Alternative Fusion Concepts

2023 Introduction to Fusion Energy and Plasma Physics Course

Derek Sutherland, Ph.D. — Zap Energy, Inc. — June 5 — 15, 2023

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

What does “alternative concept” mean?

- Historically, “alternative” has been used to refer to fusion concepts other than “mainline” ones (e.g., tokamak, ST, stellarator), but sometimes it can mean any fusion concept other than a conventional aspect ratio tokamak

- Alternative approaches are quite varied and there is a significant amount of R&D currently underway funded by government agencies and private investors

- We will cover <u>only a subset</u> of alternative fusion approaches as a taste of the breadth and interrelationships of different fusion concepts in the field!

What are the benefits of developing alternative fusion concepts?

- 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.

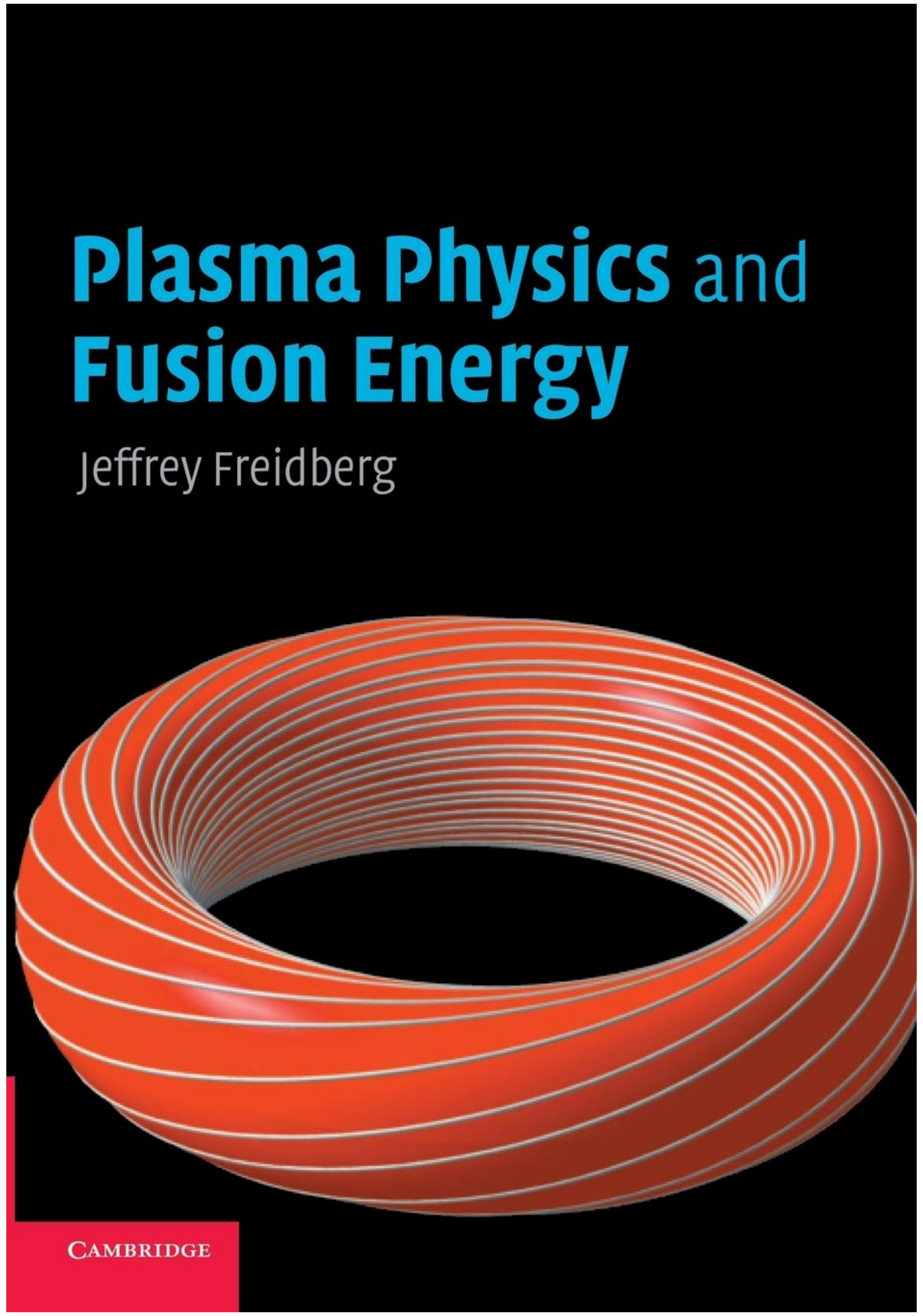
- Potentially developing multiple viable approaches to fusion energy, some of which could:
    1) be lower in cost than others that will translate into more favorable economics on the grid
    2) offer varied operational characteristics to fulfill different customer needs
    3) …

An (unpaid) public service annoucement…

Highly recommended first textbook for anyone interested in the field that provides a great overview

I read this book cover-to-cover twice and did most of the questions in it during my sophomore and junior years of undergrad

Massive help in getting up to speed with everything, and I used it extensively during my own internship experiences!



Check out the NRL and MIT plasma formularies:

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

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

Outline

Introduction and overview

Linear fusion configurations

- Z-pinch, θ-pinch, screw pinch
- Magnetic mirrors

Toroidal fusion configurations

- Reversed field pinch (RFP), Spheromak
- Field-reversed configuration (FRC)
- Levitated Dipole

The growing fusion energy landscape

Summary and resources

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All fusion energy concepts must scale to plasma conditions needed to generate net-energy — and there's more than one way to do so

Can define plasma performance in terms of triple product $nT\tau_E$ — typical units keV-s/m³ or atm-s

Knowing triple product, the plasma temperature T and the fusion fuel type with other assumptions allows for calculating the scientific gain Q_{sci} *

Given operation at an "optimal" temperature T, you can pursue high $nT\tau_E$ in various ways:

- **Magnetic fusion energy (MFE or MCF)** - low density n, high τ_E
- **Magneto-inertial fusion (MIF or MTF)** - medium density n and τ_E
- **Inertial fusion energy (IFE or ICF)** - high density n and τ_E (Net energy gain last year!)

For this talk we will primarily be focused on MFE and MIF, but a landscape summary at the end will include fusion concepts for all three categories

* See S.E. Wurzel and S.C. Hsu, "Progress toward fusion energy breakeven and gain as measured against the Lawson criterion," *Phys. Plasmas* **29**, 062103 (2022), https://doi.org/10.1063/5.0083990

Significant progress has been made in plasma performance in many fusion concepts — thus far indirect drive ICF at NIF and tokamaks are the best performers

Core double product $n_{i0}\tau_E$ v. Ion temperatures T_{i0}, $\langle T_i \rangle_n$

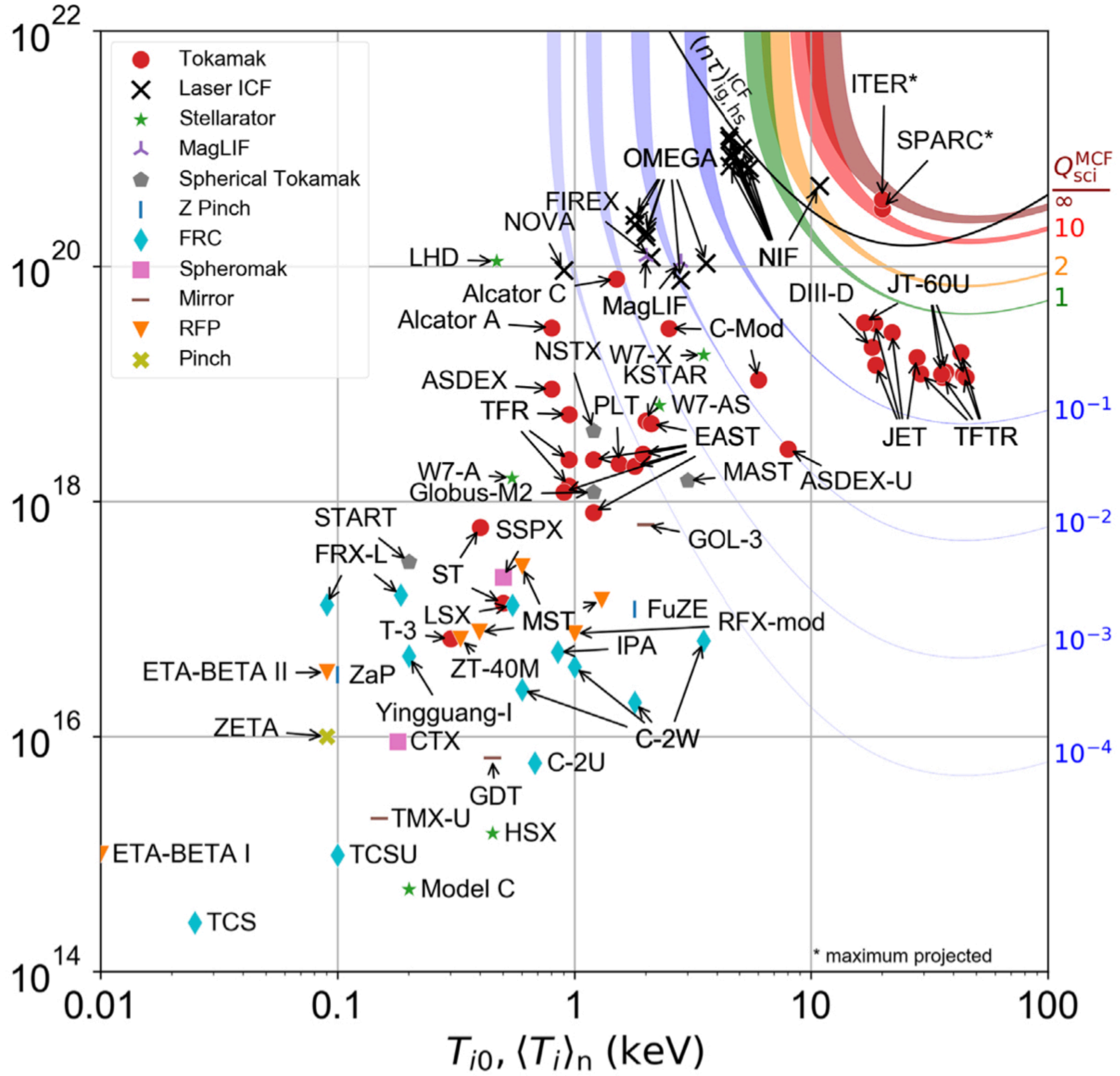


FIG. 2. Experimentally inferred Lawson parameters ($n_{i0}\tau_E^*$ for MCF and $n\tau$ for ICF) of fusion experiments vs T_{i0} for MCF and $\langle T_i\rangle_n$ for ICF (see Sec. III for definitions of these quantities), extracted from the published literature (see Tables V–VII). The colored contours correspond to the Lawson parameters and ion temperatures 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, net external-heating absorption efficiencies, and D-T fuel. For experiments that do not use D-T fuel, we use 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.

Core triple product $n_{i0}T_{i0}\tau_E$ v. Ion temperatures T_{i0}, $\langle T_i \rangle_n$

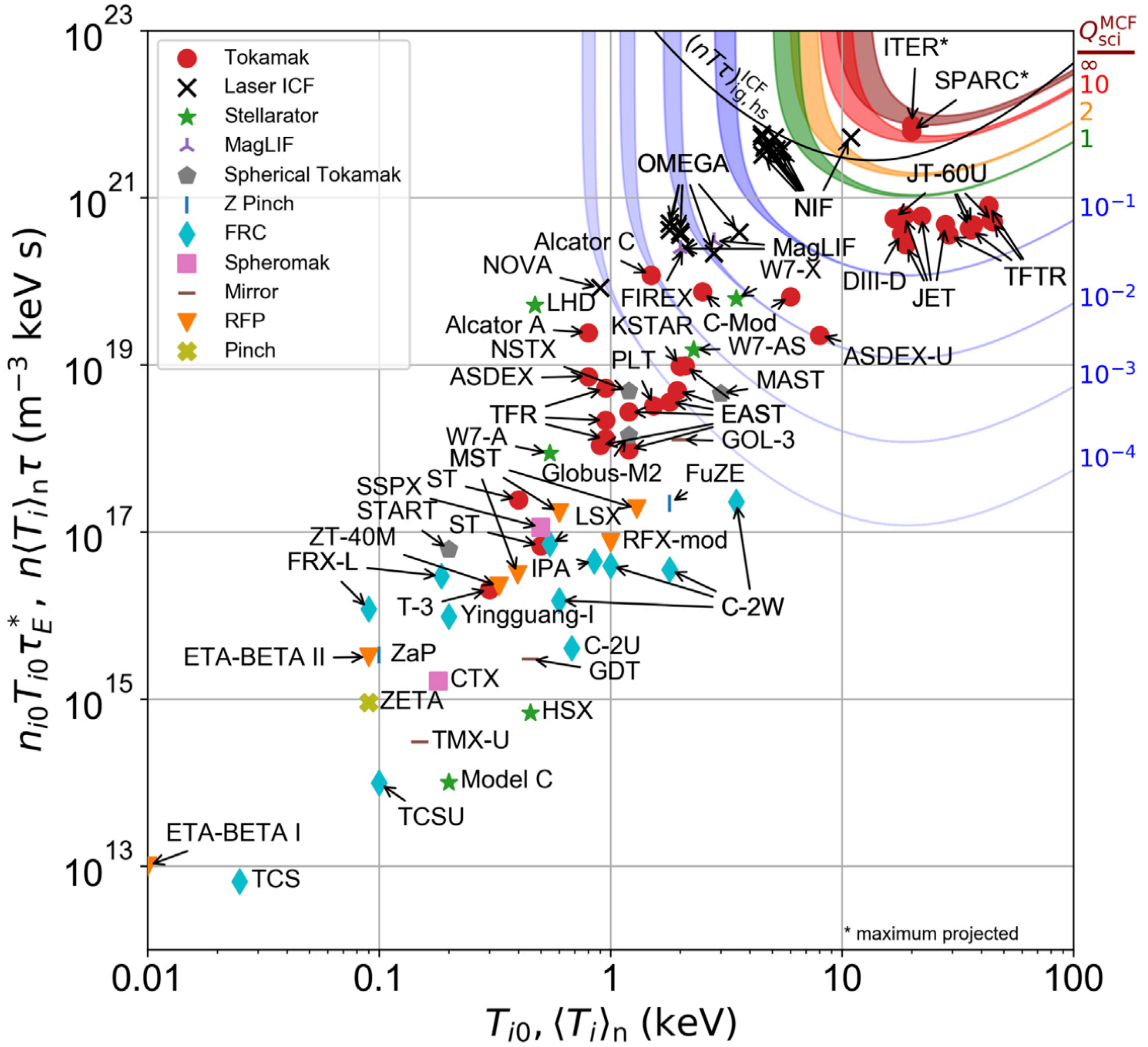


FIG. 16. Experimentally inferred, peak triple products of fusion experiments vs ion temperature, extracted from published literature. See the caption of Fig. 2 for more details.

The triple product <u>alone</u> does not tell you what Q_{sci} — you need to know the plasma temperature, the fusion fuel type, and a bit other information about the fusion plasma!

* Figures from S.E. Wurzel and S.C. Hsu, "Progress toward fusion energy breakeven and gain as measured against the Lawson criterion," *Phys. Plasmas* **29**, 062103 (2022), https://doi.org/10.1063/5.0083990

Fusion power output scaling provides insight into tradeoffs between various fusion approaches

Plasma ions are undergoing fusion events - fusion power for fusing species A and B:

$$P_{fusion} = n_A n_B \langle \sigma v \rangle_{AB} E_{AB} V_p \text{ [Watts]}$$

Assuming a quasi-neutral DT plasma with $n_D = n_T = n/2$,

$$P_{fusion} = \frac{n^2}{4} \langle \sigma v \rangle_{DT} E_{DT} V_p \propto n^2 \langle \sigma v \rangle_{DT} V_p$$

Define $\beta = p/p_{mag}$ where $p \propto nT$ and $p_{mag} \propto B^2$, substitute $n^2 \propto \beta^2 B^4 / T^2$,

$$P_{fusion} \propto \beta^2 \quad B^4 \quad \frac{\langle \sigma v \rangle_{DT}}{T^2} \quad V_p$$

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

$$\beta = \frac{2\mu_o p}{B^2}$$

Set by magnet technology/ plasma current magnitude

$$\nabla \times \mathbf{B} = \mu_o \mathbf{J}$$

Optimize for a given fusion fuel type*

Bosch & Hale, *Nucl. Fus* **32**:4, (1992) and formularies

Fusing plasma volume

Dependent on plasma geometry

Alternative form of triple product provides insight into tradeoffs of fusion approaches - is it high β, high B, both?

$$P_{fusion} \propto \beta^2 B^4 \frac{\langle \sigma v \rangle}{T^2} V_p$$

$nT\tau_E = p_i \tau_E \propto \beta B^2 \tau_E$ using $\beta \propto p/B^2$ again

It is advantageous to have high B and/or high β to:

- Maximize the fusion power density to reduce the plasma volume V_p needed for a total fusion power output (lower costs $)

- Minimize the required energy confinement time τ_E to reach Lawson conditions

Of course, there are other consideartions (enough to base an entire field on!) besides these two equations to consider for a fusion design point, but are always useful tools to compare fusion concepts

Fusion concepts can be viewed as pursuing a particular β/χ, where χ is a thermal diffusivity of the fusion plasma confinement scheme

