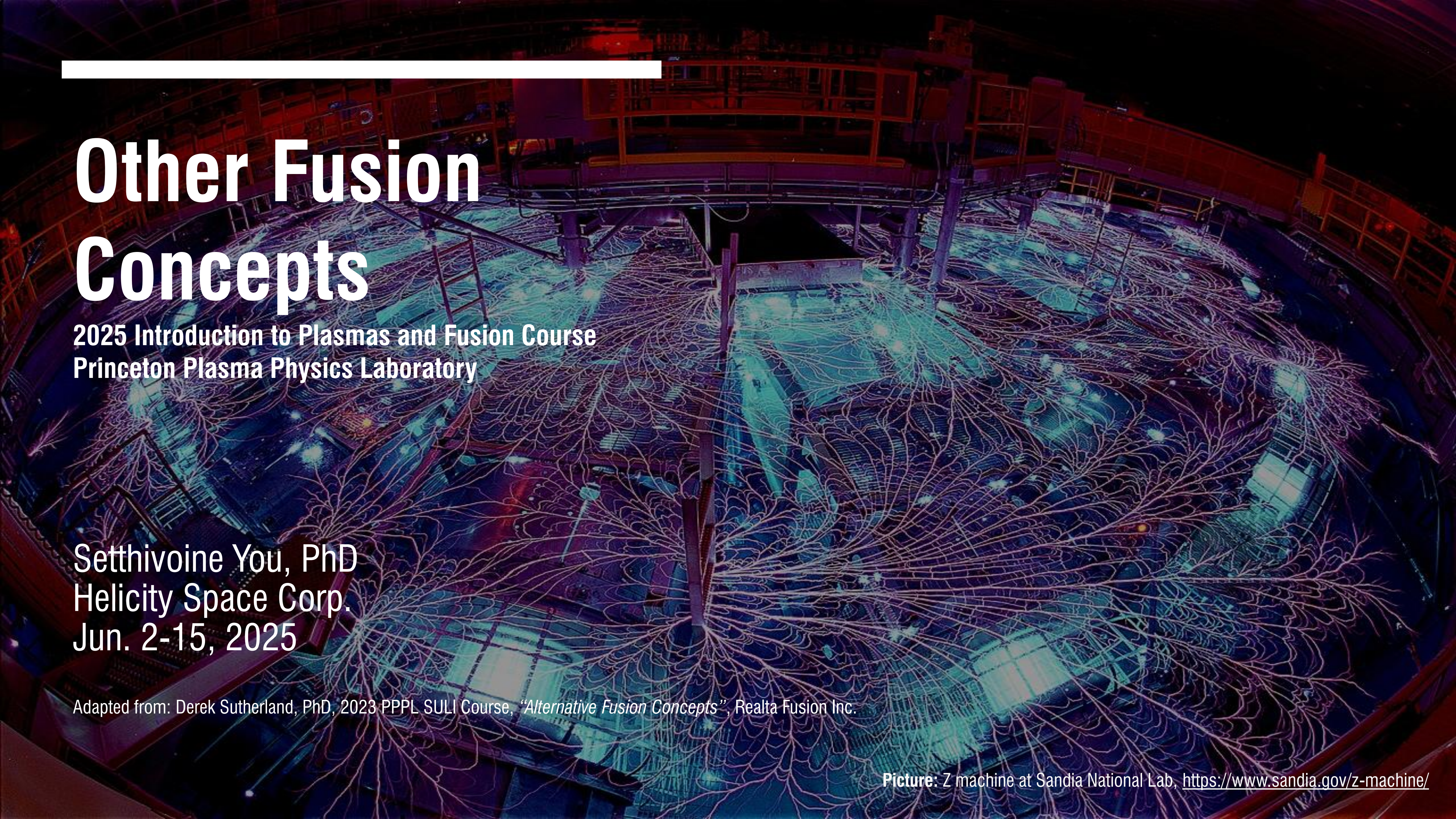


Other Fusion Concepts

2025 Introduction to Plasmas and Fusion Course
Princeton Plasma Physics Laboratory

Setthivoine You, PhD
Helicity Space Corp.
Jun. 2-15, 2025

Adapted from: Derek Sutherland, PhD, 2023 PPPL SULI Course, *“Alternative Fusion Concepts”*, Realta Fusion Inc.

Picture: Z machine at Sandia National Lab, https://www.sandia.gov/z-machine/

My Trajectory

2018-present Chief Scientist & Co-Founder, Helicity Space, Pasadena, CA
2017-2018 Vis. Assoc. Prof., Frontier Sciences, Univ. Tokyo, Japan
2009-2017 Assis. Prof., Aerosp. Eng., Univ. Washington, Seattle, WA
2007-2009 Postdoc., Elec. Eng., Univ. Tokyo, Japan
2002-2006 Postdoc., Applied Physics, Caltech, Pasadena CA
1997-2002 PhD Plasma Physics, Imperial/Culham Fusion Centre, UK
1993-1997 MSci Physics, Imperial College, London, UK
From France, grew up in Ivory Coast, Qatar and France.

Entrepreneur: take research results to develop compact fusion for space propulsion

Professorships: teach, lead research team on fusion, space propulsion, lab. astrophysics, diagnostics.

Postdocs: research on plasmas in alternative concepts, lab. astrophysics, diagnostics.
(also lucky to have been through couple of steps of ESA astronaut selection process)

Grad. school: research on tokamaks.

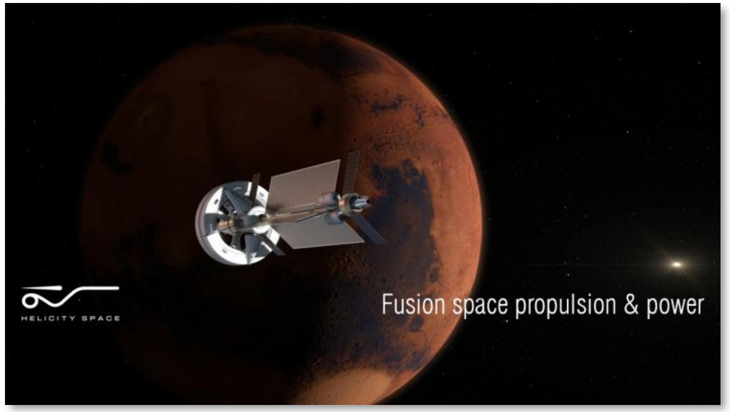
Undergrad. like you, first learnt about plasmas and fusion.

Chilldhood: read in magazine about fusion (JET tokamak at Culham) and fusion space propulsion (astronaut dreams!).

HELICITY SPACE

The mission of HelicitySpace is to develop affordable fusion reactor cores for interplanetary propulsion systems and surface power plants. The vision is to enable the expansion of humanity's economic sphere to deep space, accelerate space exploration and contribute to a clean environment on Earth with fusion power & propulsion technology.

http://www.helicityspace.com



Helicity Spaace (USA)

Outline

- Overview
- Why develop alternative fusion concepts?
- Net gain
- Plasma heating method(s)
- Plasma confinement method
- Some magnetic confinement methods
- Comparing magnetic confinement
- Linear fusion configurations
- Toroidal fusion configurations
- Summary
- Further Resources

Overview

You’ve already had an

- Intro to fusion (Monday)
- Basic plasma physics (Tuesday, Wednesday)
- Stellarators and tokamaks (this morning)
- and you will look at inertial fusion (next Monday).

We will look at other (“alternative”) fusion concepts and how they came about. There are/have been many concepts. Some are new. Some are older than tokamaks but revisited today. Some combine old ideas with new discoveries or new technologies.

In the interest of time, we will restrict ourselves to **a subset of these alternative ideas**, to get a taste of the rich and exciting R&D going on in the field, funded by government agencies and private investors.

Why develop alternative fusion concepts?

Programmatic risk reduction

- Diverse portfolio
- Orthogonal R&D needs

A potential showstopper for a given concept would not halt progress across the entire field.

Multiple viable approaches

- Optimized for different end goals (electricity, heat source, neutron source, space propulsion, ...)
- Satisfy different constraints that are particularly important for a given application (lower cost, lower mass, varied operational characteristics, ...)

For this talk, I want you to pretend you are designing a new fusion concept. Where do you start?

Net gain

The goal of many (though not all) fusion concepts is to achieve

$$Q_{sci} \equiv \frac{P_{fus}}{P_{in}} \gg 1 \qquad (1)$$

Fusion power between two fuel species A and B is

$$P_{fus} = n_A \, n_B \, \langle \sigma v \rangle_{AB} \, E_{AB} \, V_{pl} \quad [\mathrm{W}]$$

- V_{pl}: plasma volume [m^3]
- E_{AB}: energy released per fusion reaction [J]
- $\langle \sigma v \rangle_{AB}$: reaction rate [m^3/s] $\propto$ T^2 (Taylor expansion)
- $n_A\, n_B$: density of species A and B (assume $n_A = n_B = n$) [m^{-3}]

Input power should be equal to heat lost

$$P_{in} = \frac{W_{th}}{\tau_E} = \frac{n \, T \, V_{pl}}{\tau_E}$$

So Eq. 1 can be rewritten as "Triple Product"

$$\boxed{n \, T \, \tau_E > C(Q_{sci}, E_{AB}, \dots)} \quad [\mathrm{m^{-3}\ keV\ s}]$$

- C: constant that depends on choices: fuel, net gain value, etc.

