lett.* **96**, 035003 (2006), https://doi.org/10.1103/PhysRevLett.96.035003.
- **And much more…**

Additional resources (cont'd) - Spheromaks

- P.M. Bellan, "Magnetic Helicity, Spheromaks, Solar Corona Loops, and Astrophysical Jets," *World Scientific Publishing Europe Ltd.* (2018).
- M.N. Rosenbluth and M.N. Bussac, "MHD stability of spheromak," *Nucl. Fusion* **19**, 489 (1979). https://doi.org/10.1088/0029-5515/19/4/007.
- T.R. Jarboe, "Review of spheromak research," *Plasma Phys. Control. Fusion* **36,** 945 (1994). https://doi.org/10.1088/0741-3335/36/6/002.
- R.L. Hagenson and R.A. Krakowshki, "Steady state spheromak reactor studies," *Fus. Tech.* **8**, Issue 1P2B (1985), https://doi.org/10.13182/FST85-A39989
- C.W. Barnes, et al., "Experimental determination of the conservation of magnetic helicity from the balance between source and spheromak," The *Phys. Of Fluids* **29**, 3415 (1986), https://doi.org/10.1063/1.865858.
- H.S. McLean, et al., "Suppression of MHD fluctuations leading to improved confinement in a gun-driven spheromak," *Phys. Rev. Lett.* **88**, 125004 (2002) https://doi.org/10.1103/PhysRevLett.88.125004.
- T.R. Jarboe, et al., "Spheromak Formation by Steady Inductive Helicity Injection," *Phys. Rev. Lett.* **97**, 115003 (2006), https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.97.115003
- M.R. Brown, et al, "Flow dynamics and plasma heating of spheromaks in SSX," *Joul. Fus. Eng.* **27**, 16-19 (2008), https://doi.org/10.1007/s10894-007-9097-y
- T.R. Jarboe, et al., "Imposed-dynamo current drive," *Nucl. Fus.* **52**, 8 (2012), https://doi.org/10.1088/0029-5515/52/8/083017.
- D.A. Sutherland, et al., "They dynomak: An advanced spheromak reactor concept with imposed-dynamo current drive and next-generation nuclear power technologies, *Fus. Eng. Design* **89**, 4 (2014), https://doi.org/10.1016/j.fusengdes.2014.03.072
- **And much more…**

Additional resources (cont'd) –FRCs

- T. Asai, et al., "Experimental evidence of improved confinement in a high-beta field-reversed configuration plasma by neutral beam injection," *Phys. Plasmas* **7**, 2294 (2000), https://doi.org/10.1063/1.874121.
- H.Y. Guo, et al., "Formation and steady-state maintenance of field reversed configuration using rotating magnetic field current drive," *Phys. Plasmas* **9**, 195 (2002), https://doi.org/10.1063/1.1426102.
- J.M. Taccetti, et al., "FRX-L: A field-reversed configuration plasma injector for magnetized target fusion," *Rev. Sci. Instrum.* **74**, 4314 (2003), https://doi.org/10.1063/1.1606534.
- T.P Intrator, et al., "Field Reversed Configuration Translation and the Magnetized Target Fusion Collaboration," *Joul. Fus. Eng.* **28**, 165-169 (2009), https://doi.org/10.1007/s10894-008-9180-z.
- L.C. Steinhauer, "Review of field-reversed configurations," *Phys. Plasmas* **18**, 070501 (2011), https://doi.org/10.1063/1.3613680.
- M.W. binderbauer, et al, "Dynamic Formation of a Hot Field Reversed Configuration with Improved Confinement by Supersonic Merging of Two Colliding High-β Compact Toroids," *Phys. Rev. Lett.* **105**, 045003 (2010), https://doi.org/10.1103/PhysRevLett.105.045003.
- C. Grabowski, et al., "FRC lifetime studies for the Field Reversed Configuration Heating Experiment (FRCHX)," *2011 IEEE Pulsed Power Conference*, Chicago, IL (2011), doi: 10.1109/PPC.2011.6191459.
- M.W. Binderbauer, et al., "A high performance field-reversed configuration," *Phys. Plasmas* **22**, 056110 (2015), https://doi.org/10.1063/1.4920950.
- **And much more…**

Additional resources (cont'd) –Magnetic Mirrors

- R.F. Post, "The magnetic mirror approach to fusion," *Nucl. Fusion* **27**, 1579 (1987), https://doi.org/10.1088/0029-5515/27/10/001.
- T.C. Simonen, "Experimental progress in magnetic-mirror fusion research," *Proceedings of the IEEE* **69**, 8 (1981), doi: 10.1109/PROC.1981.12108.
- R.F. Post and D.D. Ryutov, "Mirror fusion research: Update and prospects," *Comments on Plasma Phys. Control. Fus.*, **16**, 6 (1995), https://www.osti.gov/etdeweb/biblio/180624.
- R.F. Ellis, et al., "An Experiment to test centrifugal confinement for fusion," *Phys. Plasmas* **8**, 2057 (2001), https://doi.org/10.1063/1.1350957.
- A.A. Ivanov, et al., "GDT Device. Recent Results and Future Plans for GDT Upgrade," *Fus. Sci. Tech.* **43**, 51-57 (2003), https://doi.org/10.13182/FST03-A11963562.
- T.C. Simonen, et al., "High Beta Experiments in the GDT Axisymmetric Magnetic Mirror," *Joul. Fus. Eng.* **29**, 558-560 (2010), https://doi.org/10.1007/s10894-010-9342-7.
- T.C. Simonen, "Extrapolation of GDT Results to a Neutron Source for Fusion Materials Testing," *Fus. Sci. Tech.* **59** (2011), https://doi.org/10.13182/FST11-A11569.
- **And much more…**

Additional resources (cont'd) –MIF

- R.C. Kirkpatrick, et al., *Fus. Tech.* **27**, 3 (1995), https://doi.org/10.13182/FST95-A30382.
- Y.C.F. Thio, et al., "Magnetized Target Fusion in a Spheroidal Geometry with Standoff Drivers," *Current Trends in International Fusion Research: Proceedings of the Second Symposium*, NRC Research Press (1993).
- G.A. Wurden, et al., "Diagnostics for a magnetized target fusion experiment," *Rev. Sci. Instrum.* **72**, 552 (2001), https://doi.org/10.1063/1.1310589.
- T.P. Intrator, et al., "A high-density field reversed configuration plasma for magnetized target fusion," *IEEE Transcations on Plasma Science* **32**, 1 (2004), doi: 10.1109/TPS.2004.823974.
- Michel Laberge, "An Acoustically Driven Magnetized Target Fusion Reactor," *Joul. Fus. Eng*. **27**, 65-68 (2008), https://doi.org/10.1007/s10894-007-9091-4.
- P.B. Parks, "On the efficacy of imploding plasma liners for magnetized fusion target compression," *Phys. Plasmas* **15**, 062506 (2008), https://doi.org/10.1063/1.2948346.
- S. Howard, et al., "Development of Merged Compact Toroids for Use as a Magnetized Target Fusion Plasma," *Joul. Fus. Eng.* **28**, 156-161 (2009), https://doi.org/10.1007/s10894-008-9167-9.
- I.R. Lindemuth, "The ignition design space of magnetized target fusion," *Phys. Plasmas* **22**, 122712 (2015), https://doi.org/10.1063/1.4937371.
- S.J. Langendorf and S.C. Hsu, "Semi-analytic model of plasma-jet-driven magneto-inertial fusion," *Phys. Plasmas* **24**, 032704 (2017), https://doi.org/10.1063/1.4977913
- **And much more…**