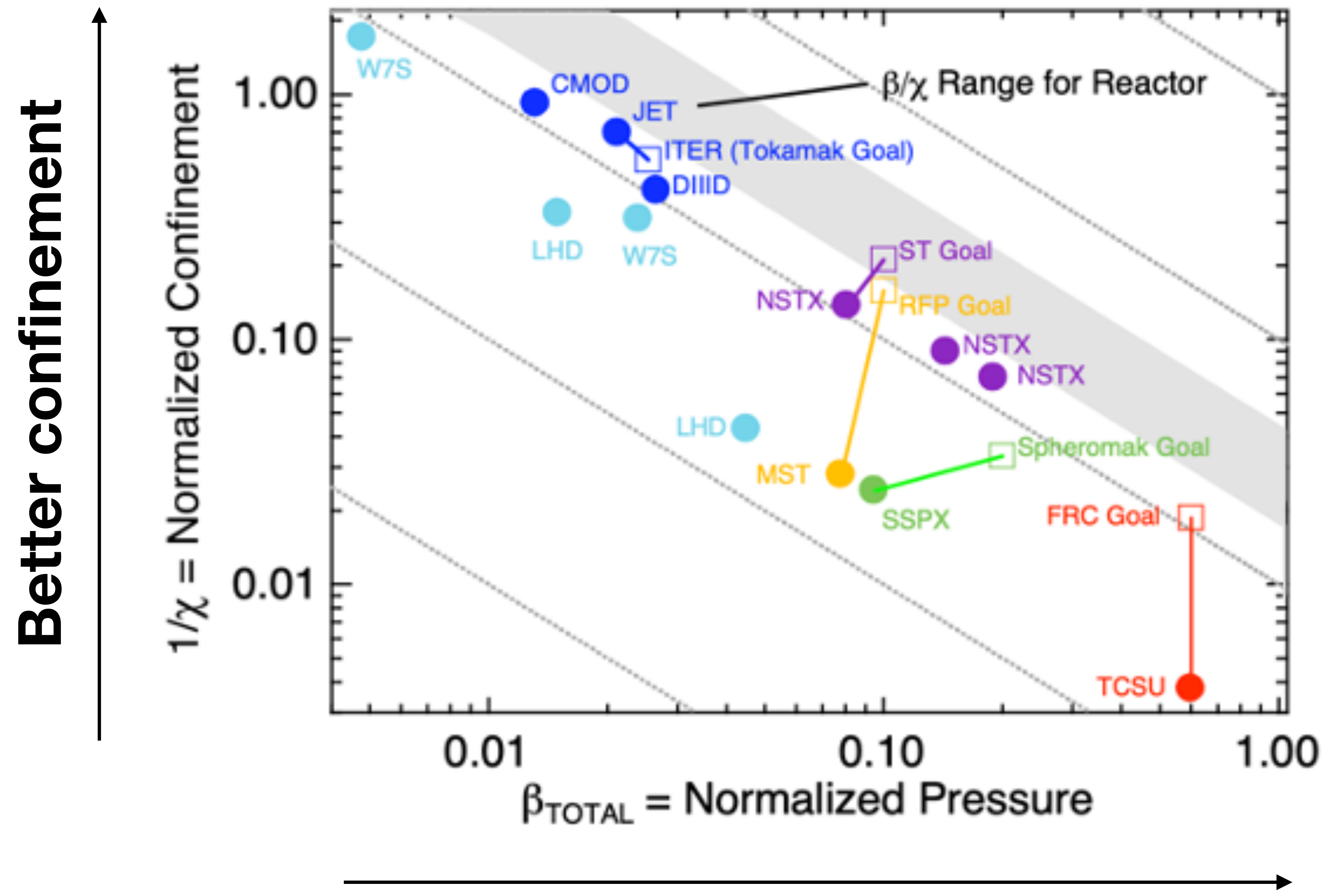
- Balance between confinement and accessible β when scaling to fusion conditions

- Tokamaks and stellarators tend to be lower β with good confinement

- STs, RFPs, Spheromak tend to have medium β and confinement goals

- FRC tends to have high β with shorter confinement times (similar to Z-pinch)

- Higher plasma pressure allows for worse confinement while still hitting net-gain



Higher plasma relative to magnetic pressure

● Tokamak ● Stellarator ● Spherical Tokamak (ST)
● Reversed-field pinch (RFP) ● Spheromak
● Field-Reversed Configuration (FRC)

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

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The growing fusion energy landscape

Summary and resources

Z-pinch plasma configurations have axial plasma currents that generate azimuthal magnetic felds

- Axial current density in “Z” direction gives this configuration its name

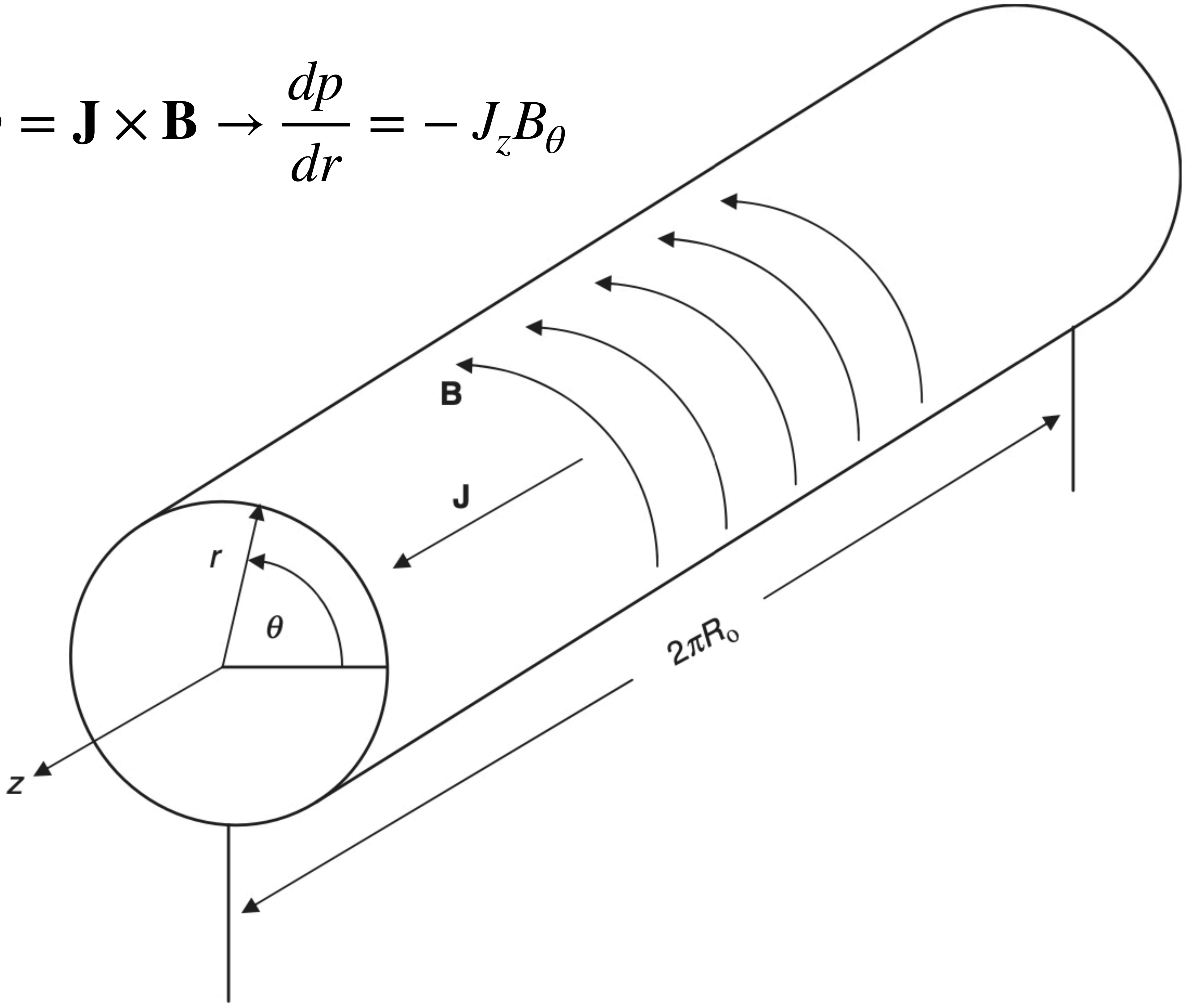
- Azimuthal magnetic field crossed with axial current “pinches” the plasma column

- High $\langle\beta\rangle \approx 1$ and large magnetic fields $B = 10$+ T — large fusion power density with very small plasma volume

- Perpendicular transport is favorable for reaching high plasma temperatures, volume near axis is weakly/unmagnetized

Linear Z-pinch

$$\nabla p = \mathbf{J} \times \mathbf{B} \rightarrow \frac{dp}{dr} = -J_z B_\theta$$

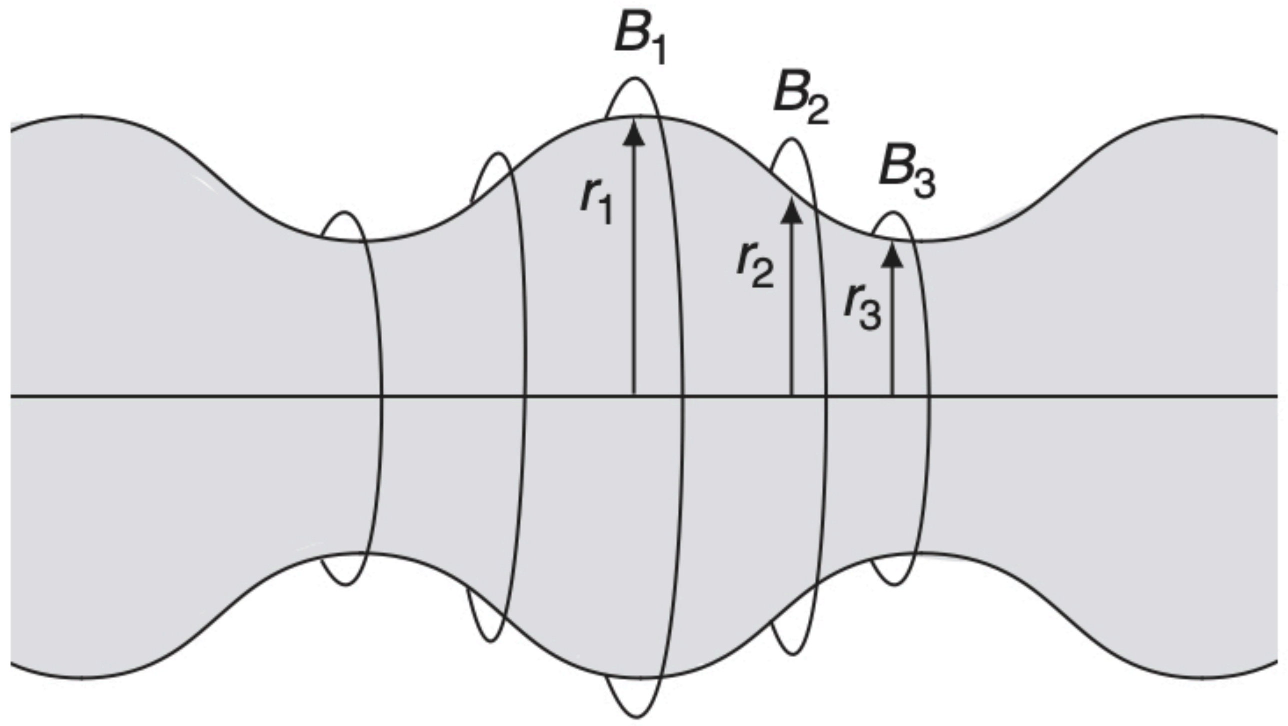


* Figure from J.P. Freidberg, *Ideal MHD,* Cambridge University Press (2007).

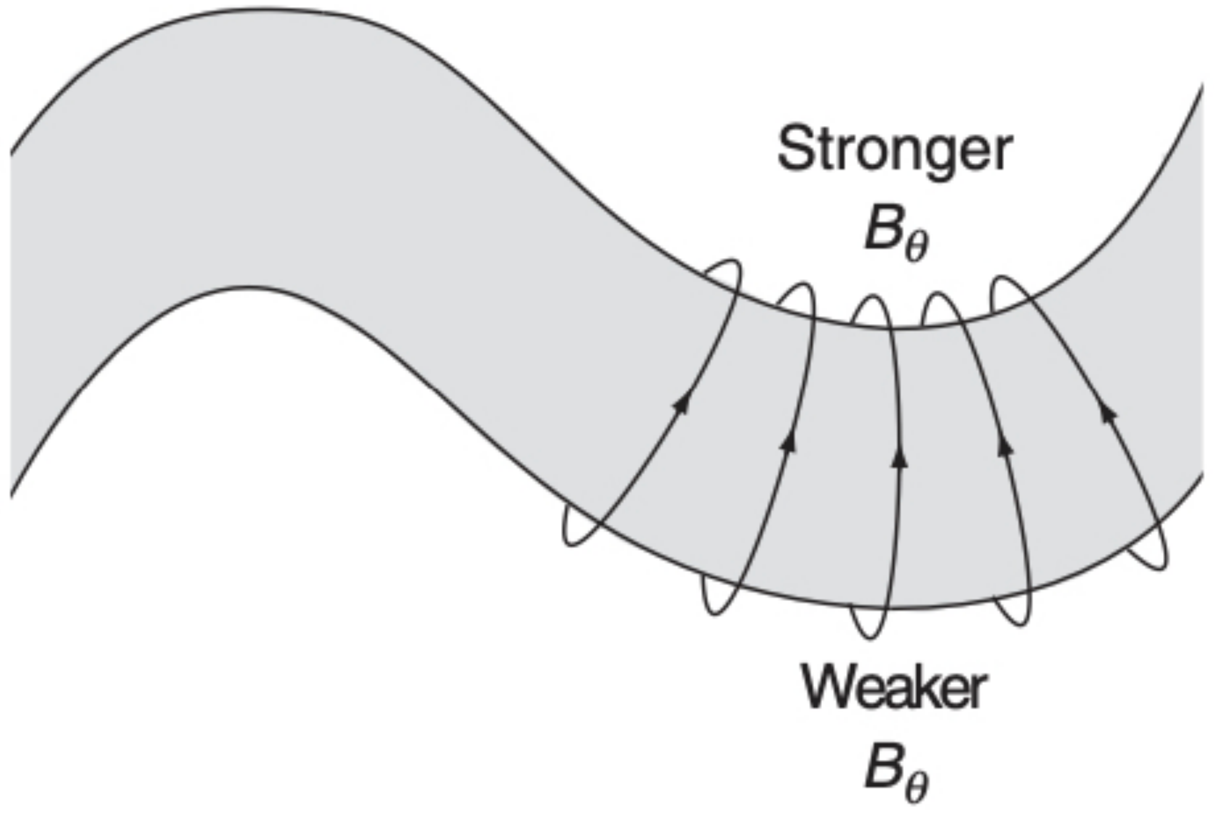
Static Z-pinches are unstable to fast growing Ideal-MHD modes that limit configuration lifetimes

- Ideal-MHD modes generally grow very quickly and can limit plasma lifetime
- Need to make enough fusion energy before the plasma goes unstable to pay for the energy put in to make it — otherwise cannot be a net-gain system
- As is true for the static Z-pinch and other fusion concepts, plasma stability is often required for good enough confinement to reach net-gain
- There are multiple ways we can stabilize the Z-pinch, but one that is especially promising is sheared-flow-stabilization (SFS)