Fusion has an "optimum" temperature (around peak of cross-section curve) and the triple product becomes the "Lawson Criterion"

$$\boxed{n \, \tau_E > C(Q_{sci}, E_{AB}, T, \dots)} \qquad (2)$$

So to achieve net gain we need to simultaneously satisfy 3 conditions:

1. Hold the plasma at desired density n,
2. for an appropriate time $t \geq \tau_E$ and
3. heat it to fusion temperature $T \sim 10 - 50\ \mathrm{keV}$ (depending on the fuel choice, etc.).

Aside: You then also have to think of your desired application and associated constraints... (beyond scope)

First, choose plasma heating method(s)

Plasma heating methods

1. Ohmic heating

   or viscous heating.

2. Radio-frequency wave heating

   ECRH (electron cyclotron resonance)

   ICRH (ion cyclotron resonance)

3. Energetic particle beam injection

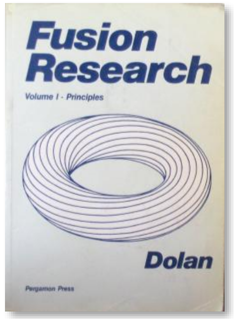
   NBI (neutral beam injection), charged particle beam

4. Compression heating

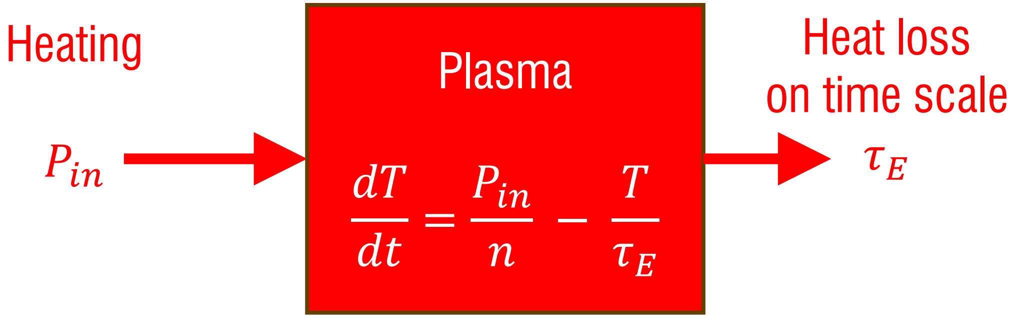
   Adiabatic compression, shock compression

5. Magnetic reconnection heating

   Natural phenomenon (e.g. space plasmas & laboratory plasmas) extensively studied. More recent application as fusion heating method (see for ex. [Ono et al., *Phys. Plasmas*, **22**, 055708 (2015)].



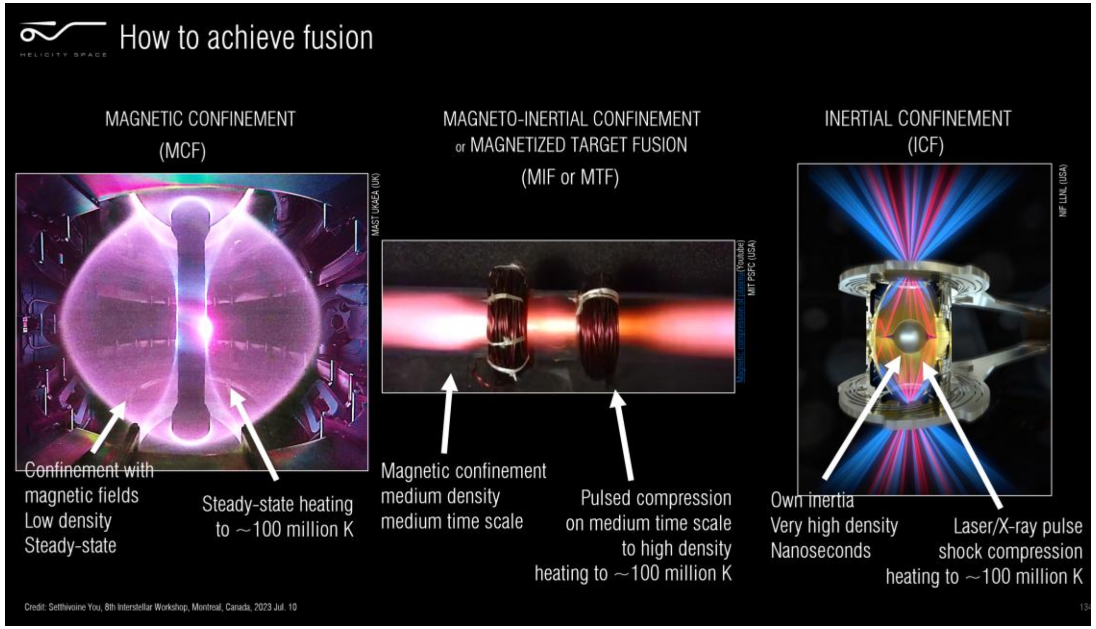
Described in many textbooks



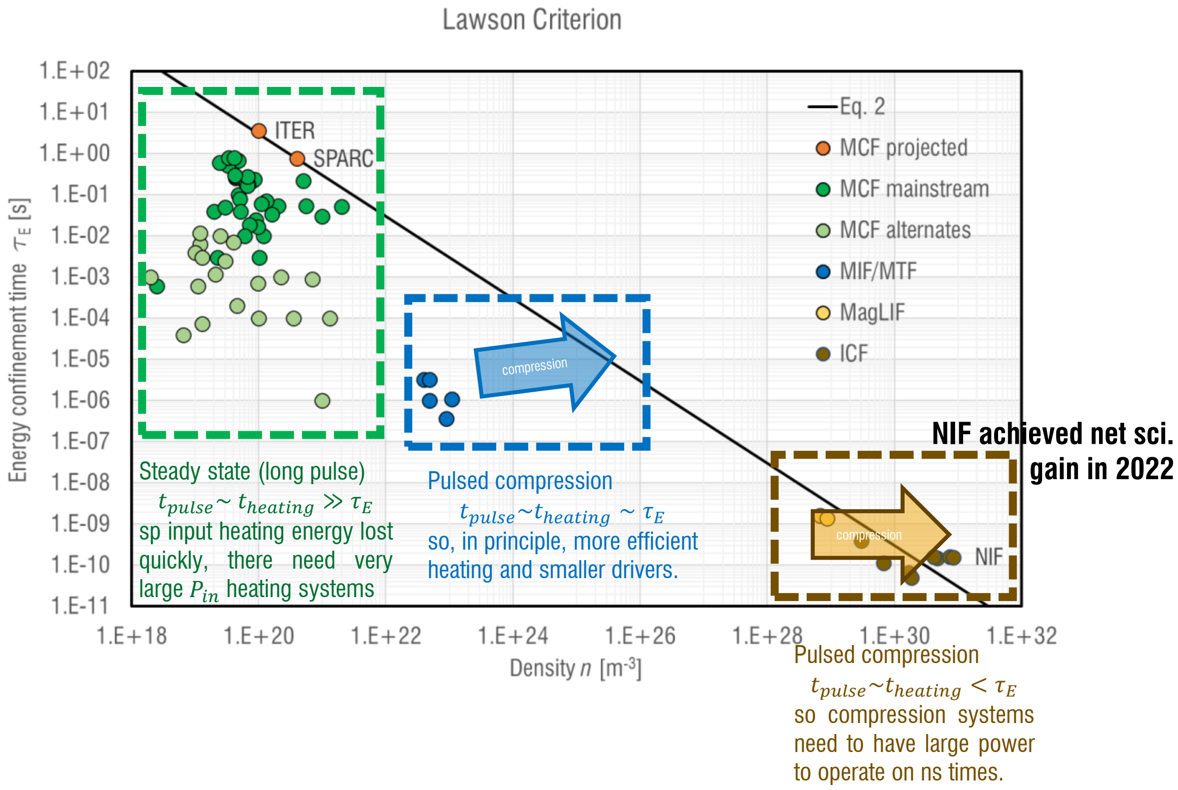
Heat loss mechanisms (→ plasma confinement methods $\{n, \tau_E\}$)

1. Conduction (avoid contact with container walls)
2. Convection (reduce heat transfer diffusion across ΔT between core and edge)
3. Radiation (reduce impurities but bremmstrahlung & synchrotron at high electron temperatures)
4. Mass transfer (reduce cold particles entering, reduce hot particles leaving)