“Sausage” m = 0 mode



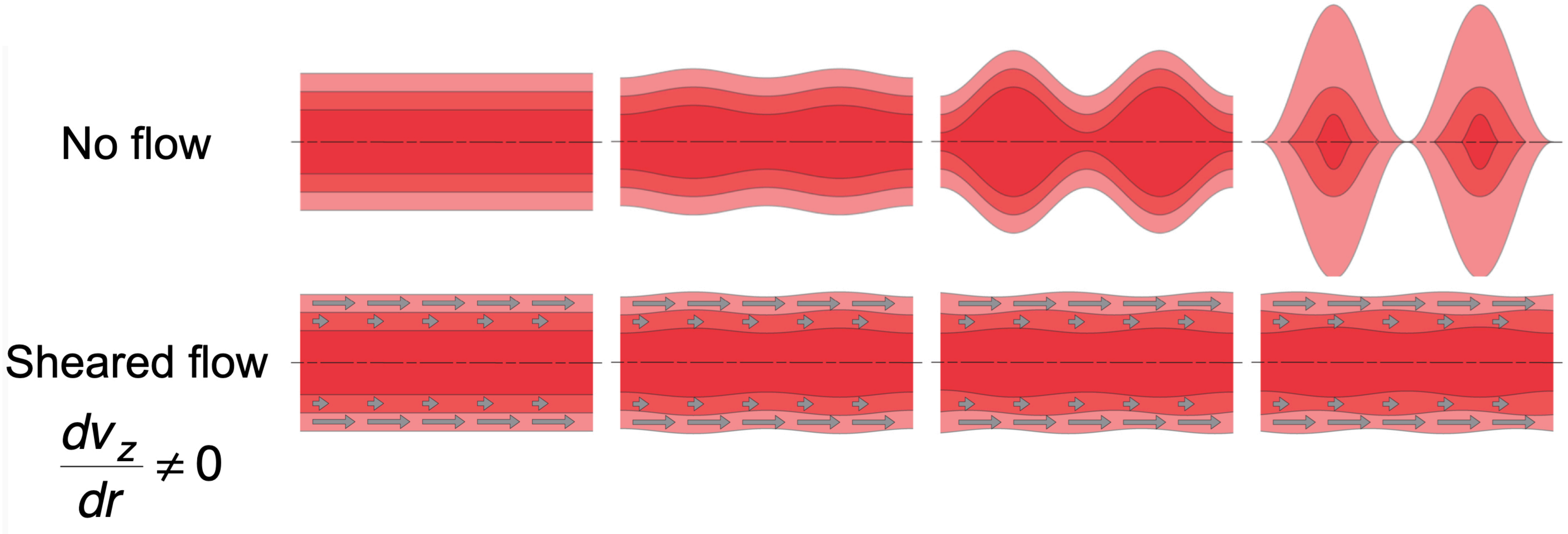
“Kink” m = 1 mode

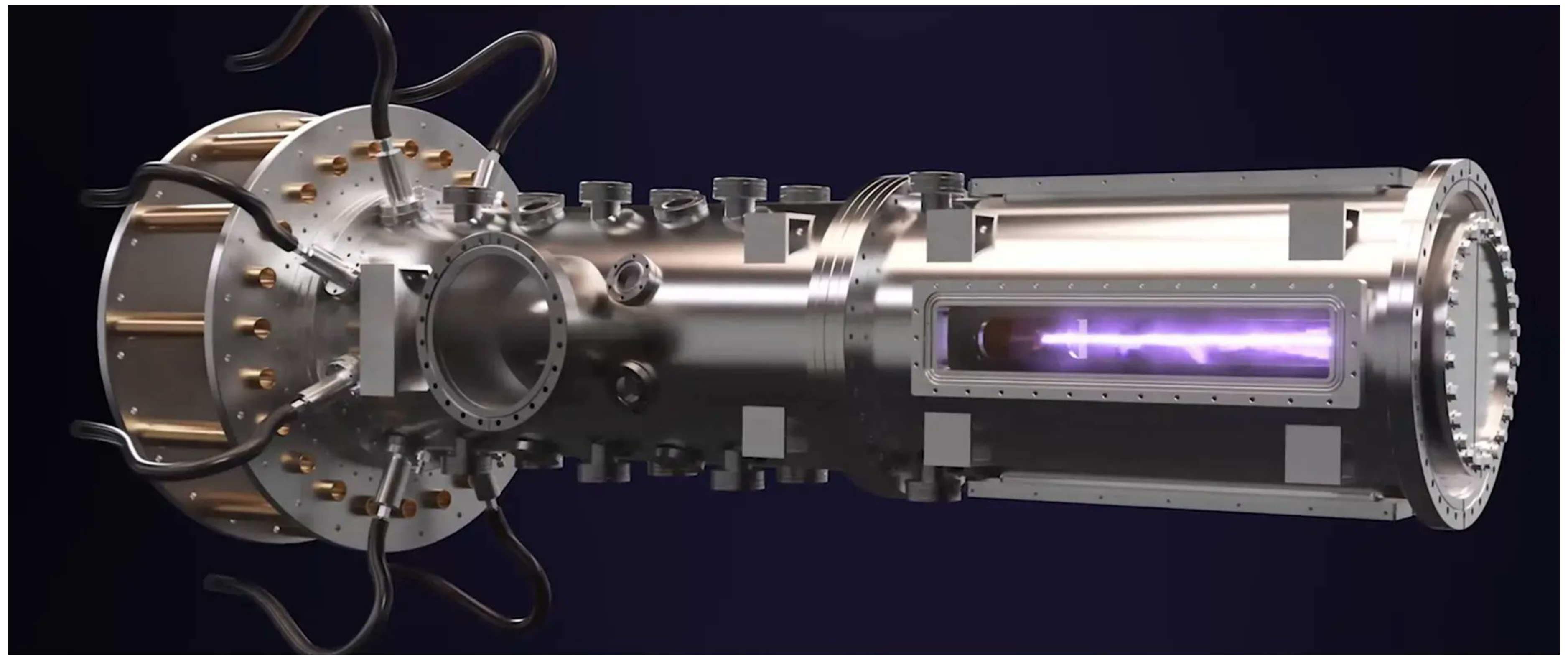


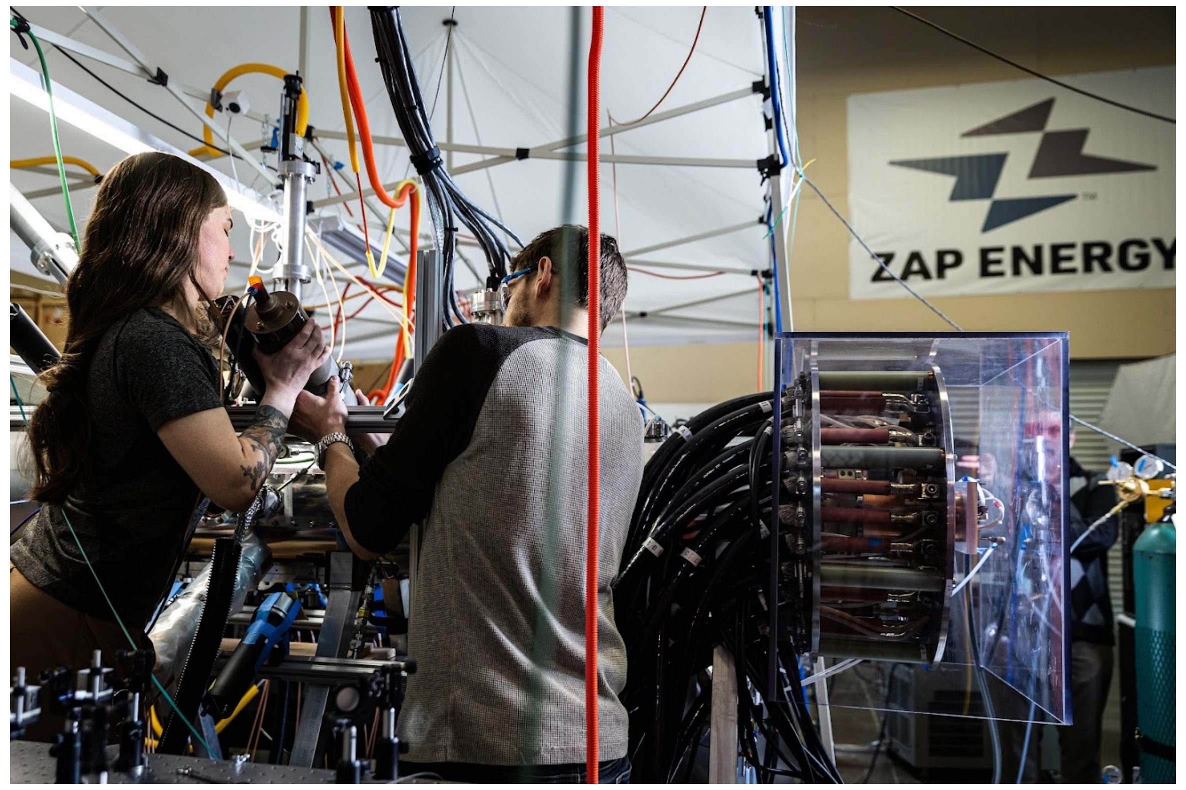
* Figures from J.P. Freidberg, *Ideal MHD,* Cambridge University Press (2007).

The Sheared-Flow-Stabilized (SFS) Z-pinch is being developed at Zap Energy for compact, modular fusion energy systems

- A radially-sheared axial flow is embedded in a Z-pinch, making it a “flow” Z-pinch
- The radially sheared axial flow stabilizes Ideal-MHD modes
- Longer stability period allows for much more fusion energy to be made per pulse
- Multi-keV plasmas with many times longer than Ideal-MHD instability growth timescale
- <u>Very</u> compact fusion cores with high fusion power density and low CapEx/OpEx
- Targeting pulsed ~ 200 MWth D-T fusion cores with liquid metal first walls







* See papers at https://www.zapenergy.com/research that details the concept!

Sheared-flow-stabilized (SFS) Z-pinch is being developed at Zap Energy for compact, modular fusion energy systems

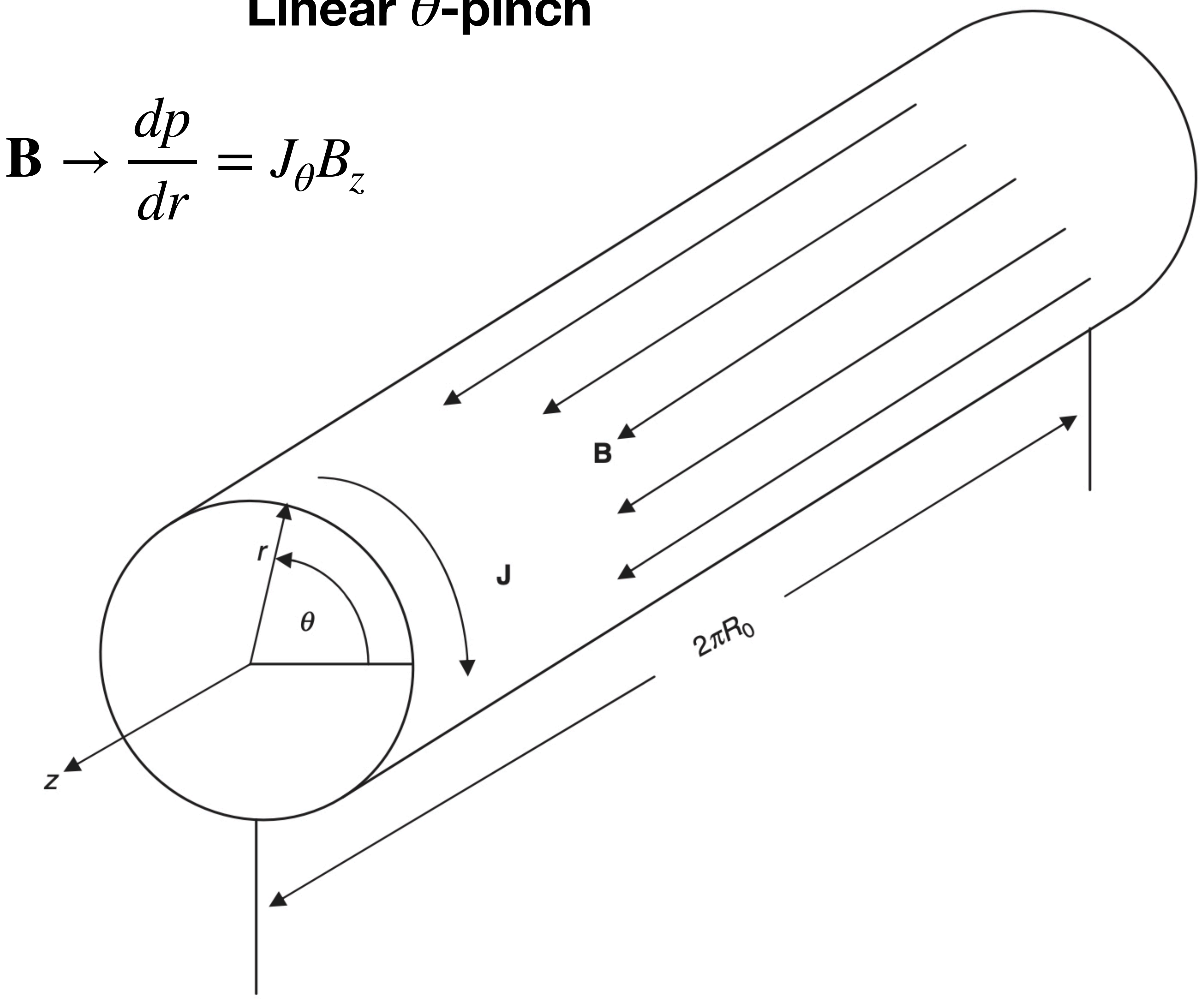
* See papers located at https://www.zapenergy.com/research that details the concept! All images are from Zap Energy, Inc.

θ-pinch plasma configurations have azimuthal plasma currents that generate axial magnetic fields

- Azimuthal current density in "θ" direction gives this configuration its name
- Axial magnetic field crossed with azimuthal current "pinches" the plasma column
- "Pulsed" azimuthal current in surrounding coil induces azimuthal current in plasma
- Lower β than Z-pinch and parallel transport along field lines is unfavorable for scaling to a net-gain fusion system, but more stable
- ***Teaser:*** θ-pinch formation is often used to make field-reversed configurations (FRCs) that we'll see in a bit!

Linear θ-pinch

$$\nabla p = \mathbf{J} \times \mathbf{B} \rightarrow \frac{dp}{dr} = J_\theta B_z$$

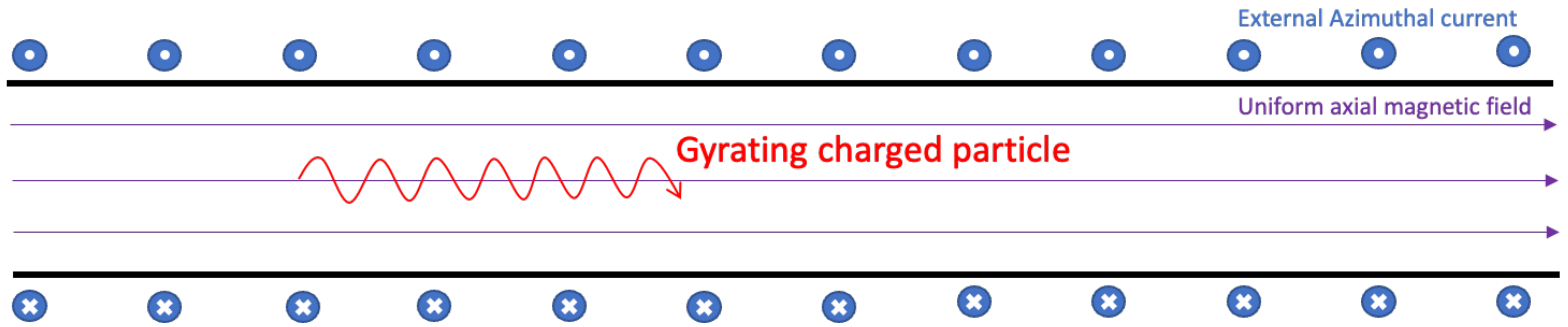


* Figure from J.P. Freidberg, *Ideal MHD,* Cambridge University Press (2007).

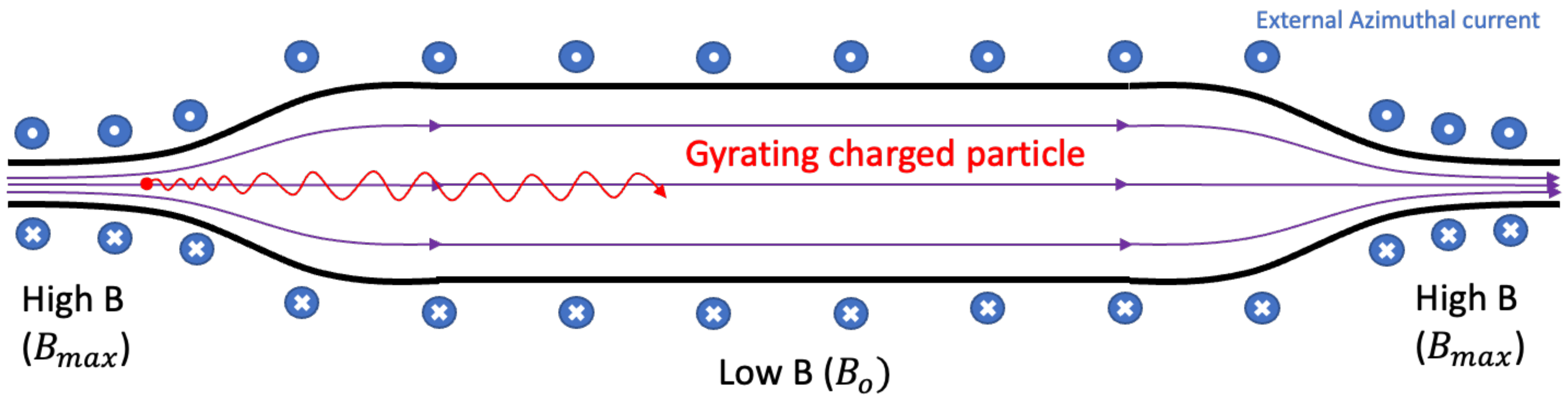
Magnetic mirrors are steady-state and uses a high field “plug” confine particles as they bounce back and forth

- The “endloss” issue of a linear θ-pinch can be reduced by using “magnetic mirroring”
- Exploits the conservation of magnetic moment of a gyrating particle that feels a force when there is a magnetic field gradient
- Regions of higher field on each end of the mirror “reflect” particles back and forth instead of being lost out the end
- Some particles still do leak out the ends (i.e., the loss cone) but higher field at the plug relative to the center of the machine helps reduce losses (i.e., increasing the mirror ratio $R_m = B_{max}/B_0$)
- ***Teaser:*** The physics of mirrors appear in a variety of concepts: Check out banana orbits in tokamaks, stellarators ~ an ensemble of mirrors linked toroidally, and in the levitated dipole!

“Endless” Linear θ-pinch



Simple Magnetic Mirror



Magnetic mirrors are attractive due to steady-state operation and relative simplicity - methods of reducing losses and maintaining stability are needed

Gas Dynamic Trap (GDT) in Russia

- $R_m \approx 100$
- NBI and ECRH heating
- $T_e \approx 1$ keV, $n_i \approx 1 \times 10^{20}$ m^{-3}

Two recent/ongoing ARPA-E funded mirror projects:

Centrifugal Mirror Experiment (University of Maryland)

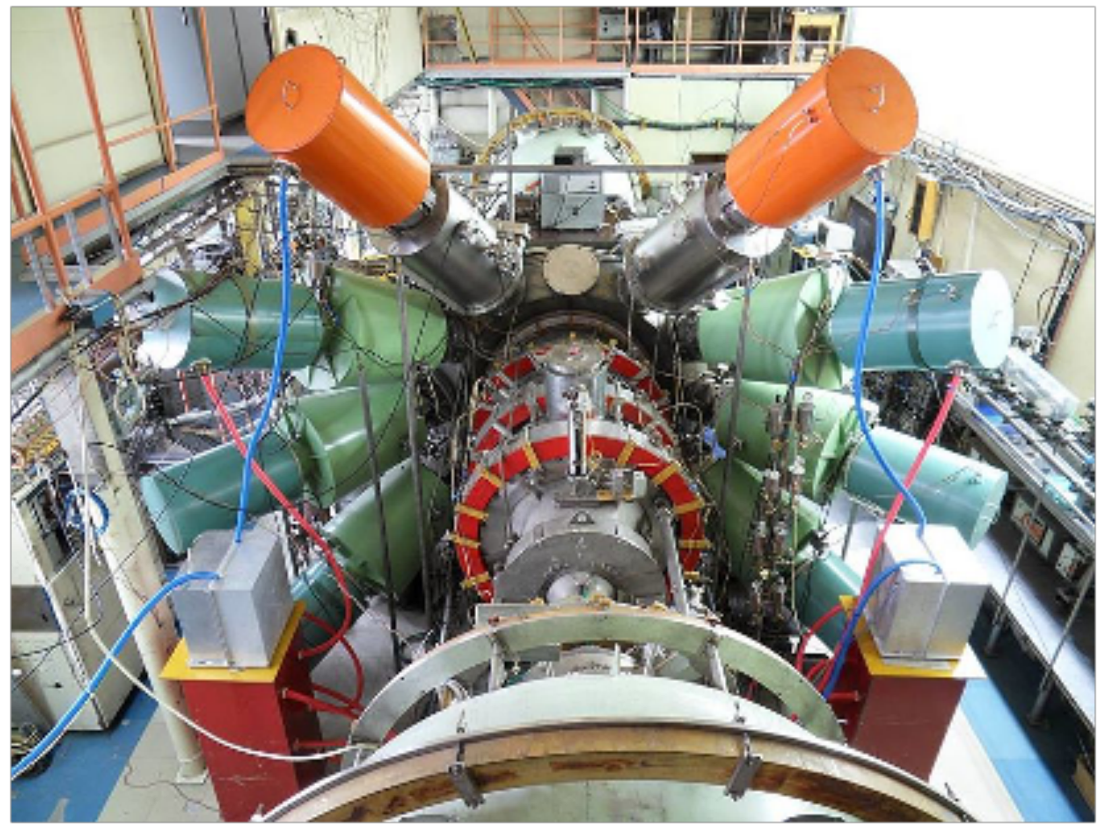
- Using supersonic rotation of mirror to help close loss cone to reduce parallel end losses.
- Velocity shear to help stabilize interchange instability modes.

Wisconsin High-field Axisymmetric Mirror - WHAM (University of Wisconsin-Madison)

- Use high-temperature superconductors capable of much higher steady-state magnetic fields than previously possible – increase mirror field strength B~ 17-20+ T.

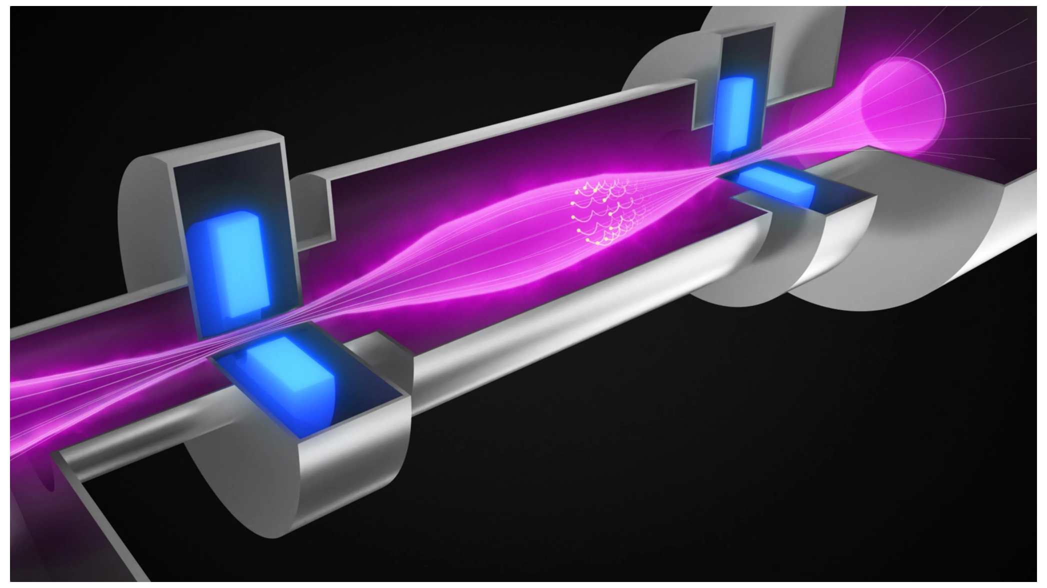
One recently funded private fusion company: Realta Fusion spun out from UWisc-Madison!