Next, choose plasma confinement method $\{n; \tau_E\}$

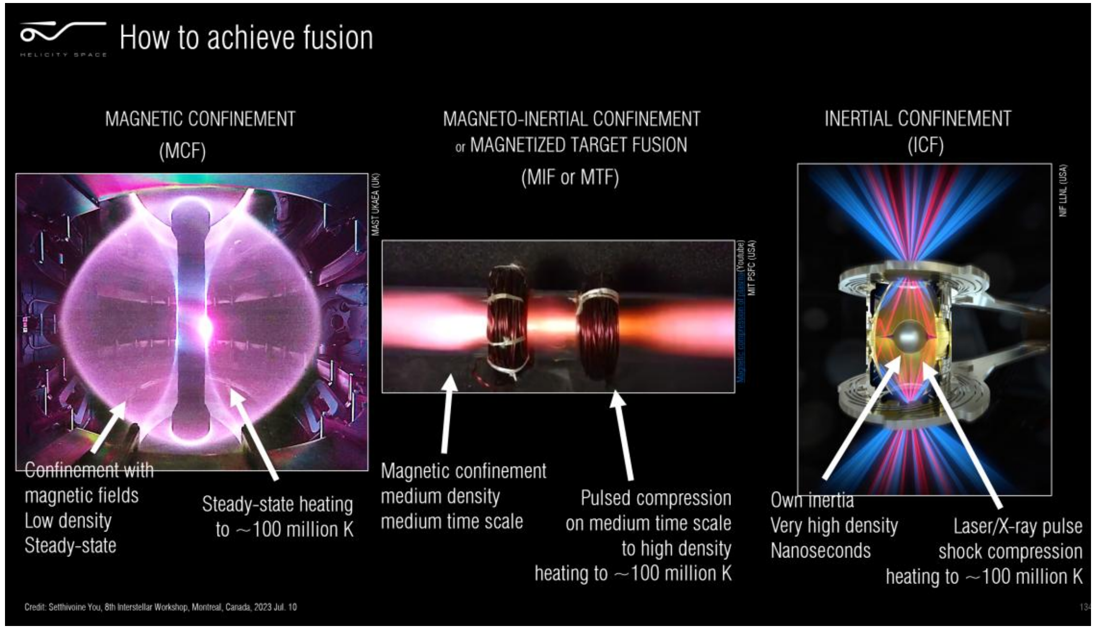


Illustrations of three categories of fusion concepts (MCF, MIF/MTF here shown with a tabletop demonstration of magnetic compression, and ICF). There are several more categories possible based on chosen combinations of heating & confinement methods: electrostatic confinement, hypervelocity impact, etc.. **We will cover here mainly MCF alternates and MIF/MTF,** since you have already had an intro to MCF mainstream (stellarators and tokamaks) and will soon have an intro to ICF.



Data points from [Wurzel, Hsu, *Phys. Plasmas*, **29**, 062103 (2022)]. The solid line is Eq. 2 (slide 5) with the constant $C \sim 3 \times 10^{20}$ [m^{-3}s] to approximately indicate the net scientific gain threshold for DT plasma at 10 keV.

Next, choose plasma confinement method $\{n; \tau_E\}$



Illustrations of three categories of fusion concepts (MCF, MIF/MTF here shown with a tabletop demonstration of magnetic compression, and ICF). There are several more categories possible based on chosen combinations of heating & confinement methods: electrostatic confinement, hypervelocity impact, etc.. **We will cover here mainly MCF alternates and MIF/MTF,** since you have already had an intro to MCF mainstream (stellarators and tokamaks) and will soon have an intro to ICF.

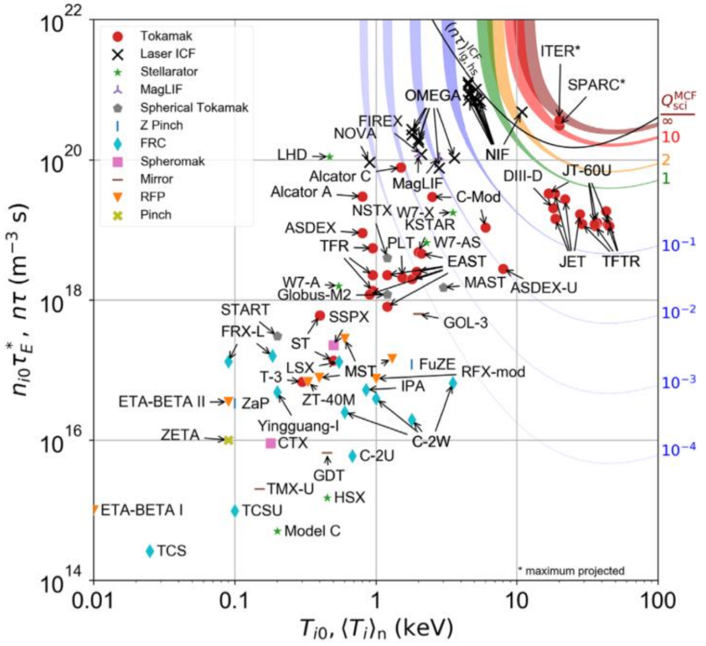
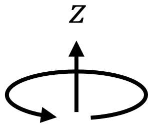


FIG. 2. Experimentally inferred Lawson parameters ($n_{i0}\tau_E^*$ for MCF and $n\tau$ for ICF) of fusion experiments vs T_{i0} for MCF and $\langle T_i \rangle_n$ for ICF (see Sec. III for definitions of these quantities), extracted from the published literature (see Tables V–VII). The colored contours correspond to the Lawson parameters required to achieve the indicated values of scientific gain Q_{sci}^{MCF} for MCF. The black curve labeled $(n\tau)_{ig,hs}^{ICF}$ corresponds to the Lawson parameters and ion temperatures required to achieve hot-spot ignition for ICF. We assume representative density and temperature profiles, external-heating absorption efficiencies, and D-T fuel. For experiments that do not use D-T, the contours represent a D-T-equivalent value. The finite widths of the Q_{sci}^{MCF} contours represent a range of assumed impurity levels. See the rest of this paper for details on how individual data points are extracted and how the Q_{sci}^{MCF} and $(n\tau)_{ig,hs}^{ICF}$ contours are calculated.

Figure from [Wurzel, Hsu, *Phys. Plasmas*, **29**, 062103 (2022)] showing more detail by plotting $n\,\tau_E$ as a function of T with more accurate threshold calculations for Q_{sci}. This shows significant progress in plasma performance of the various fusion concepts (NIF having crossed the $Q_{Sci} > 1$ threshold in 2022).

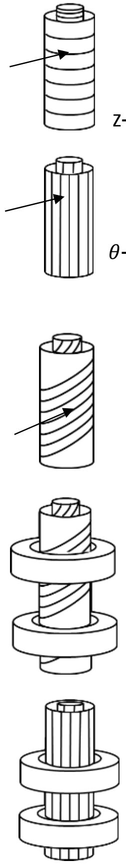
Some magnetic confinement methods: $\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}$

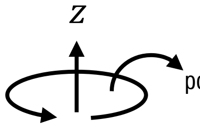
Choose how to generate (and, for steady state concepts, how to sustain) $\boldsymbol{J}$ to create $\boldsymbol{B}$ to trap particles (Larmor orbits in particle point-of-view) or equivalently, providing the Lorentz force to balance the pressure gradient $\boldsymbol{J} \times \boldsymbol{B} = \boldsymbol{\nabla} P$ (fluid point-of-view).



In Plasma J_z	In Plasma J_θ	In Ext. Coils J_z	In Ext. Coils J_θ	Plasma & Walls geom.	
Y	--	--	--	cylindrical (linear)	z-pinch, dense pinch focus
--	Y transient	--	--	cylindrical (linear)	θ-pinch
Y	Y	--	--	cylindrical (linear)	screw-pinch, plectonemic Taylor states [Lavine, You, *Phys. Plasmas*, **28**, 040703 (2021)]
Y	--	--	Y	cylindrical (linear)	screw-pinch
--	--	--	Y transient, steady	cylindrical (linear)	θ-pinch, magnetic mirror

open plasmas





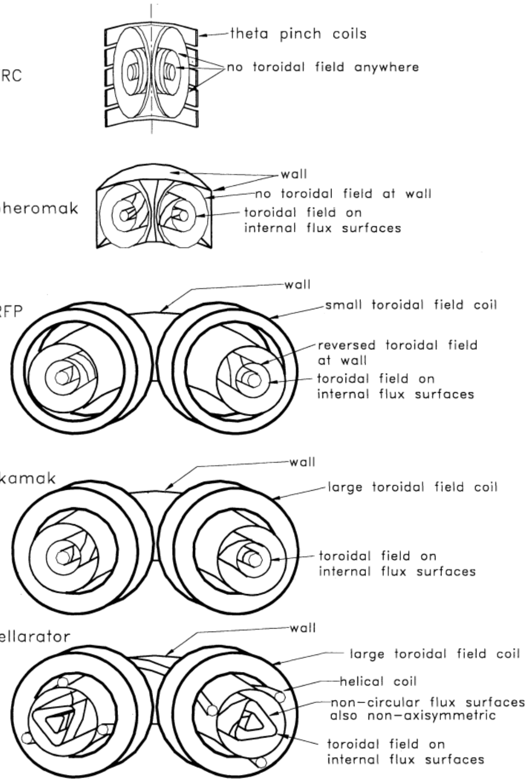
Plasma geom.	Walls geom.	In Plasma J_{tor}	In Plasma J_{pol}	In Ext. Coils J_{tor}	In Ext. Coils J_{pol}
toroidal	cylindrical	Y transient	--	--	(Y) formation
toroidal	cylindrical	Y transient	Y transient	--	--
toroidal	toroidal	Y	Y	--	(Y) formation
toroidal	toroidal	Y transient	--	--	Y
toroidal	toroidal	--	--	Y steady	Y steady

"toroidal Taylor states"

plasma can be translated along z

closed plasmas

plasma fixed inside



Some figures adapted from [Bellan, *Spheromaks*, Imperial College Press (2000)].
For more concepts see also [Dolan, *Fusion Research*, *Vol. II. Experiments*, Pergamon Press (1982), correct. ed. (2000)].
and for wonderful historical insight, see [Bishop, *Project Sherwood: The U.S. Program in Controlled Fusion*, Addison-Wesley (1958)].