Interest in these devices for commercial fusion (heat and power) and also a potential relatively low-cost volumetric neutron source (VNS) to test materials/components in DT fusion neutron environment



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

REALTA FUSION



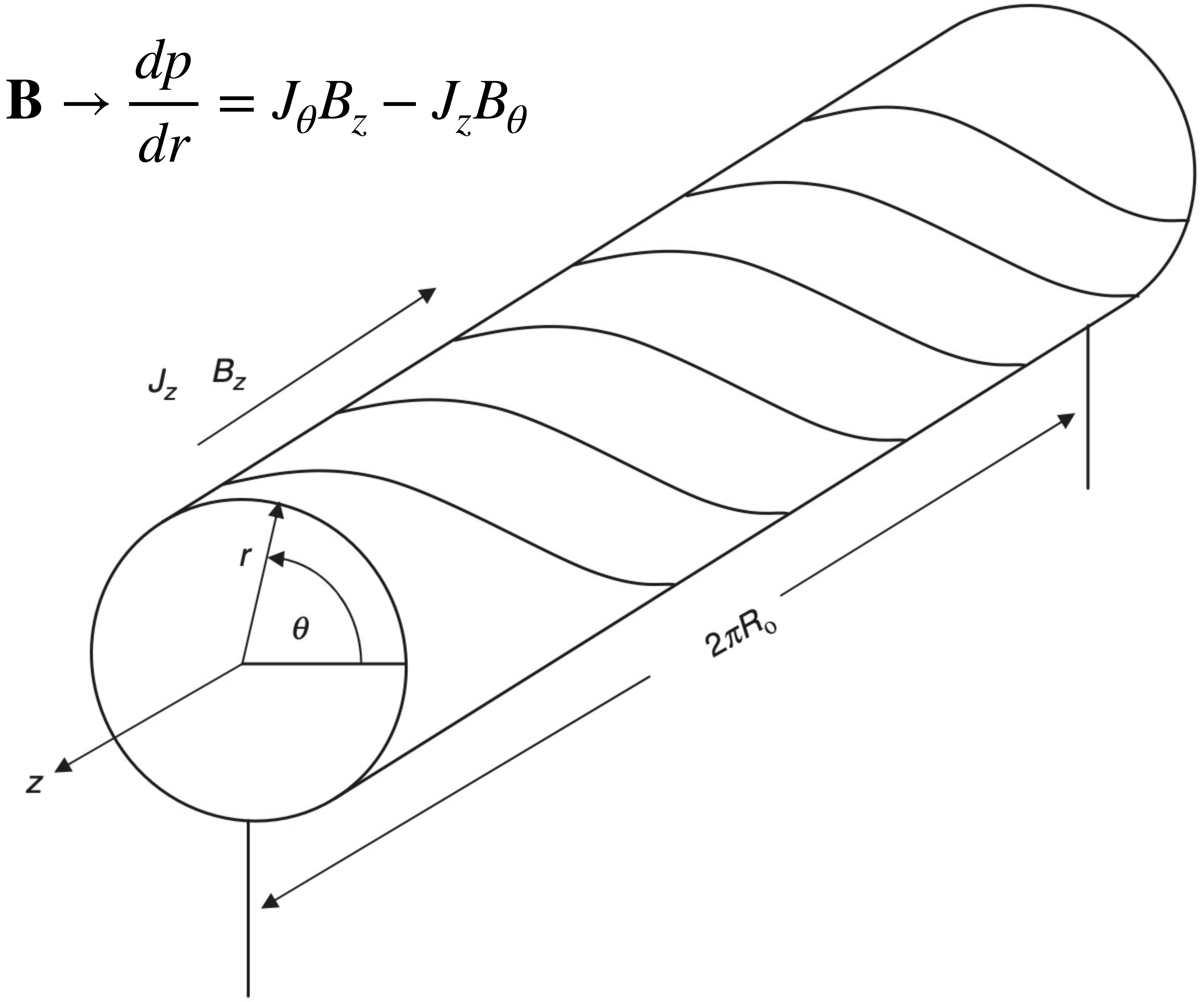
* Logo and Image from Realta Fusion

Screw pinches effectively combine the Z-pinch and θ-pinch creating a helical magnetic field

- Use axial field instead of sheared-flow to stabilize a Z-pinch — screw pinch!
- Parallel losses still present — wrap into a torus to avoid end losses instead of using “mirror plugs”
- Change ratio of axial field to azimuthal field and how field is made (coils v. plasma current) — stellarator, tokamak, spherical tokamak (ST), reversed-field-pinch (RFP), spheromak
- Linear concepts are used as building blocks of toroidal concepts and much physics is shared!

Linear Screw Pinch

$$\nabla p = \mathbf{J} \times \mathbf{B} \rightarrow \frac{dp}{dr} = J_\theta B_z - J_z B_\theta$$



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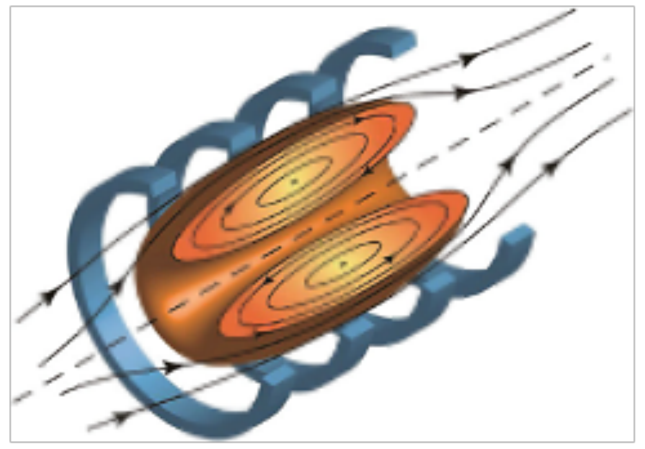
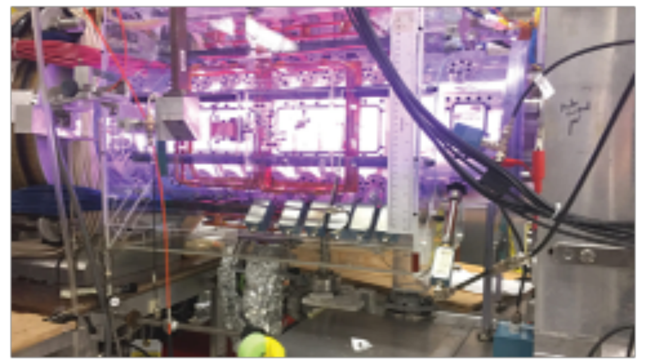
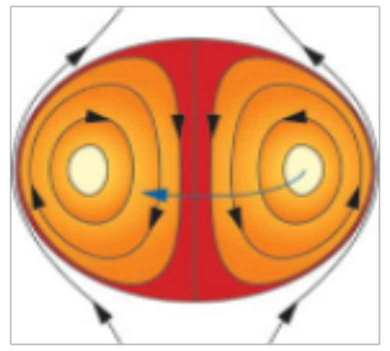
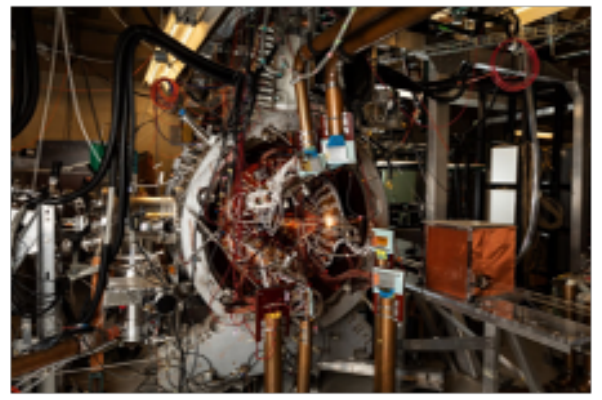
A spectrum of toroidal fusion concepts with varying magnetic field topologies and generation methods



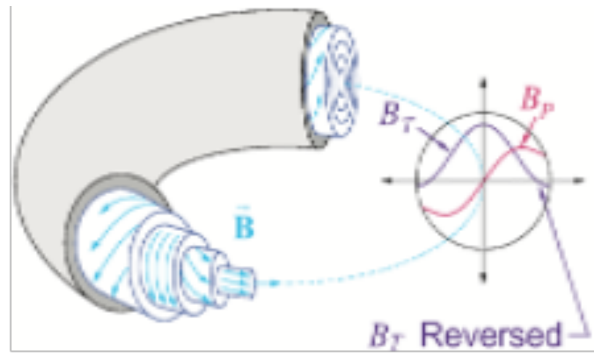


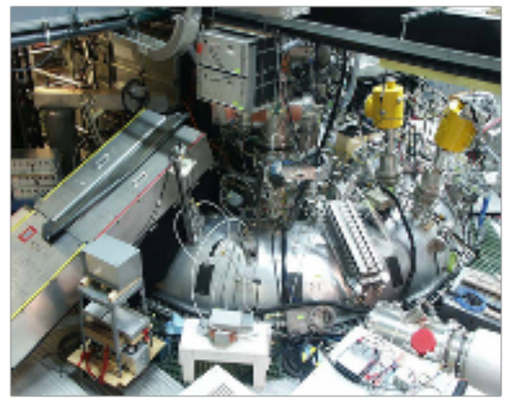
Field-reversed configuration (FRC)





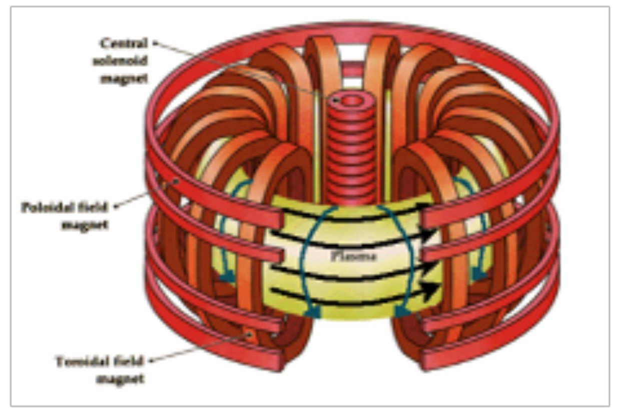
Spheromak

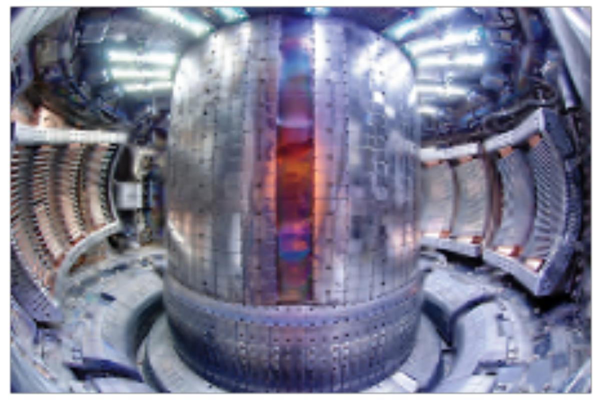




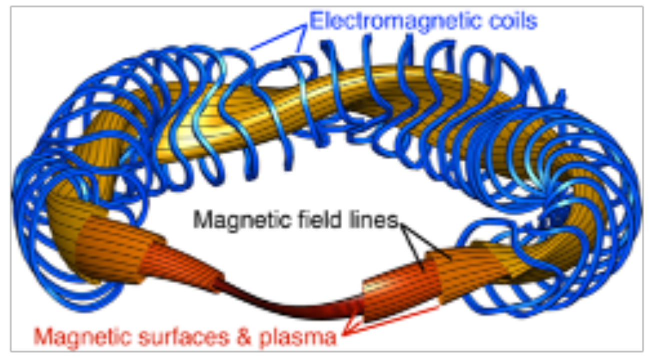
Reversed-Field Pinch (RFP)

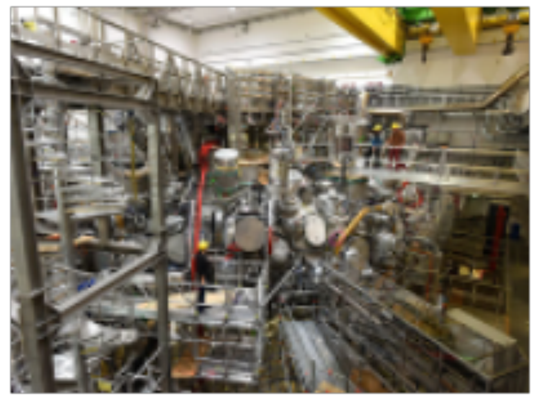
Spherical Tokamak





Tokamak





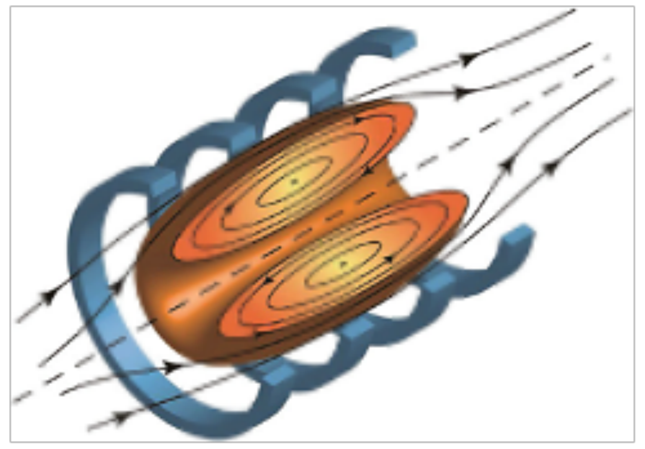
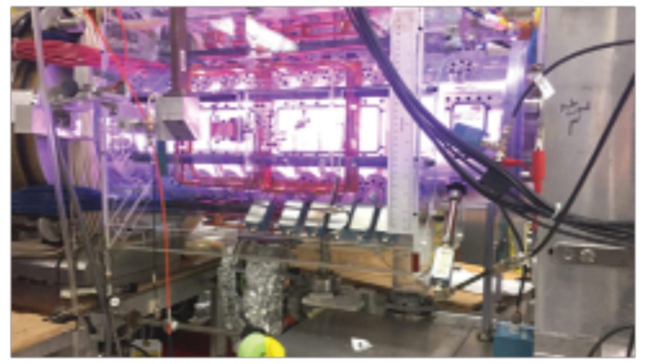
Stellarator

Where is the current flowing? $\nabla \times \mathbf{B} = \mu_o \mathbf{J}$

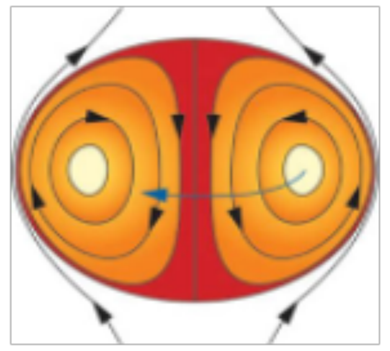
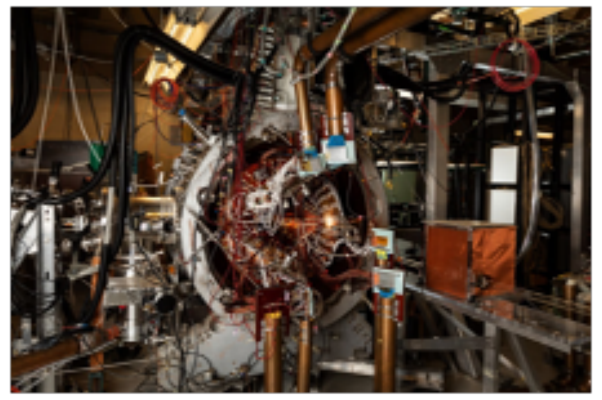
Plasma current **External coils**

Magnetic field generation method

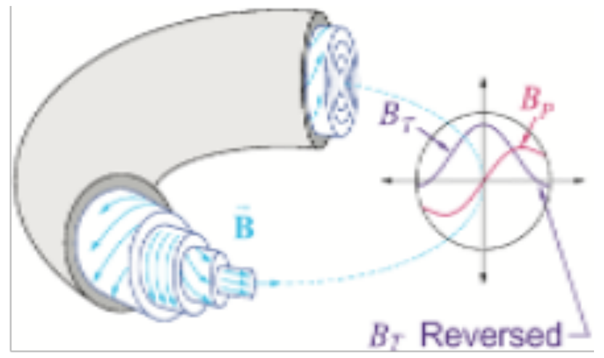
Many toroidal concepts share the foundational idea of a "screw pinch" - both toroidal (axial) and poloidal (azimuthal) fields present

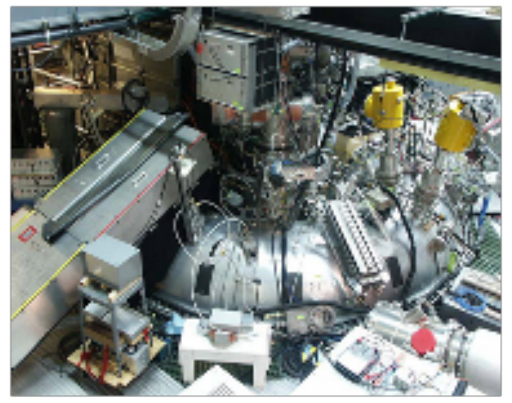



Field-reversed configuration (FRC)

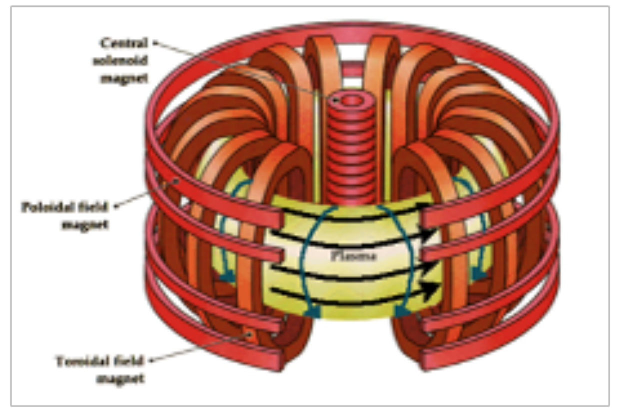
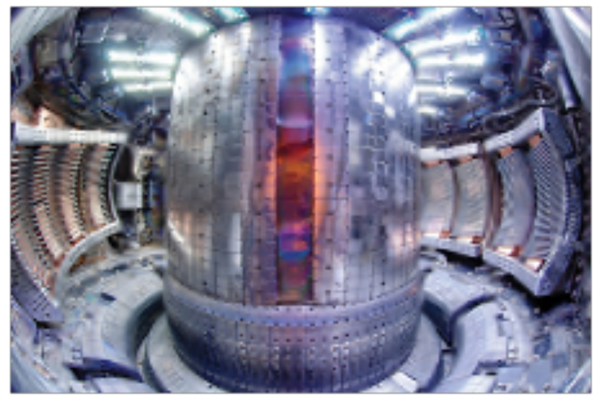
Spheromak