Comparing magnetic confinement

How much plasma can be held by a given magnetic field (engineering limits on how strong a field can be made)? Characterize with a normalized plasma pressure to magnetic pressure:

$$\beta \equiv \frac{nT}{B^2}$$

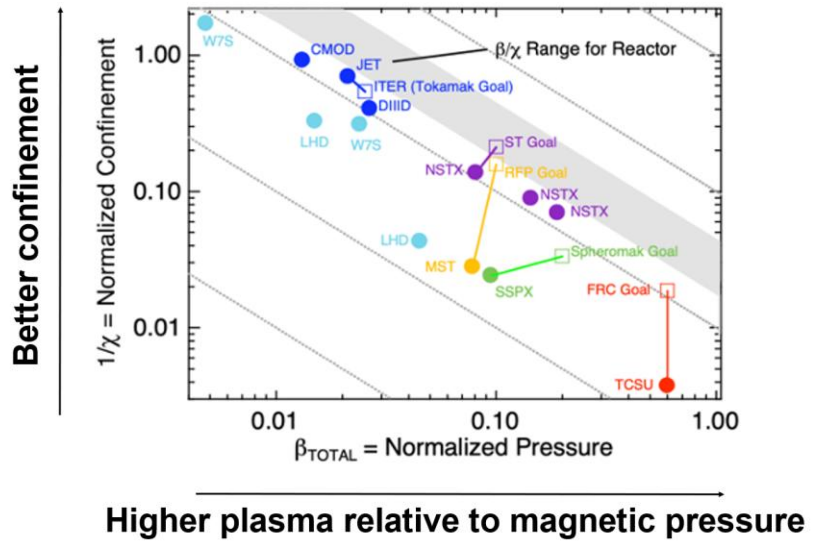
How well confined is the heat (good thermal insulation)? Characterize with heat diffusivity coefficient χ (random walk out of a plasma of size a):

$$\tau_E \propto \frac{a^2}{\chi}$$

Triple product then becomes

$$nT\tau_E \propto \frac{\beta}{\chi} a^2 B^2$$

So for a given concept (β/χ determined by the physics of the magnetic confinement design), a way to increase the triple product is to increase the plasma size and/or the magnetic field. Can compare concepts by comparing their β and χ. Of course, high β and low χ is desirable.



Tokamak **Stellarator**
good confinement, low pressure

Spherical Tokamak (ST)
medium confinement, medium pressure

Reversed-field pinch (RFP)
medium confinement, medium pressure

Spheromak
medium confinement, medium pressure

Field-Reversed Configuration (FRC)
low confinement, high pressure

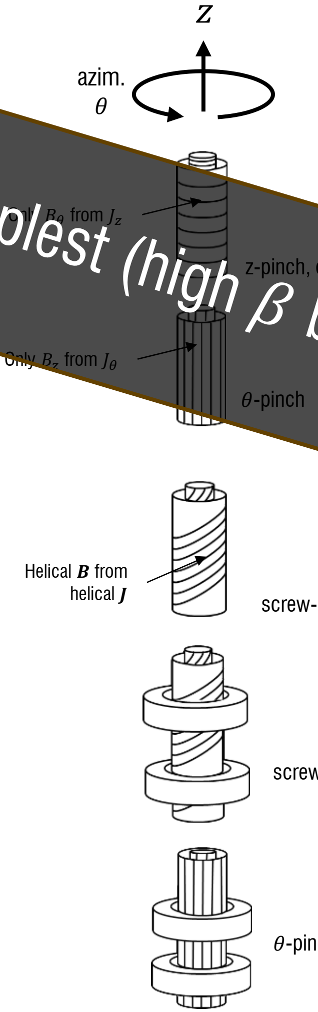
Figure from "Report of the FESAC Toroidal Alternates Panel," (2008).

Some magnetic confinement methods: $\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}$

Choose how to generate (and, for steady state concepts, how to sustain) $\boldsymbol{J}$ to create $\boldsymbol{B}$ to trap particles (Larmor orbits in particle point-of-view) or equivalently, providing the Lorentz force to balance the pressure gradient $\boldsymbol{J} \times \boldsymbol{B} = \nabla P$ (fluid point-of-view).

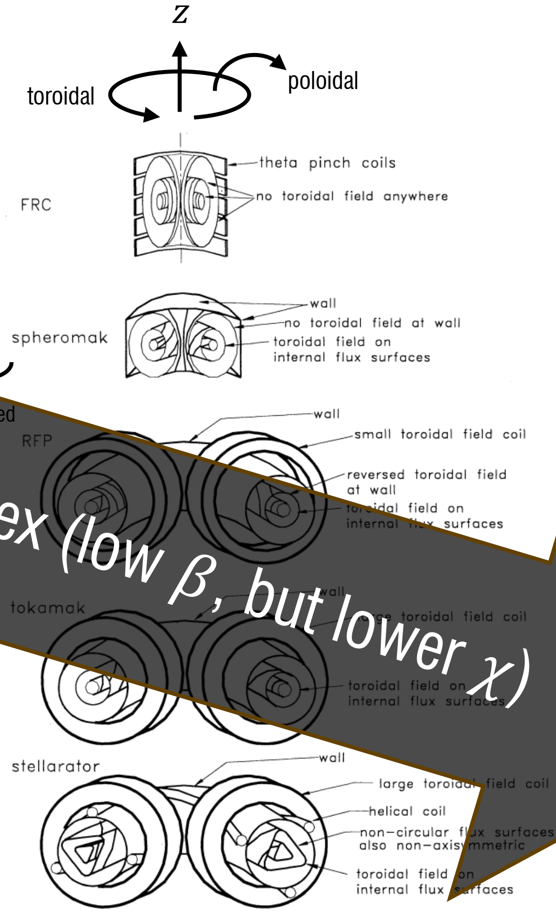
Simplest (high β but high χ)

Most Complex (low β, but lower χ)



In Plasma J_z	In Plasma J_θ	In Ext. Coils J_z	In Ext. Coils J_θ	Concept	Plasma & Walls geom.
Y	--	--	--	z-pinch, dense pinch focus	cylindrical (linear)
--	Y transient	--	--	θ-pinch	cylindrical (linear)
Y	Y	--	--	screw-pinch, plectonemic Taylor states [Lavine, You, *Phys. Plasmas*, **28**, 040703 (2021)]	cylindrical (linear)
Y	--	--	Y	screw-pinch	cylindrical (linear)
--	--	--	Y transient, steady	θ-pinch, magnetic mirror	cylindrical (linear)

open plasmas



Concept	Plasma geom.	Walls geom.	In Plasma J_{tor}	In Plasma J_{pol}	In Ext. Coils J_{tor}	In Ext. Coils J_{pol}
FRC	toroidal	cylindrical	Y transient	--	--	(Y) formation
spheromak	toroidal	cylindrical	Y transient	Y transient	--	--
RFP	toroidal	toroidal	Y	Y	--	(Y) formation
tokamak	toroidal	toroidal	Y transient	--	--	Y
stellarator	toroidal	toroidal	--	--	Y steady	Y steady

"toroidal Taylor states" (spheromak, RFP)

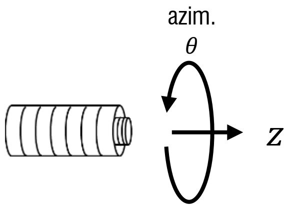
plasma can be translated along z (spheromak)

closed plasmas

plasma fixed inside

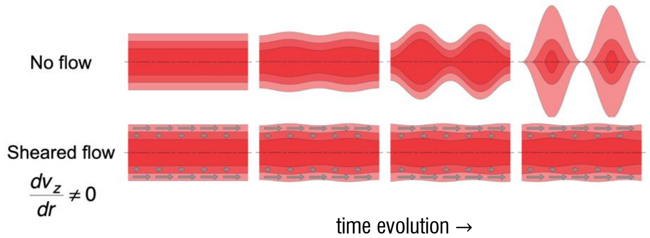
Some figures adapted from [Bellan, *Spheromaks*, Imperial College Press (2000)].
For more concepts see also [Dolan, *Fusion Research*, *Vol. II. Experiments*, Pergamon Press (1982), correct. ed. (2000)].
and for wonderful historical insight, see [Bishop, *Project Sherwood: The U.S. Program in Controlled Fusion*, Addison-Wesley (1958)].

Z-pinch



Many stabilization techniques to lengthen lifetime for more fusion reactions per pulse

e.g. shear flow (axial)

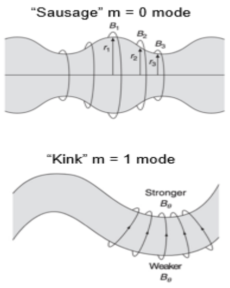


Some Advantages

- Simple (no coils, compact)
- High $\beta \sim 1$
- Large magnetic fields $B_\theta > 10\ T$ (internal J_z only)
- Internal field gradient favors reaching high temp.

Some Issues

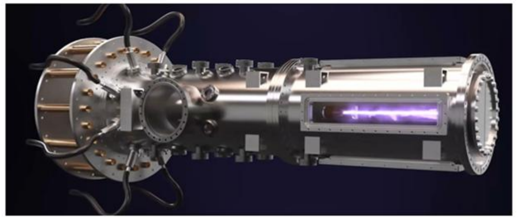
Unstable to MHD modes which shortens lifetime before heating to fusion can happen.