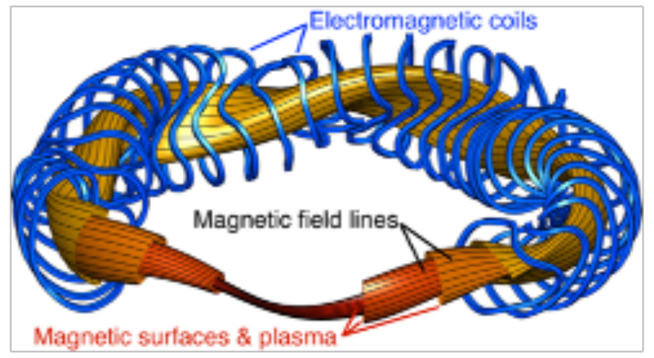


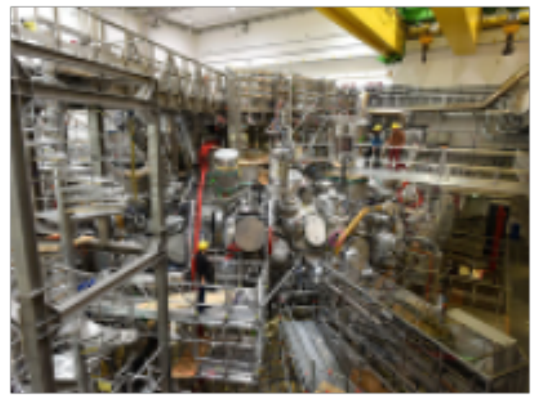
Reversed-Field Pinch (RFP)


Spherical Tokamak

Tokamak



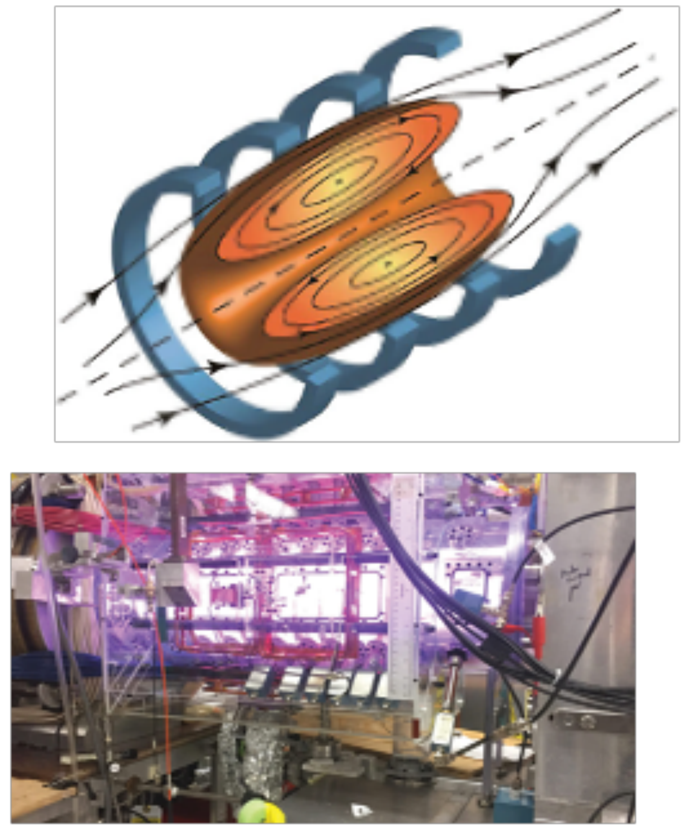


Stellarator

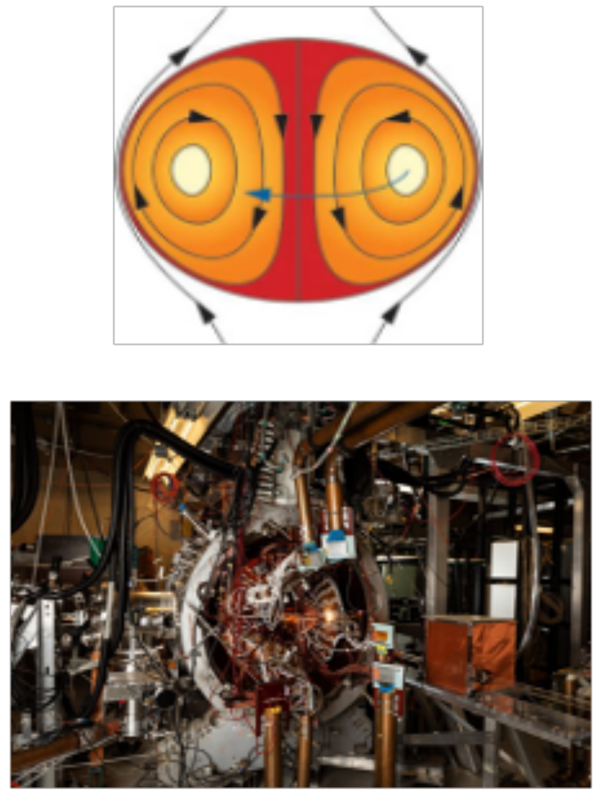
Where is the current flowing? $\nabla \times \mathbf{B} = \mu_o \mathbf{J}$

Plasma current ⟵ **Magnetic field generation method** ⟶ **External coils**

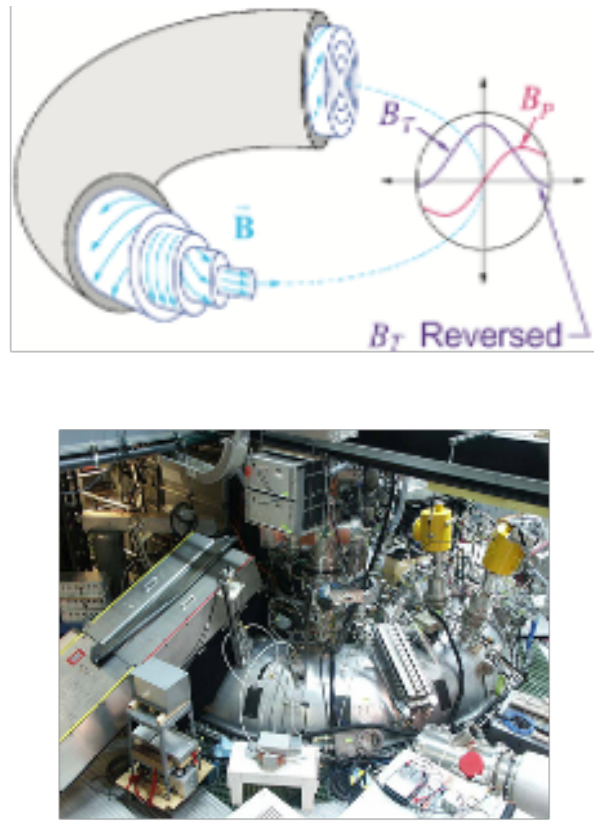
We'll focus on a subset of these "screw pinch like" toroidal concepts



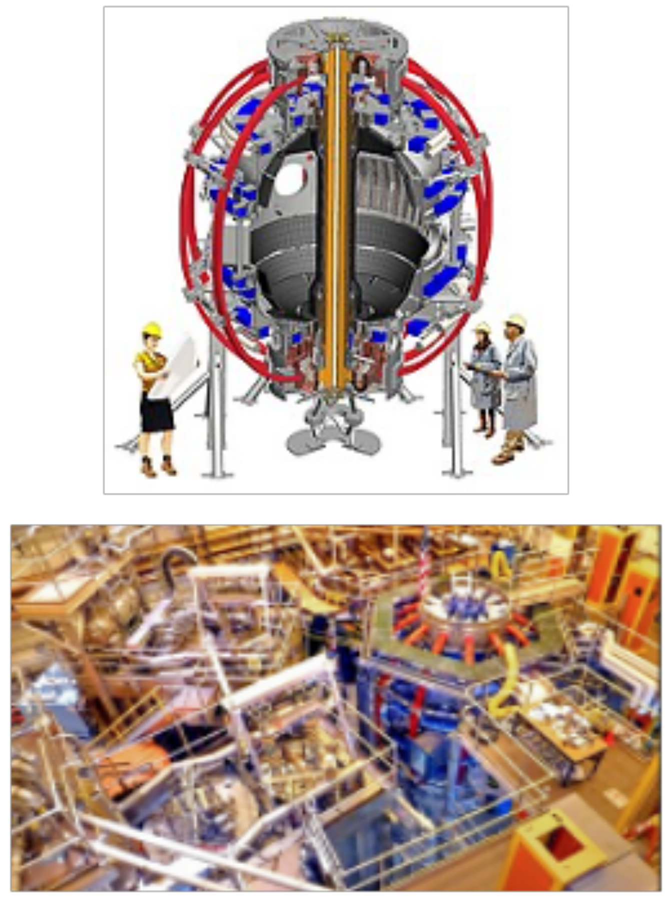
Field-reversed configuration (FRC)



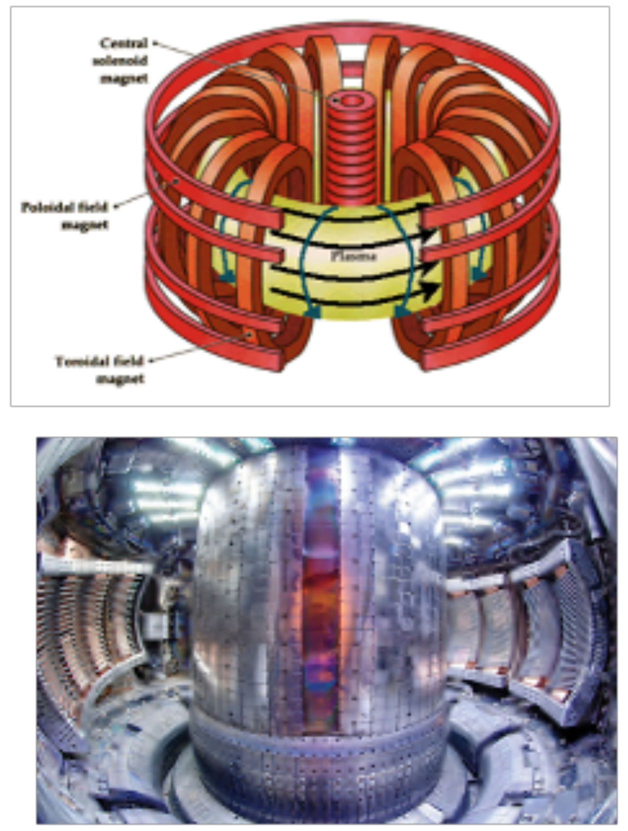
Spheromak



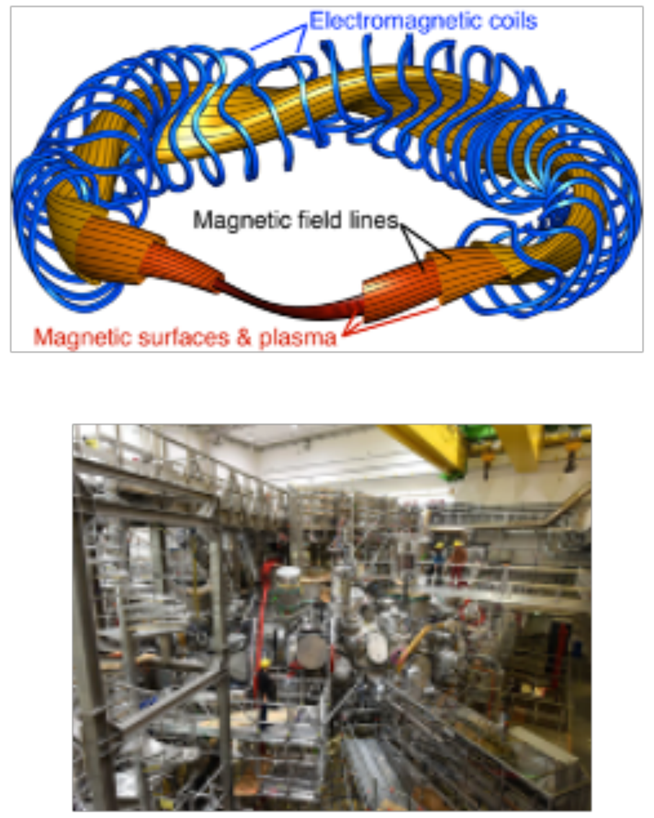
Reversed-Field Pinch (RFP)



Spherical Tokamak



Tokamak



Stellarator

Where is the current flowing? $\nabla \times \mathbf{B} = \mu_o \mathbf{J}$

Plasma current ⟵ **Magnetic field generation method** ⟶ **External coils**

Reversed-field pinches (RFPs): low externally 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 ($B_T \approx B_p$) 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
- Connection to spheromak physics

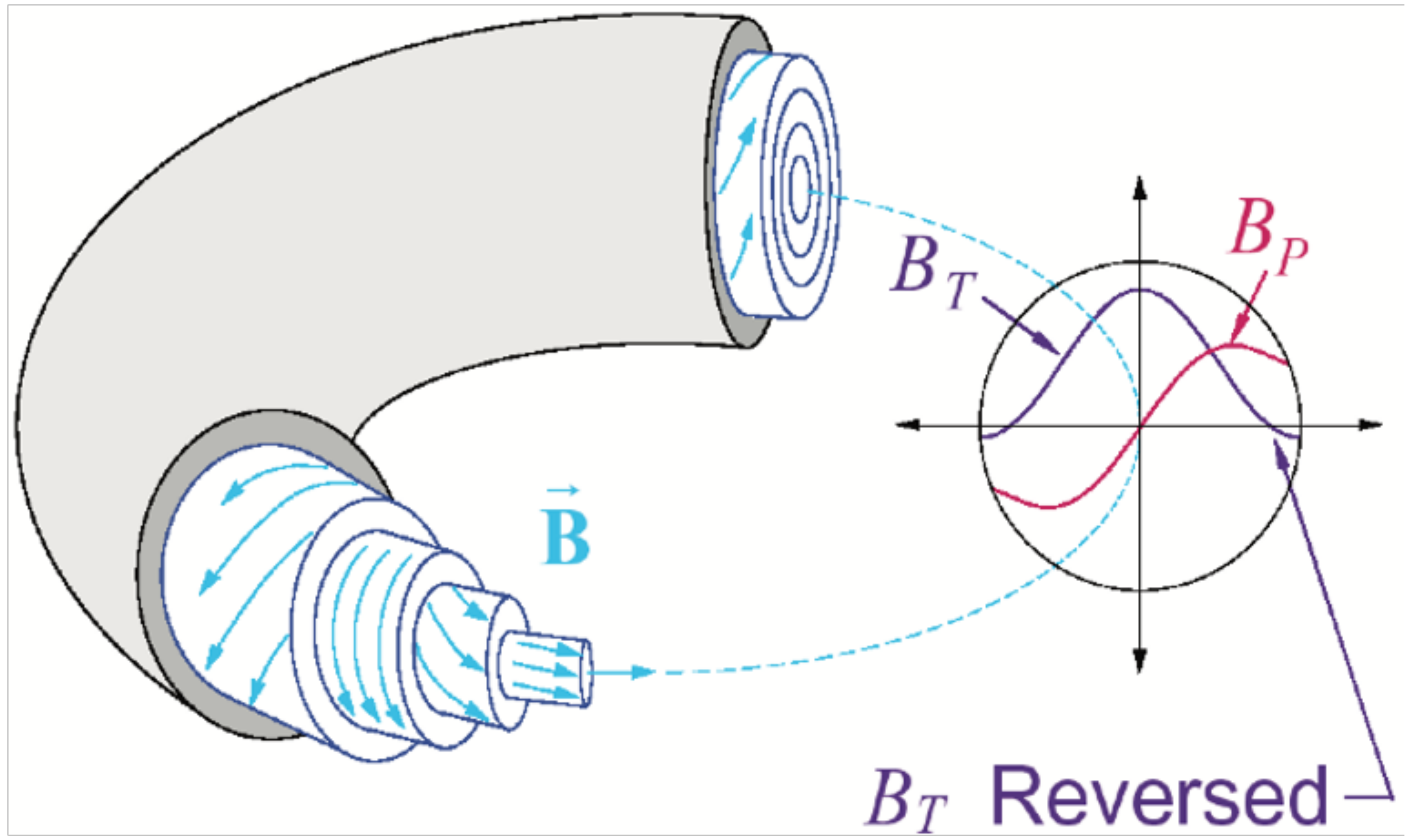


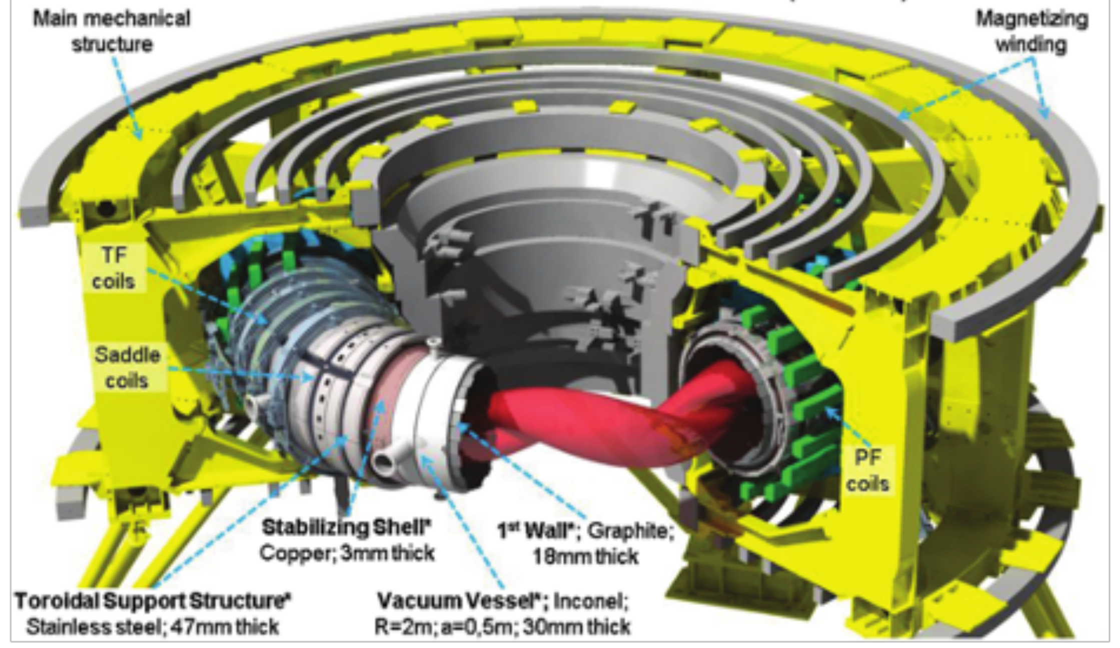
Figure: J. Sarff, Perspectives on Reversed Field Pinch (RFP) Fusion Research, FPA (2011)