* Figures from J.P. Freidberg, *Ideal MHD*, Cambridge University Press (2007).

ZAP ENERGY™

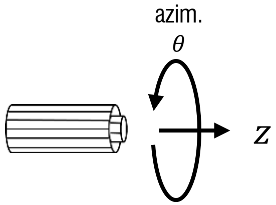
- multi-keV plasmas
- neutrons
- Very compact cores
- High power density
- Low CapEx/OpEx
- Aiming for 200MWth DT core with liquid metal first wall.



Images from ZaP Energy (USA)

See [Zap Energy website] for the latest and papers detailing the concept,.

θ-pinch



Some Advantages

Simple, compact

More stable than Z-pinch

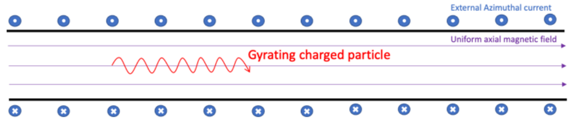
Some Issues

- Parallel transport along z magnetic field leads to unfavorable scaling to net gain fusion (“endloss”)
- θ-pinch’s β < Z-pinch’s β
- J_θ in plasma necessarily transient because it is generated by induction: with a pulse ***J_θ* in external coils**

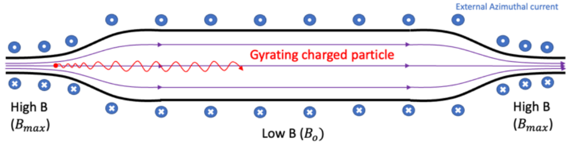
No J_θ in plasma, only J_θ **in external coils** (steady state) & stronger fields at both ends (plugs)

⇒ **Magnetic Mirrors**

“Endless” Linear θ-pinch



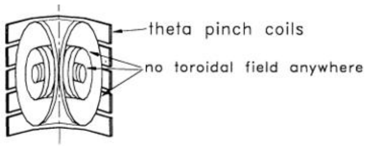
Simple Magnetic Mirror



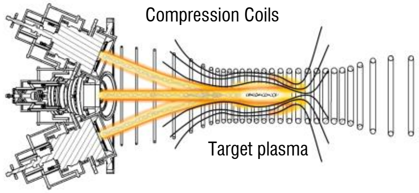
in fact, quite useful

for initial plasma formation

Bend into torus to get a “field reversed configuration” FRC

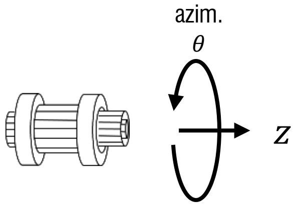


for magnetic compression of plasmas



...

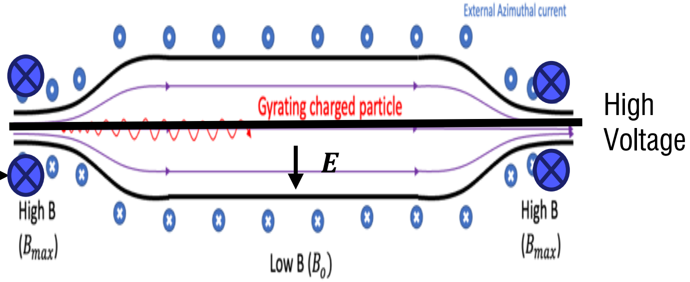
Magnetic mirrors



Gas Dynamic Trap (Russia)

Images Wikipedia page for GDT

Mirror ratio 35-100 (B_{max}~15 T), T_e~1 keV, ~10^{20} m^{-3}, β~0.6, quasi-stationary temp. for ~1 ms. ECRH + NBI.



Some Advantages

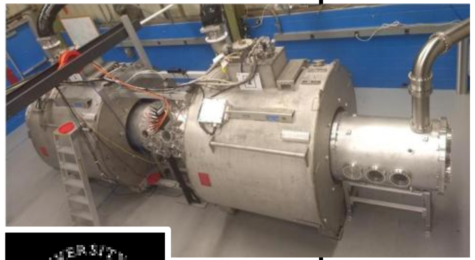
- Simple
- More stable than Z-pinch
- Steady-state
- Reduced endloss (exploits particle's magnetic moment conservation, so some particles can reflect back from stronger fields → this physics appears in many concepts, see banana orbits in tokamaks, stellarators, levitated dipoles, cusps, and in nature, see Van Allen belts, auroras)

Some issues

- Still particle loss through ends because of finite mirror ratio B_{max}/B_{min} (loss cone).
- Mirror β < Z-pinch's β
- Unstable interchange modes (MHD flute instability where plasma pressure pushes agains unfavourable magnetic curvature)

Stronger mirror fields

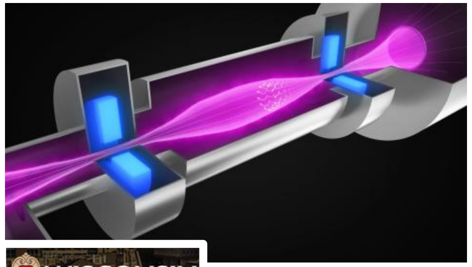
High-temperature superconducting (HTS) coils
B_{max} ~ 17-20+ T



Images from Terra Fusion U. Maryland (USA)

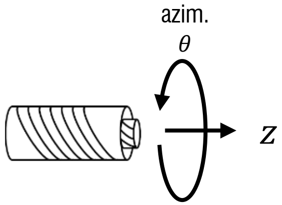
+Azimuthal supersonic rotation (centrifugal mirror)

Add a radial electric field with axial high voltage electrode to induce $\boldsymbol{E} \times \boldsymbol{B}$ azimuthal rotation to supersonic speeds (Mach > 10-50). Shear flows (azimuthal) stabilizes the flute modes.



Images from Realta Fusion (USA)

Screw pinch



"current-carrying magnetic flux tubes"

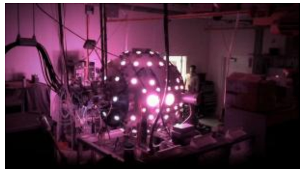
Some Advantages

- Helical magnetic field shear (instead of axial flow shear) to stabilize some MHD modes.
- Relatively simple: also good as **building block** for various fusion concepts. Good for understanding complex plasmas in nature (e.g. astrophysical jets, solar prominences, ...) & study of fundamental plasma behavior (e.g. **Taylor relaxation**, magnetic reconnection, ...).

Some issues

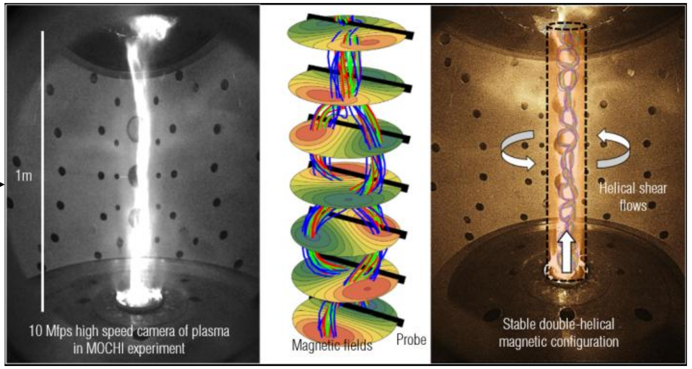
- Some MHD modes (e.g. kink) are still not stabilized.
- End losses still.

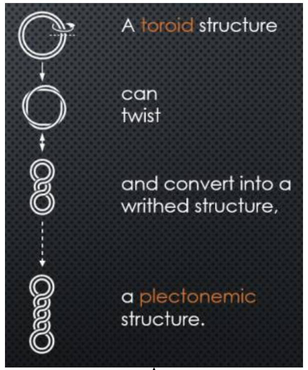
Helical flow shear + **helical** magnetic shear stabilized the screw pinch against kink !
[Lavine & You, *PRL*, 2019;]



MOCHI, Univ. Wash. & HelicitySpace (USA)

But the screw pinch also relaxed into **a double-helical (plectonemic) Taylor magnetic configuration** !
[Lavine & You, *POP*, 2021]; (Scilight feature)]

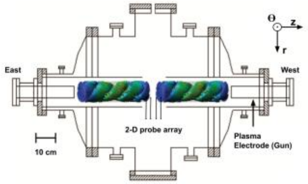




Images adapted from [DNA supercoil – Wikipedia]

Observations of long stable current-carrying magnetic flux tubes with **double-helical (plectonemic) Taylor state** inside the helical shear flow stabilized jet of the MOCHI experiment at Univ. Wash.
[Lavine & You, *PRL*, 2019;]
[You et al, *ApJSS*, 2017;]

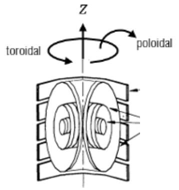
Double-helical (plectonemic) Taylor states were first discovered in the SSX experiment at Swarthmore College, with a close-fitting flux conserving walls. Studied merging reconnection heating of two plectonemes.
[Cothran et al, *PRL*, 2009;]
[Brown et al, *Plasma*, 2020;]



SSX, Swarthmore College (USA)

Bend into torus to give stellarators, tokamaks, $\underbrace{\text{RFPs, spheromaks, ...}}_{\text{toroidal Taylor configurations}}$

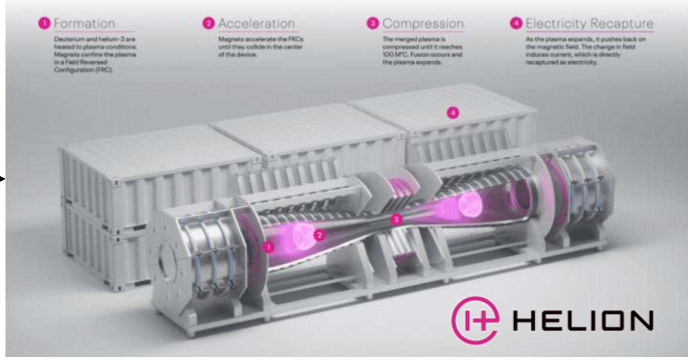
FRC (Field Reversed Configuration)



"compact torus"

Some Advantages

- High β with field null on axis
- If needed can translate along z from one region to another, e.g. from formation to sustainment or compression region, can merge two FRCs into one.



Images and logo Helion Energy (USA)

Some issues

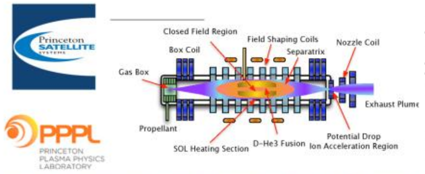
- Stability (tilt, wobble) away from walls

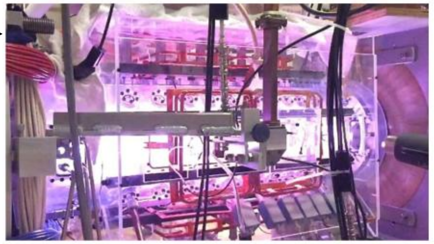
  Some progress in experiments with biasing electrodes on open field lines
- Needs auxiliary current drive for sustainment after formation if want steady state. e.g.

  Neutral beam(s) injection

  Rotating magnetic field (RMF) antennas.

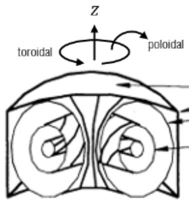
* Logo and Images from TAE Technologies





Images and logo PPPL and PSS (USA)

Spheromak



Mathematical aside:
Taylor states are solutions to $\nabla \times \boldsymbol{B} = \lambda\,\boldsymbol{B} \;\Leftrightarrow\; \mu_0\,\boldsymbol{J} = \lambda\,\boldsymbol{B}$ so are also known as **force-free configurations** (i.e. no net $\boldsymbol{J}\times\boldsymbol{B}$ forces).
Many possible solutions (helical states) depending on choice of boundary:

- Toroidal solution in short singly-connected volume  = **spheromak**
- Plectonemic solution in long singly-connected volume  = **plectoneme**
- Toroidal solution in doubly-connected volume  = **RFP**
- **...** some types of flux ropes, etc.

Some Advantages

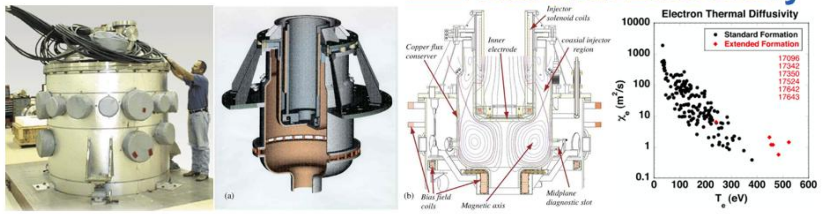
- Simple, compact torus (too)
- Large $\boldsymbol{J}$ so possible ohmic heating alone sufficient to reach ignition if energy confinement is good enough.
- Can translate from one location to another (like FRC)

Some issues

- Current drive (if we want steady-state): how to sustain $\boldsymbol{J}$ against resistive dissipation? how to do it without losing heat? (note that this is also an issue with tokamaks)

SSPX

Lawrence Livermore National Laboratory

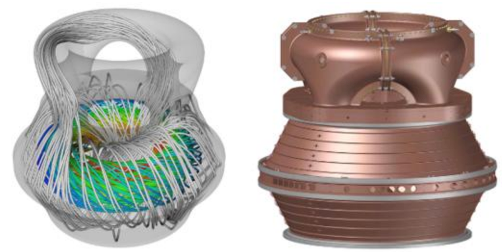


B. Hudson, et al., Physics of Plasmas 15, 056112 (2008).

SSPX (Sustained Spheromak Physics eXperiment) reached $T_e > 500$ eV during decay phase, but plasma instabilities during current drive phase degraded confinement.

UNIVERSITY of WASHINGTON

CTFusion

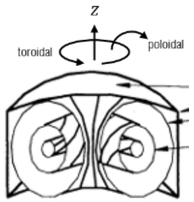


Figures: HIT-SI Research Group, University of Washington (subcontract with CTFusion, Inc.)

HIT-SI (Helicity Injection Torus – Steady Inductive) at Univ. Wash. and CTFusion explored a novel method to inductively inject helicity (responsible for driving current $\boldsymbol{J}$) in a steady state into a small machine. Need to scale up to fusion relevant plasmas (good enough confinement for $T_e \gg 1$ keV).

Some ideas tried exploiting ability to freely translate the spheromak/Taylor state:
Merge two (or more?) decaying spheromaks/plectonemic Taylor states repeatedly (SSX), spheromaks/FRCs/STs (Univ. Tokyo TS series, Helion, TAE), STs (TS, MAST, START, Tokamak Energy) for non-inductive formation. Inject spheromaks into a tokamak (Caltech). Inject helical flux ropes into spherical tokamak (U. Wisc., PPPL). etc... → observation of fundamental plasma physics: **magnetic reconnection could result in intense direct heating of plasma ions.** See [Ono et al., *Phys. Plasmas*, **22**, 055708 (2015)]

Spheromak



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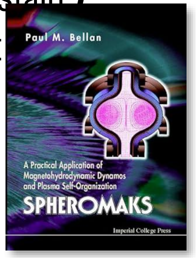
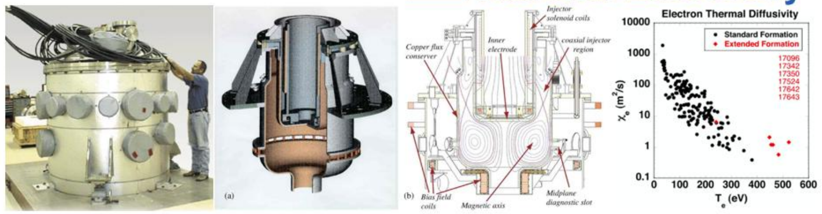


very rich and interesting plasma physics:
e.g. plasma self-organization

SSPX



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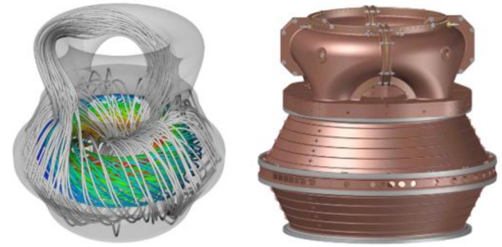

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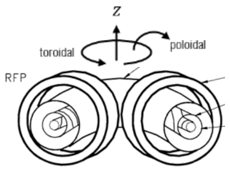
Reversed Field Pinch (RFP)



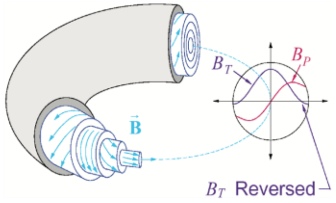


Figure: J. Sarff, Perspectives on Reversed Field Pinch (RFP) Fusion Research, FPA (2011)

Some Advantages

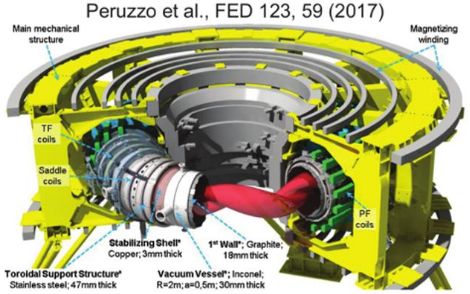
- Like a tokamak but simpler ($B_{tor} \sim B_{pol}$) than a tokamak ($B_{tor} \gg B_{pol}$) so avoids need for HTS coils.
- Large $\boldsymbol{J}$ so possible ohmic heating alone sufficient to reach ignition if energy confinement is good enough so avoids needs of auxiliary heating.

Some issues

- MHD instability related to self-organization processes can degrade confinement, particularly at magnetic boundary (reversal surface) and internal core resonant surfaces.
- Density profile control, particularly at high currents. Edge can be denser than core, so cools more rapidly because it is more resistive. Active area of research...