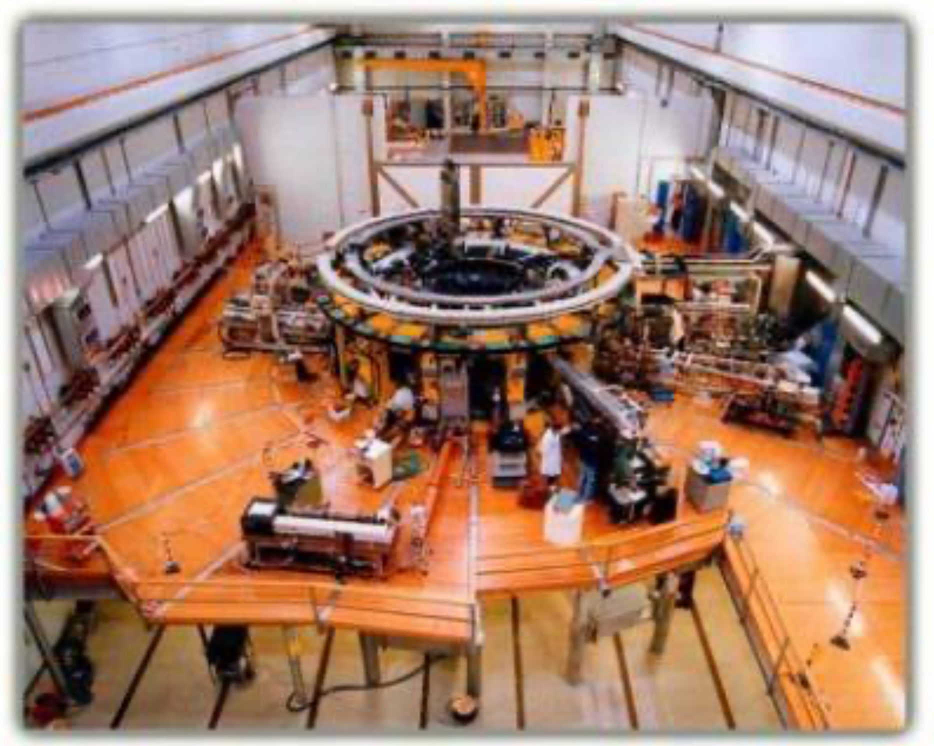
Most significant recent RFP experiments are MST at UWisc-Madison and RFX-Mod in Italy

- RFPs produce keV plasma temperatures with higher average β than a tokamak
- 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

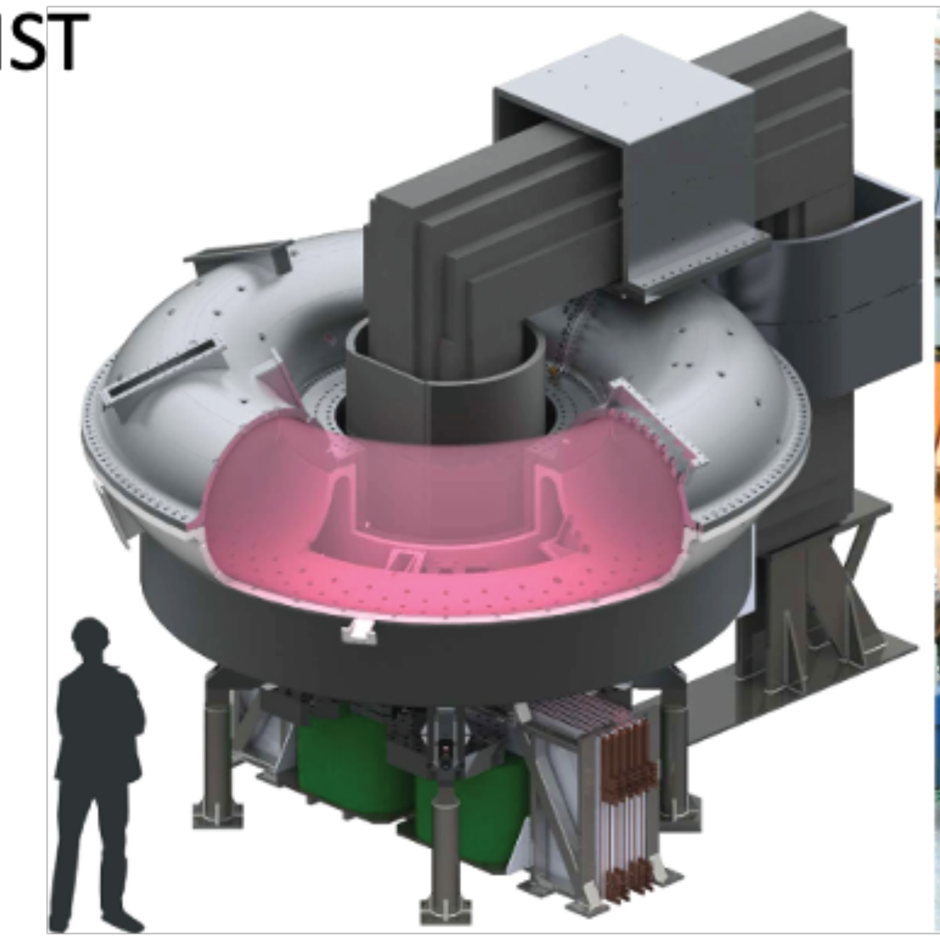
RFX-Mod

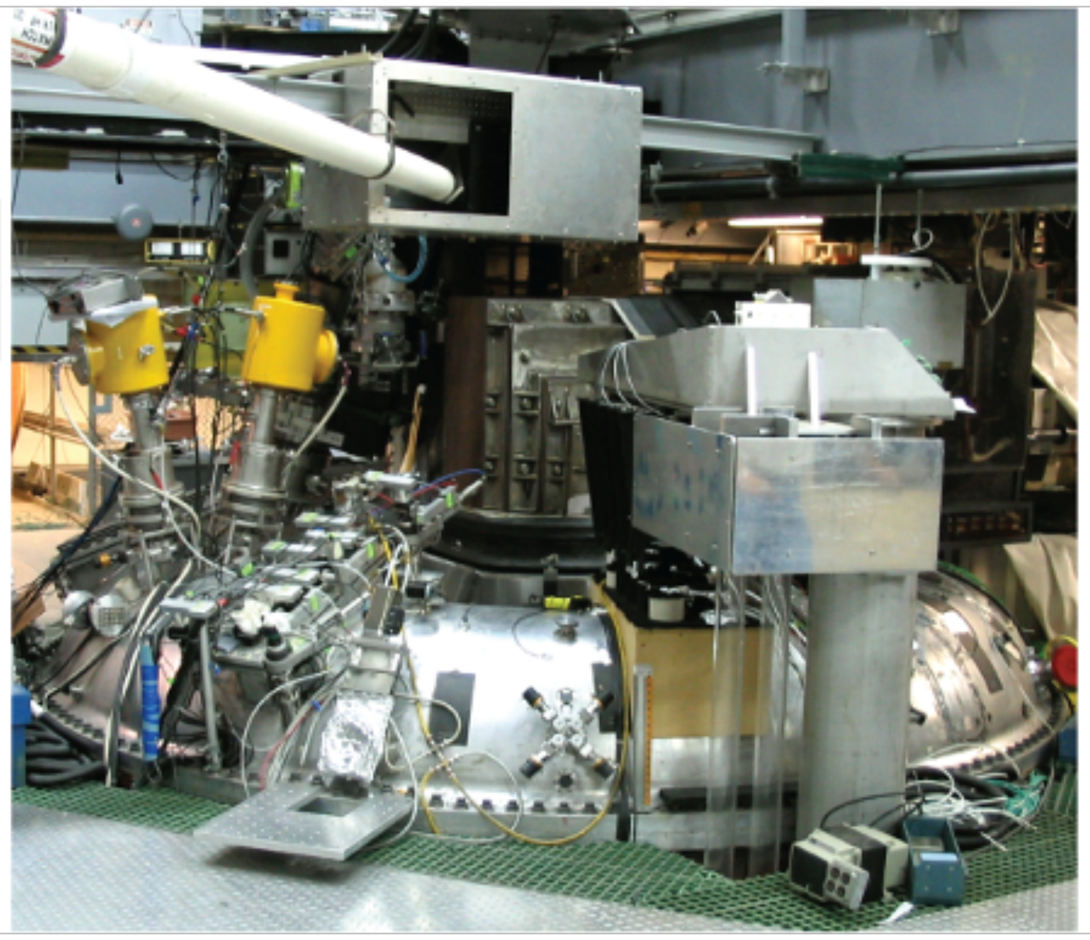
Peruzzo et al., FED 123, 59 (2017)





MST





MST images from University of Wisconsin-Madison

Spheromak : a simply connected, compact toroidal (CT) confinement concept with no externally applied 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 plasma is a torus, but the confinement chamber is "simply" connected, or spherical in topology)

- Spheromaks belong to a family of "compact torus" (CT) confinement concepts alongside the field-reversed configuration (FRC) we will discuss soon!

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

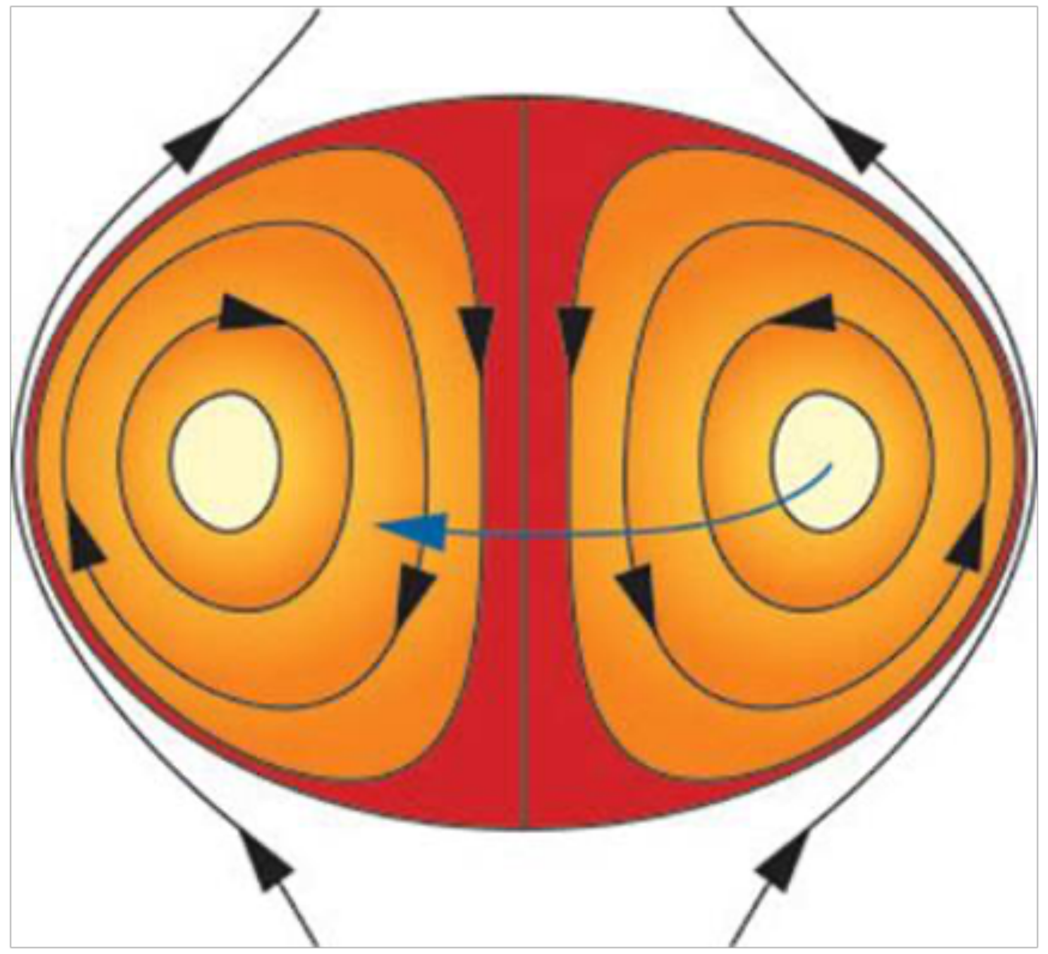


Figure: UW A&A Department, https://www.aa.washington.edu/research/HITsi/research/spheromak

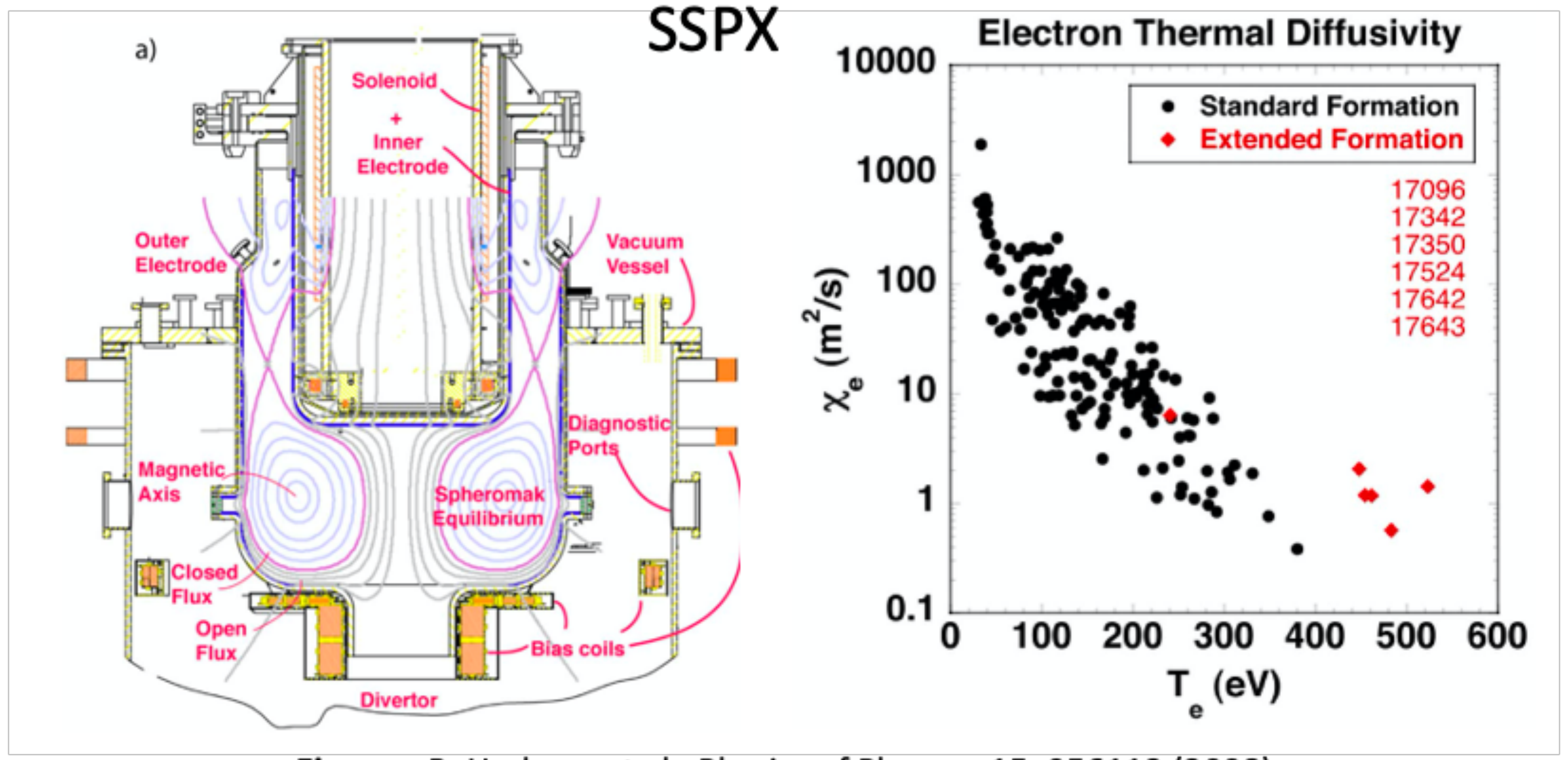
- Toroidal plasma current generated confining poloidal magnetic field B_p.

- Poloidal plasma current creates stabilizing toroidal magnetic field B_T.

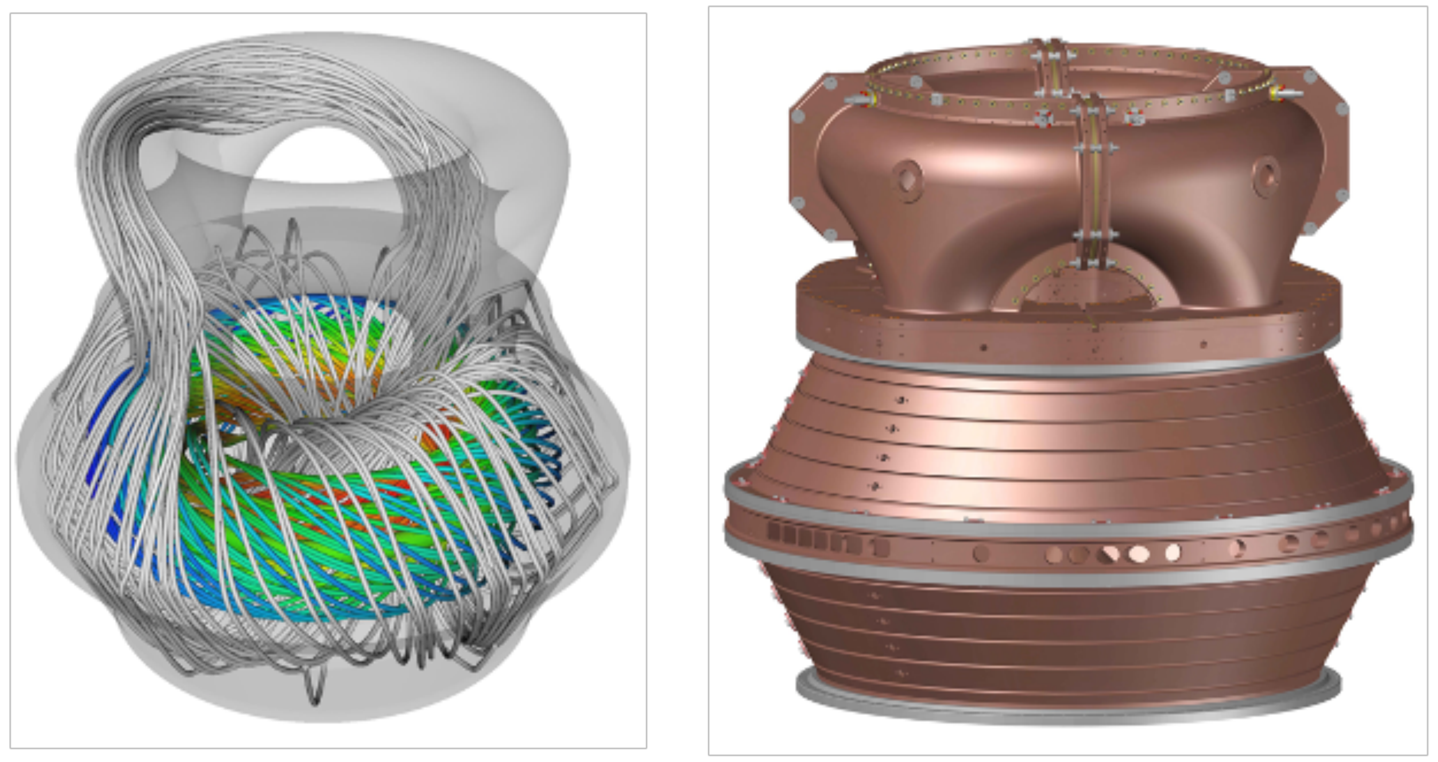
- Comparable strengths $B_T \sim B_p$.

Spheromaks have reached transient plasma temperatures in excess of 500 eV, but sustainment with good confinement remains an R&D need

- The plasma currents in spheromaks must be sustained against resistive dissipation to maintain continuous or quasi-steady operation
- Sustained spheromak physics experiment (SSPX) at LLNL had $T_e > 500$ eV during spheromak decay, but plasma instabilities during plasma current sustainment degraded confinement
- Advanced helicity injection current drive schemes (e.g. steady, inductive helicity injection (SIHI)) have been recently explored to provide better confinement during sustainment
- Concept must be demonstrated to scale to fusion grade plasmas with good enough confinement to advance further $T_e \gg 1$ keV

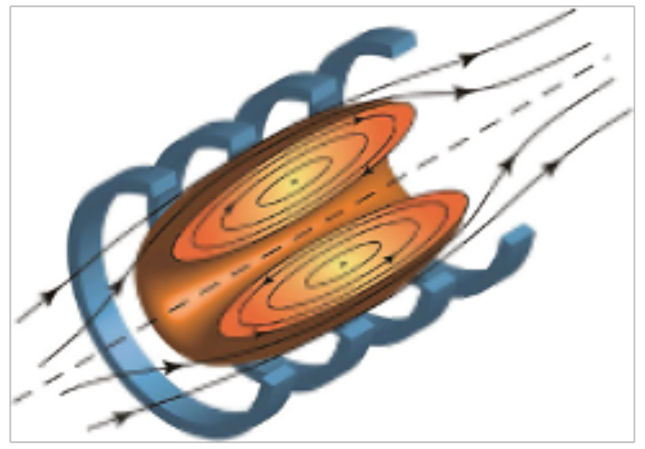
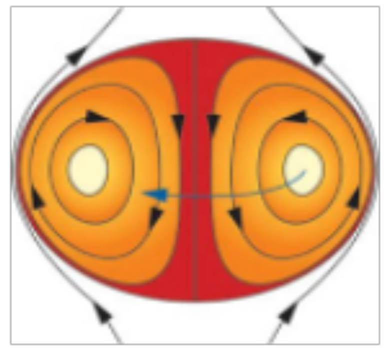
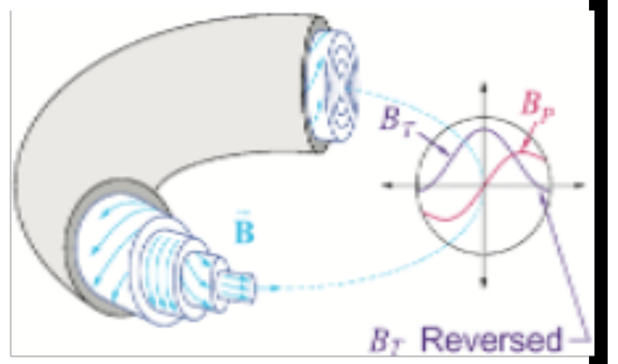


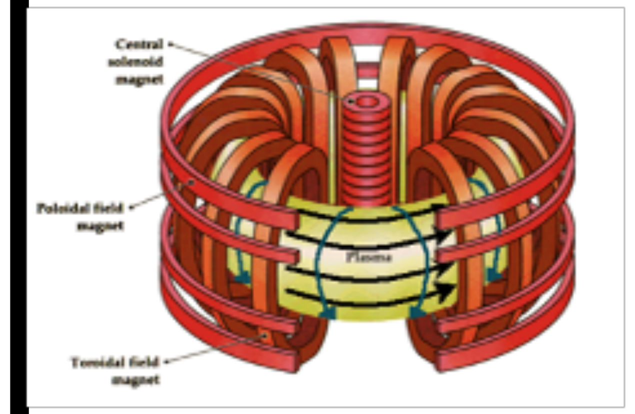
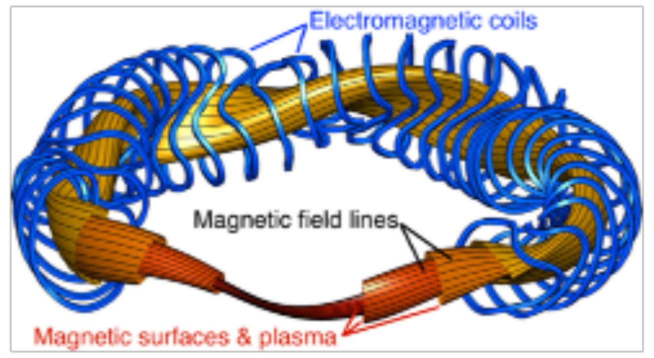
Figures: B. Hudson, et al., Physics of Plasmas 15, 056112 (2008).

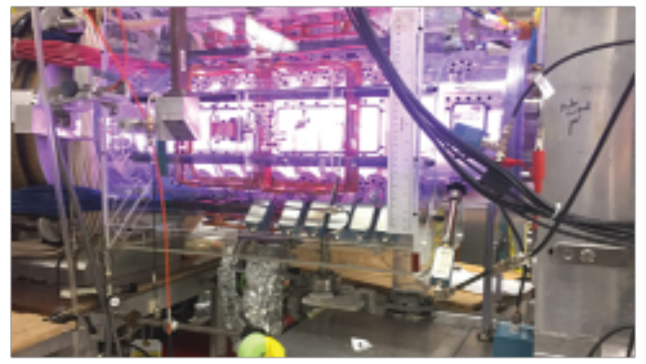
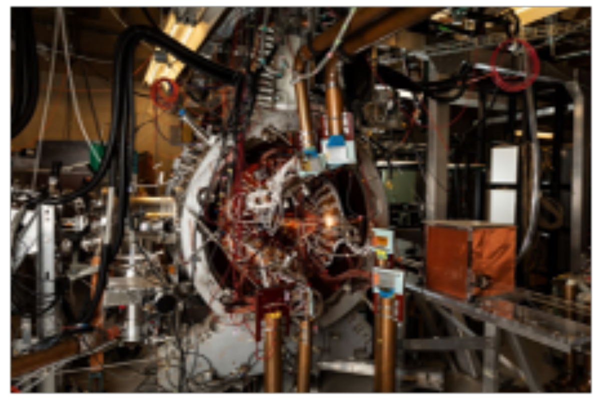
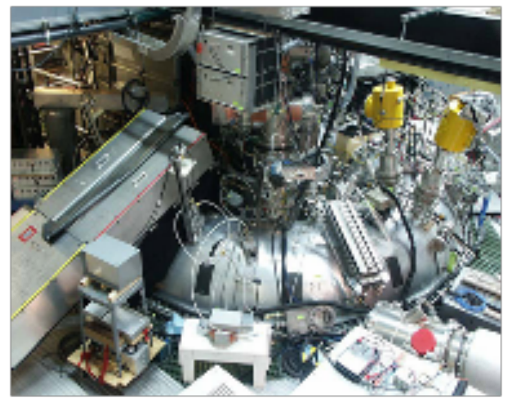


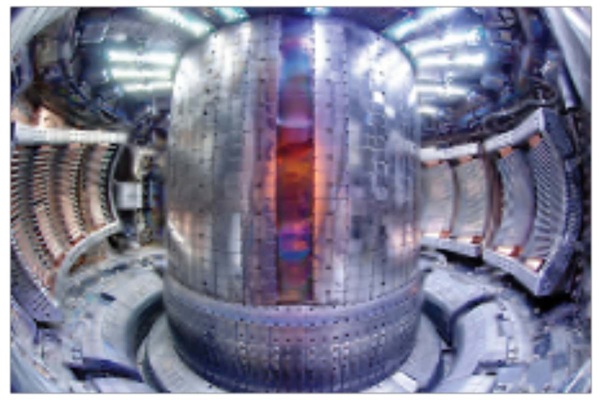
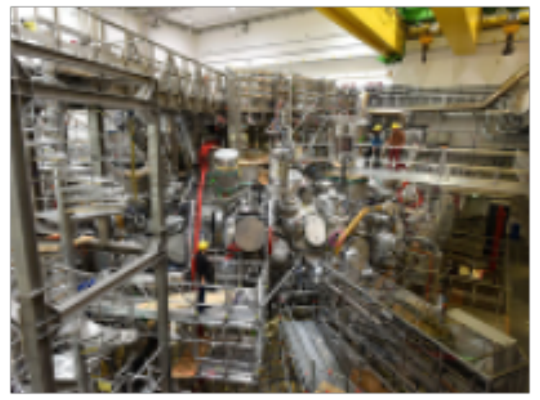
Figures: HIT-SI Research Group, University of Washington (subcontract with CTFusion, Inc.)

Spherical tokamak — compact aspect ratio tokamaks for both MFE and MIF under development

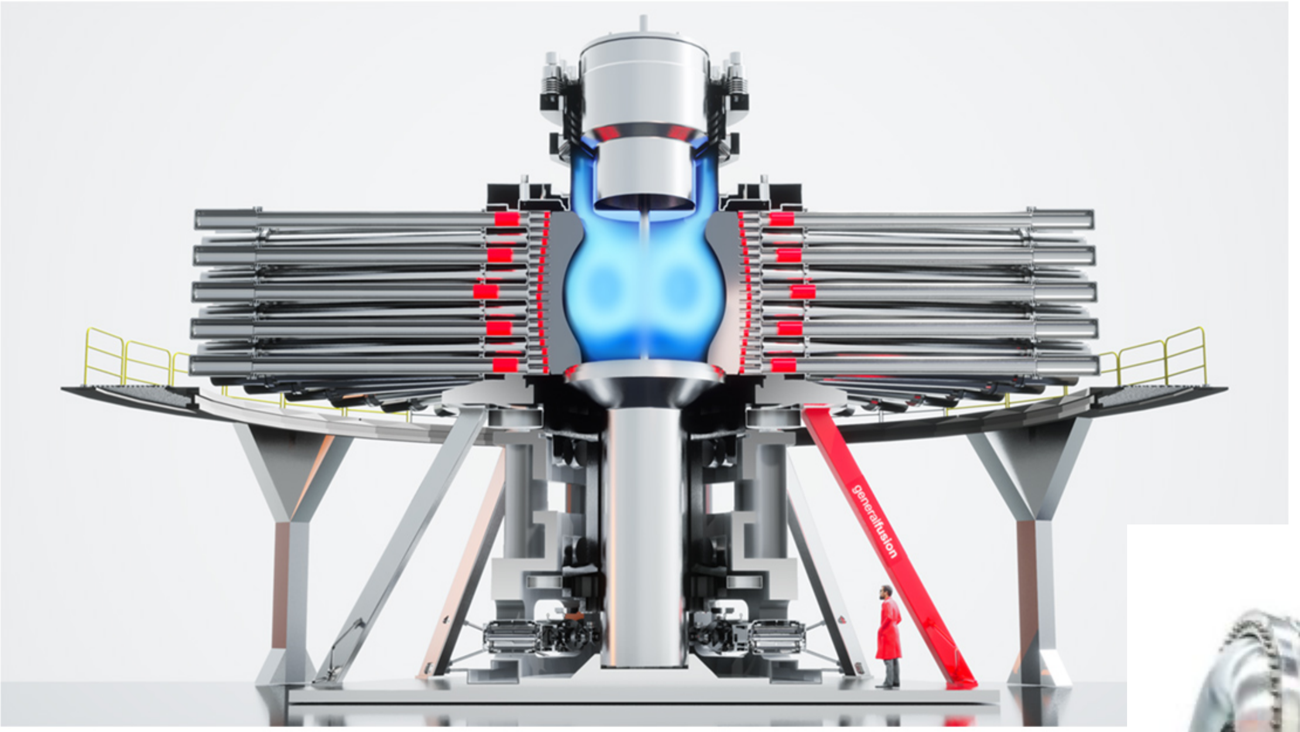



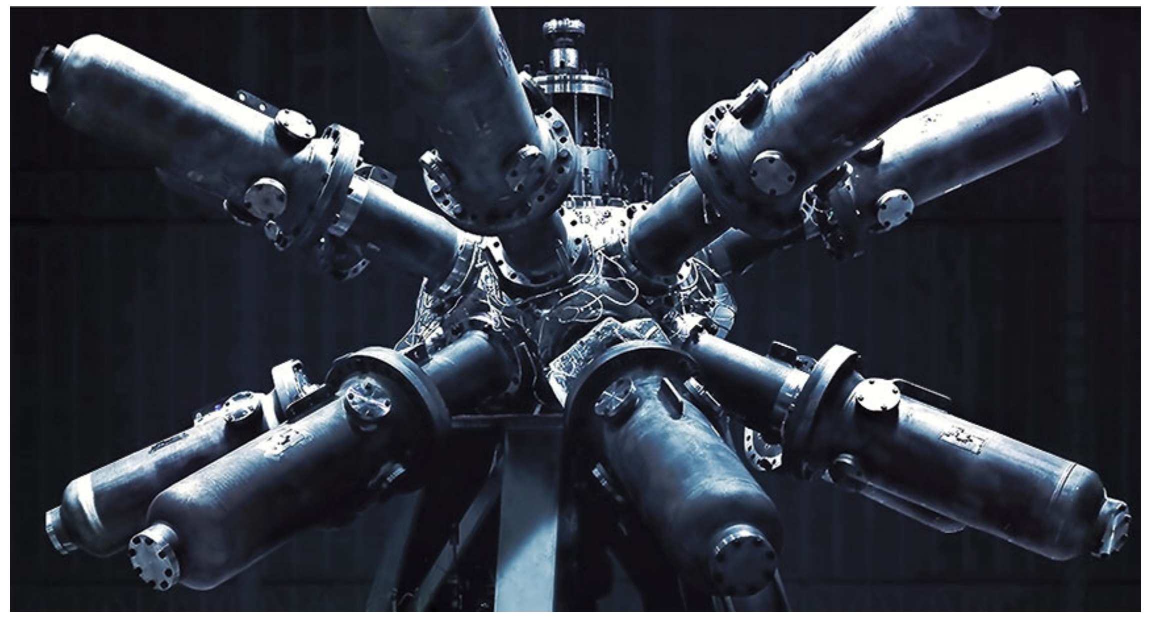
Field-reversed configuration (FRC) | Spheromak | Reversed-Field Pinch (RFP) | **Spherical Tokamak** | Tokamak | Stellarator

Plasma current — Where is the current flowing? $\nabla \times \mathbf{B} = \mu_o \mathbf{J}$ — **External coils**

Magnetic field generation method

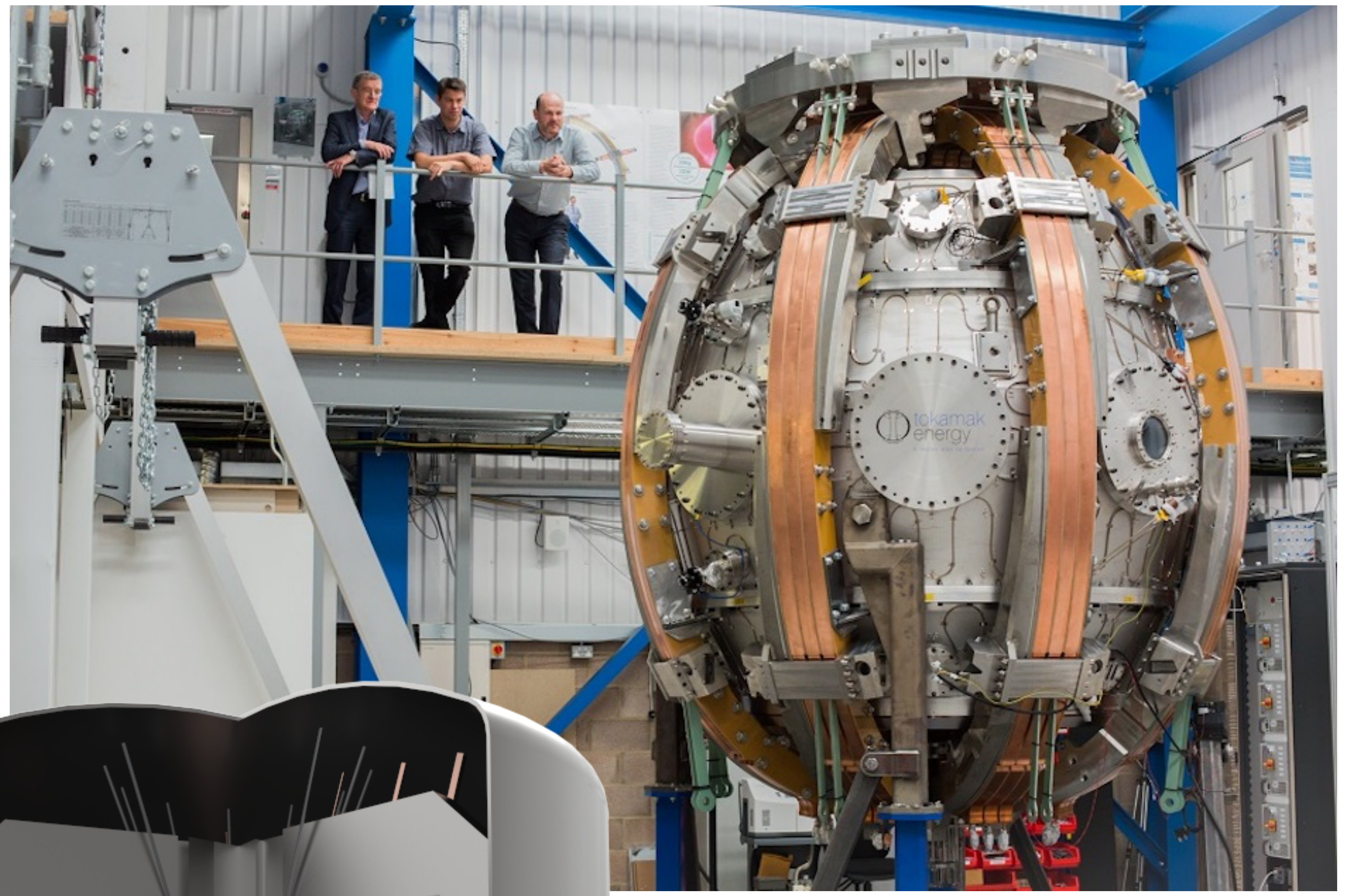
Both MFE and MIF ST concepts under development in the public and private sector