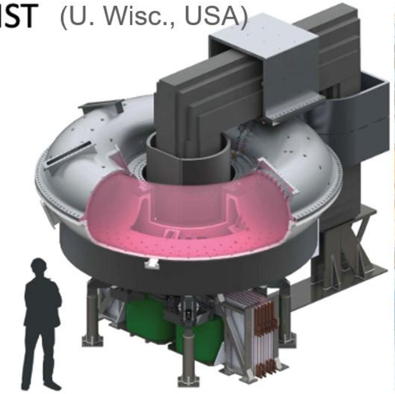
RFX-Mod (Italy)

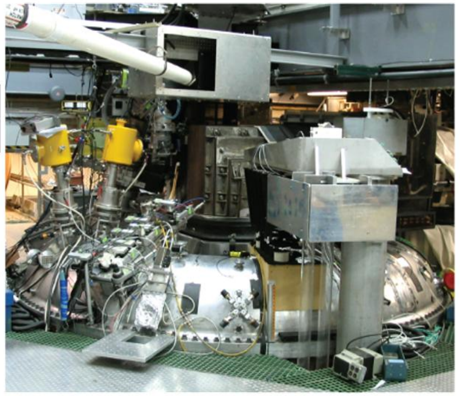
Peruzzo et al., FED 123, 59 (2017)



keV

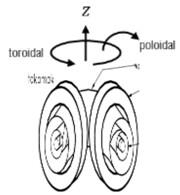
MST (U. Wisc., USA)





RFPs use close-fitting thick conducting shell (flux conserver) to stabilize, just like spheromaks. But need to push plasma away from shell to heat, so add currents (shell as magnet) and do active feedback stability control and advanced oscillating field current drive (OFCD).

Spherical Tokamak (ST)

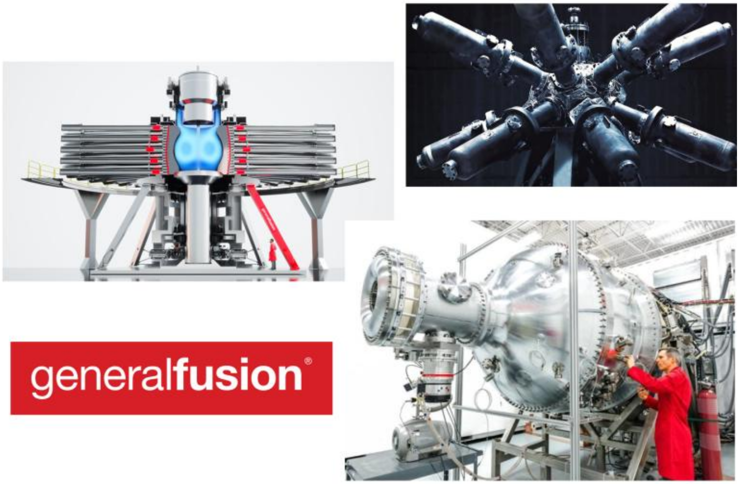


"compact torus" – bridge between alternates and conventional magnetic confinement (has some properties of both)

Like a tokamak but more compact than a conventional tokamak by reducing aspect-ratio. Higher β, lower χ than RFP, spheromaks, FRCs.

High-field D-T spherical tokamak (ST) plasma using REBCO HTS magnets for magnetic fusion energy (MFE)

⇒ Even higher β because of higher HTS fields



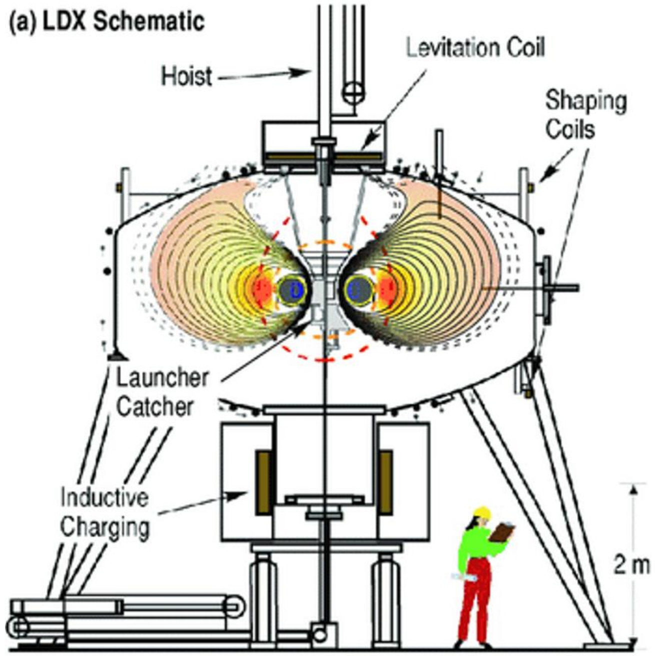
Pneumatic compression of a D-T spherical tokamak (ST) plasma for magneto-inertial fusion (MIF) energy

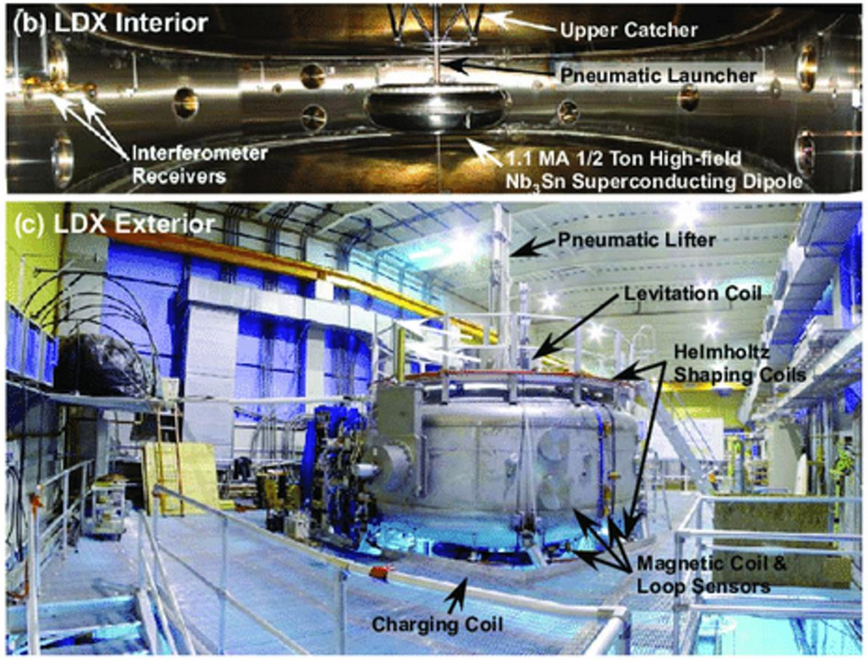
Early attempts at pneumatic liquid liner compression of spheromaks/FRCs suffered from low lifetime of spheromaks/FRC targets on time scale of liquid liner.

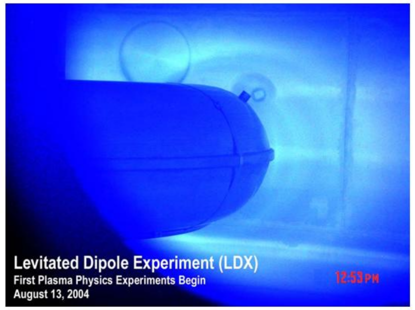
http://tanuki.t.u-tokyo.ac.jp/english-lab/

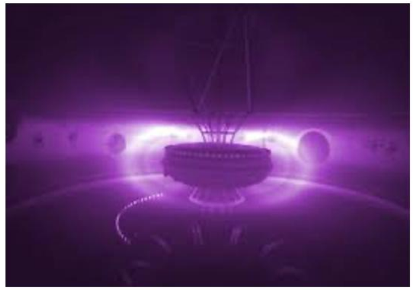
Univ. Tokyo TS experiments: merging 2×compact toruses (FRCs, spheromaks, STs) to study magnetic reconnection, reconnection heating, non-inductive formation of tokamaks, etc.

Levitated Dipole

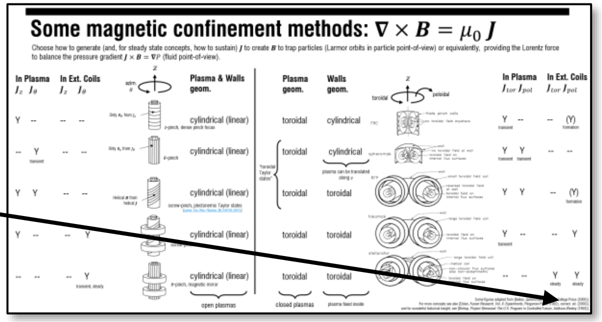








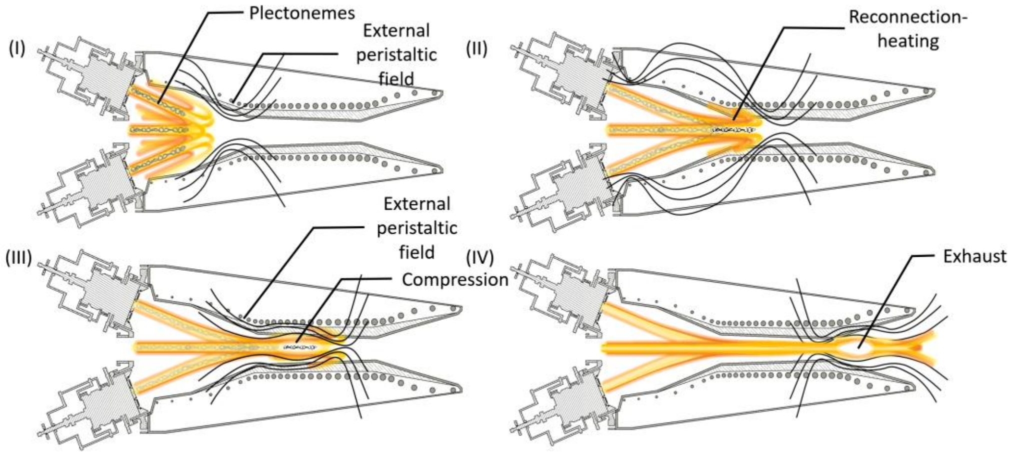
[J. Kesner and M. Mauel, et al., Images from Columbia University and the Massachusetts Institute of Technology]



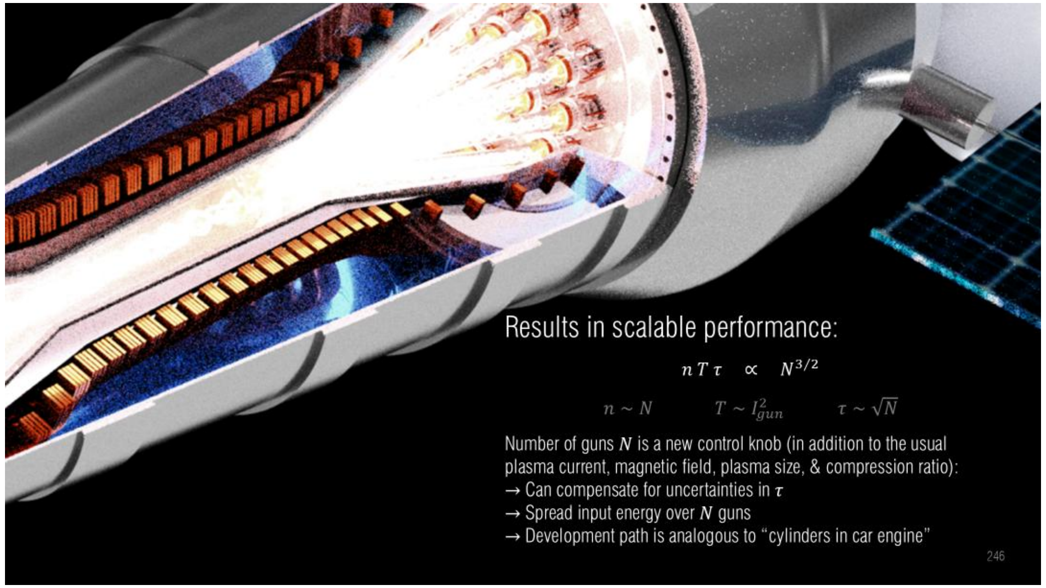
Floating superconducting coil to generate a dipole field for plasma confinement.
“Inside out” where the external J_{tor} is “inside” the plasma, like magnetospheres.

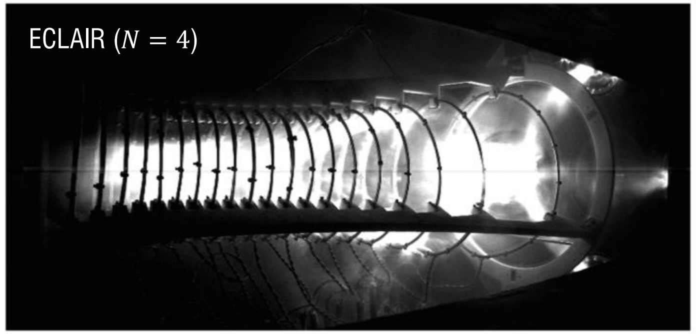
Helicity Drive (plug!)

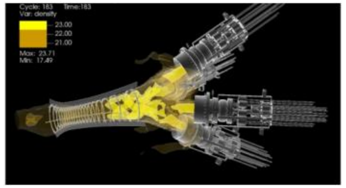
New unique pulsed MIF/MTF concept that puts together some of what you have seen today.
[S. You, “Helicity Drive: a novel scalable fusion concept for deep space propulsion”, AIAA Propulsion & Energy Forum, AIAA-2385 (2020)]

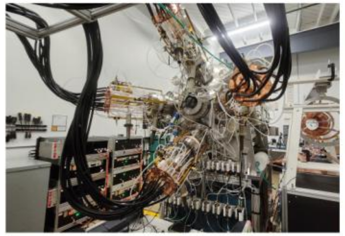


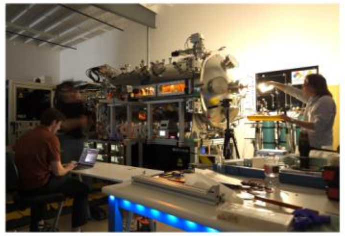
(I) Form $N\times$ plectonemic Taylor states inside helical shear flow stabilized plasma jets.
(II) Merge into one, heats up via reconnection and collisional heating.
(III) Magnetic compression with peristaltic (double pulse traveling wave in tapered coil) magnetic field to fusion conditions.
(IV) Expansion section of hot plasma against coils provides direct electric conversion and thrust with mixing too cooler propellant for adjusting specific impulse.

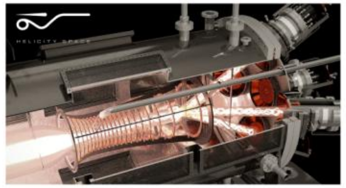












Helicity Space (USA)

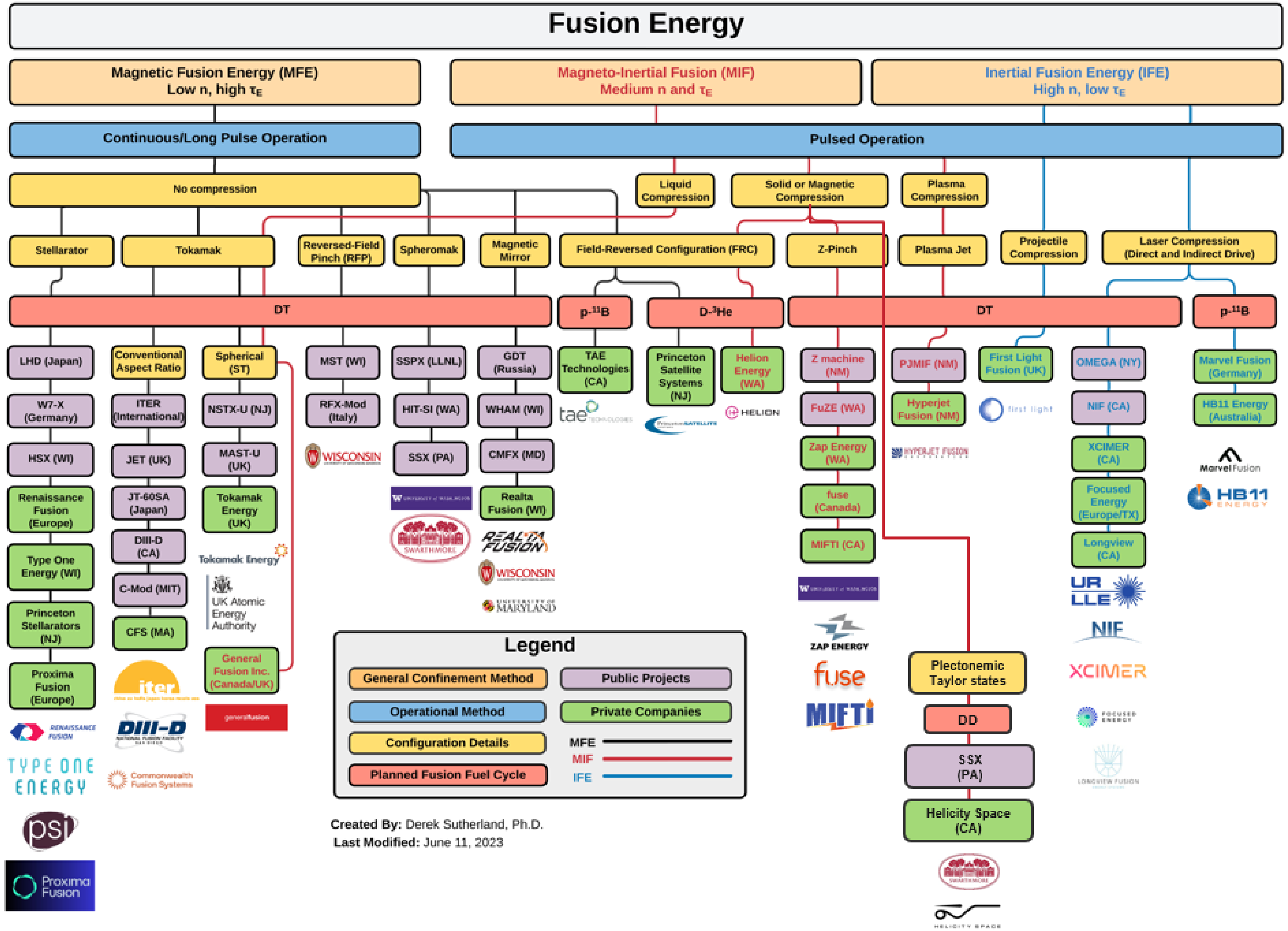
Summary

Many other fusion concepts beyond the mainline MCF and ICF, past and present.

Advantages for some applications can be attractive, so need effort to tackle the challenges.

Share much physics and engineering foundations. Learning on smaller, simpler systems helps building blocks towards larger more complex systems. Learn !

Growing diverse field in addition to academia & national laboratories like PPPL, private ventures now also join the community to accelerate many fusion energy applications.



Great time to join the field!

Further Resources

[Fusion Industry Association](#) for private companies and supporting technology companies.

NRL Plasma Formulary: https://library.psfc.mit.edu/catalog/online_pubs/NRL_FORMULARY_19.pdf

MIT Plasma Formulary: https://www-internal.psfc.mit.edu/research/MFEFormulary/