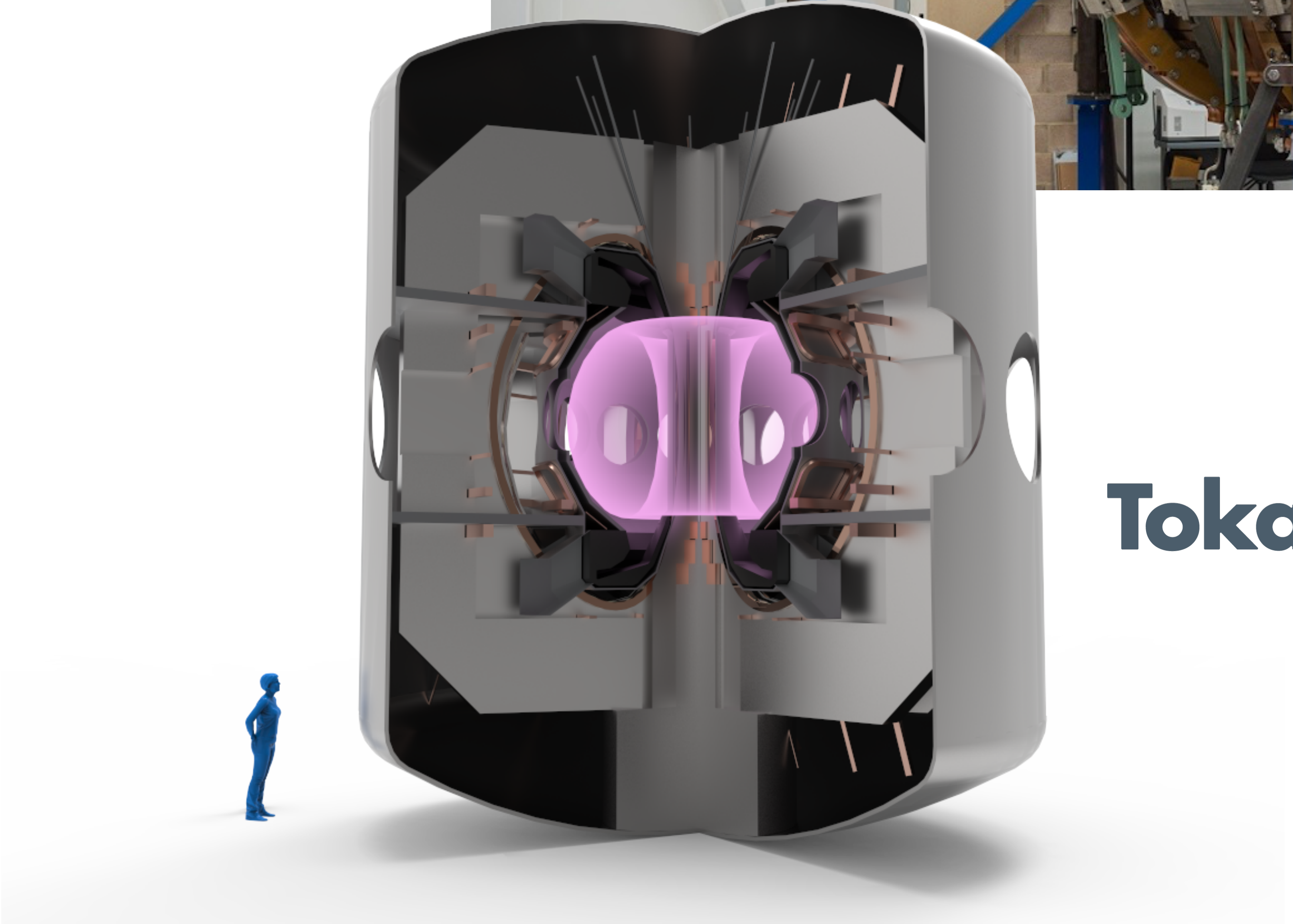




generalfusion®

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

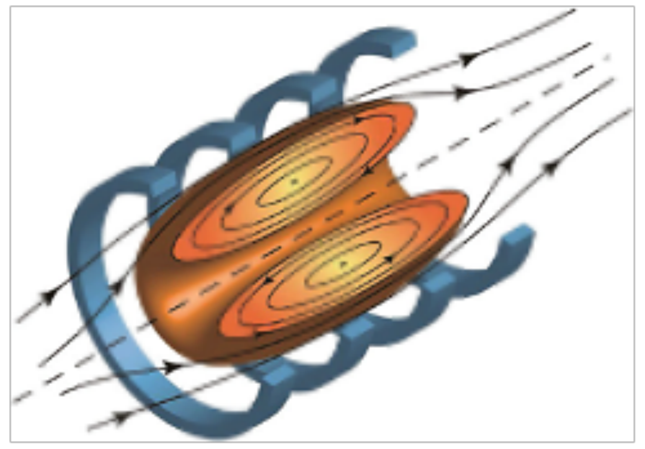
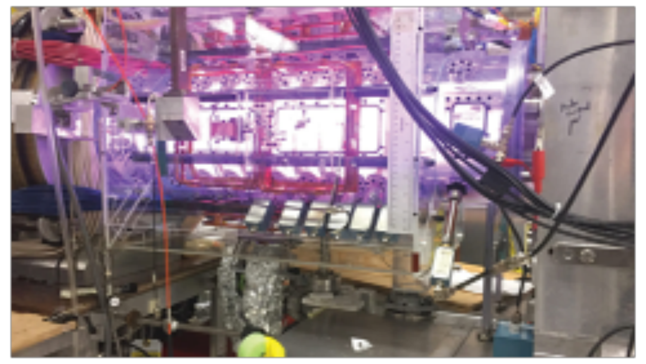




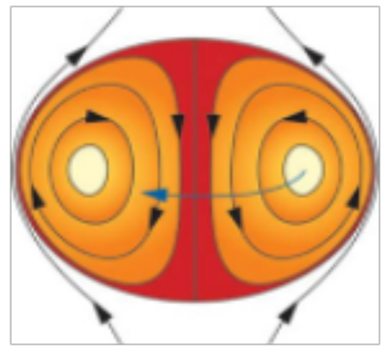
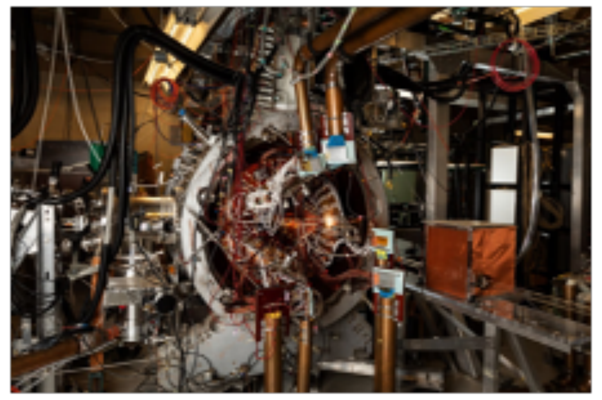
Tokamak Energy

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

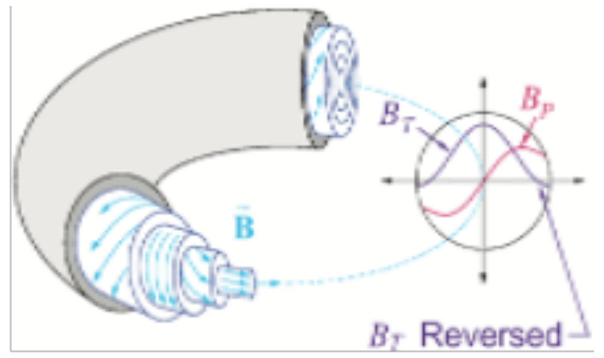
FRCs nominally have no toroidal magnetic field, and so are more like the Z-pinch or Levitated Dipole we will speak to later

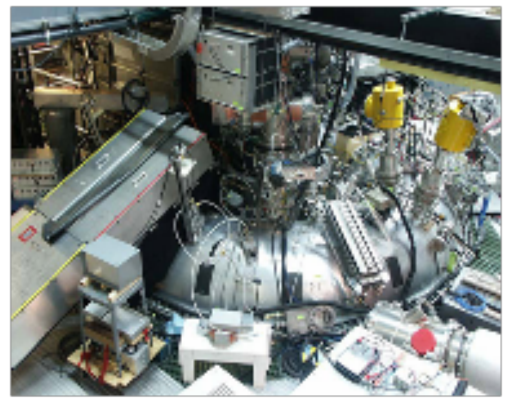



Field-reversed configuration (FRC)

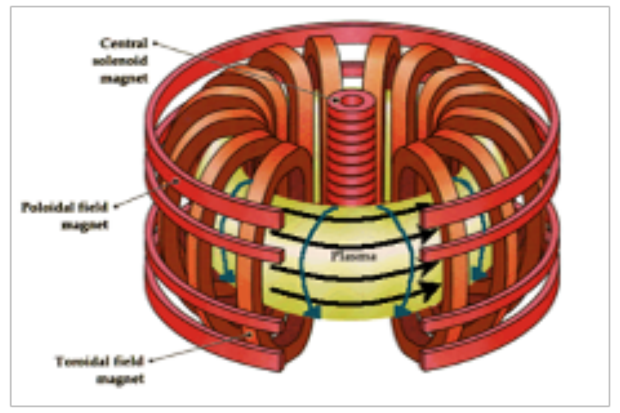
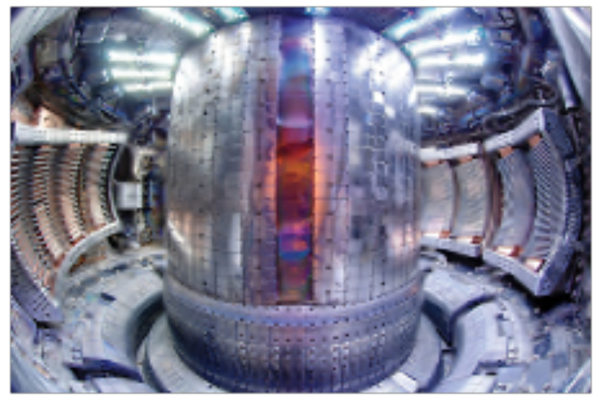
Spheromak



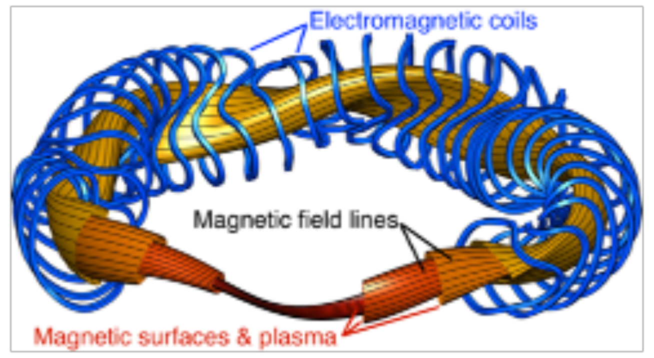


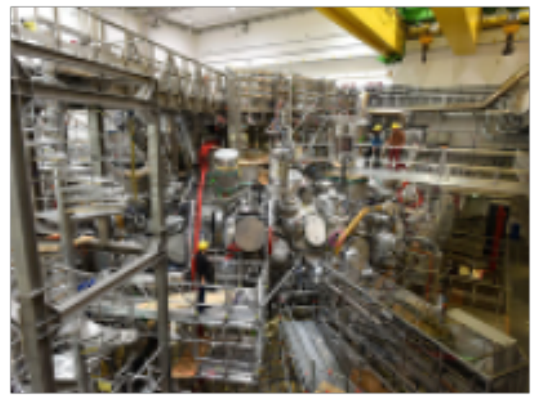
Reversed-Field Pinch (RFP)


Spherical Tokamak

Tokamak





Stellarator

Where is the current flowing? $\nabla \times \mathbf{B} = \mu_o \mathbf{J}$

Plasma current ⟷ **External coils**

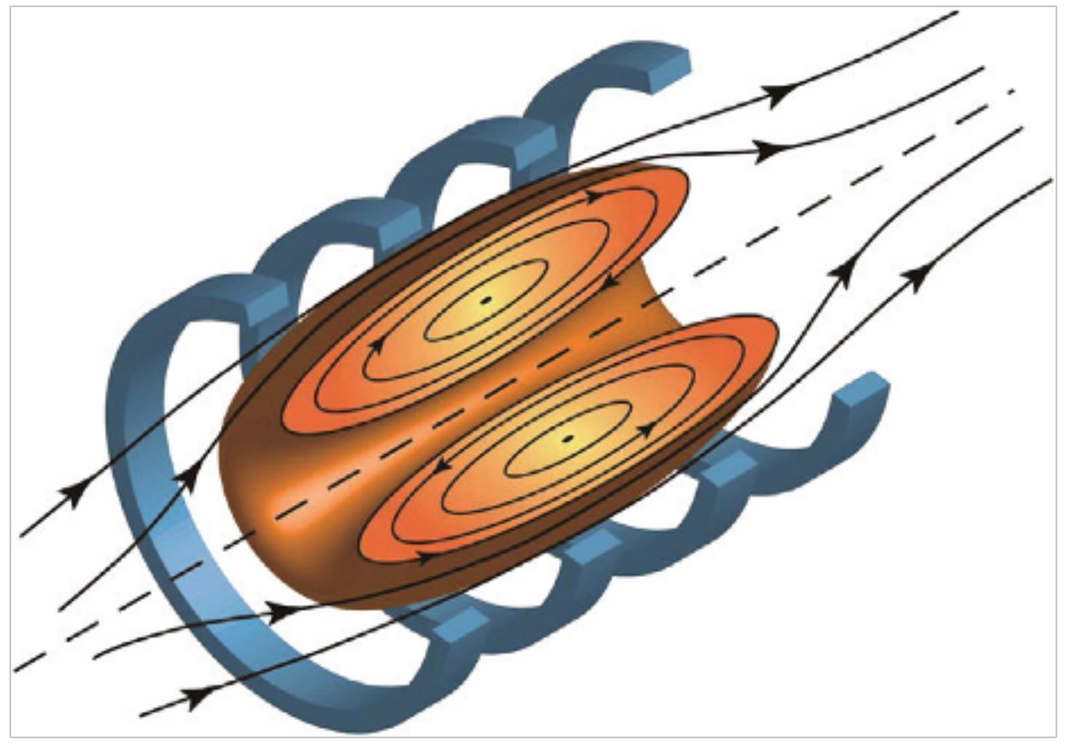
Magnetic field generation method

Field-reversed configuration (FRC) is a toroidal plasma with only poloidal field that often uses θ-pinch formation

- 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

Multiple private companies working on this type of configuration for steady-state (and/or very long pulse) fusion systems:

- TAE Technologies (Sustained FRC with Neutral Beam Injection)
- Princeton Satellite Systems (Sustained FRC with RMF current drive)



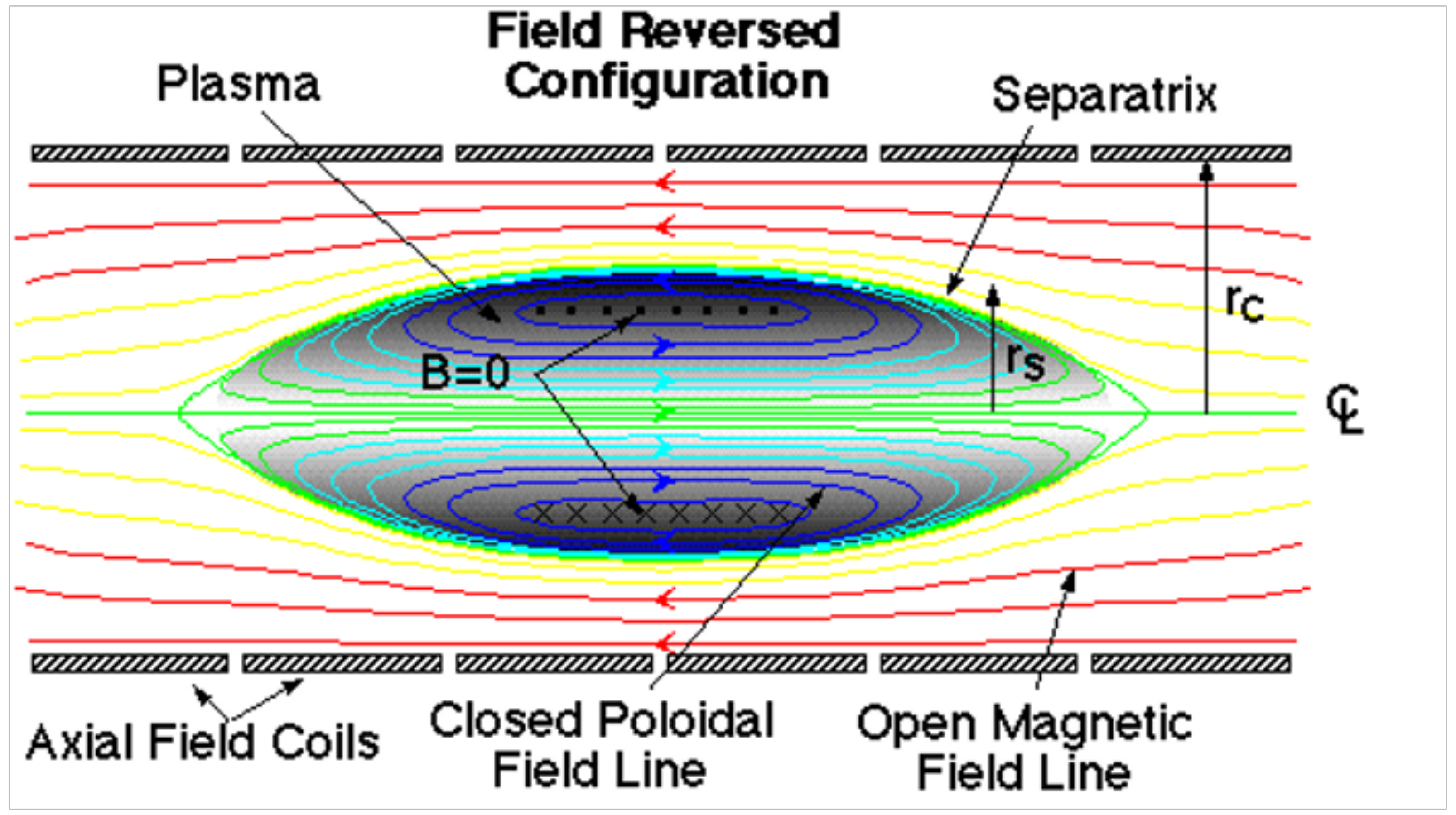
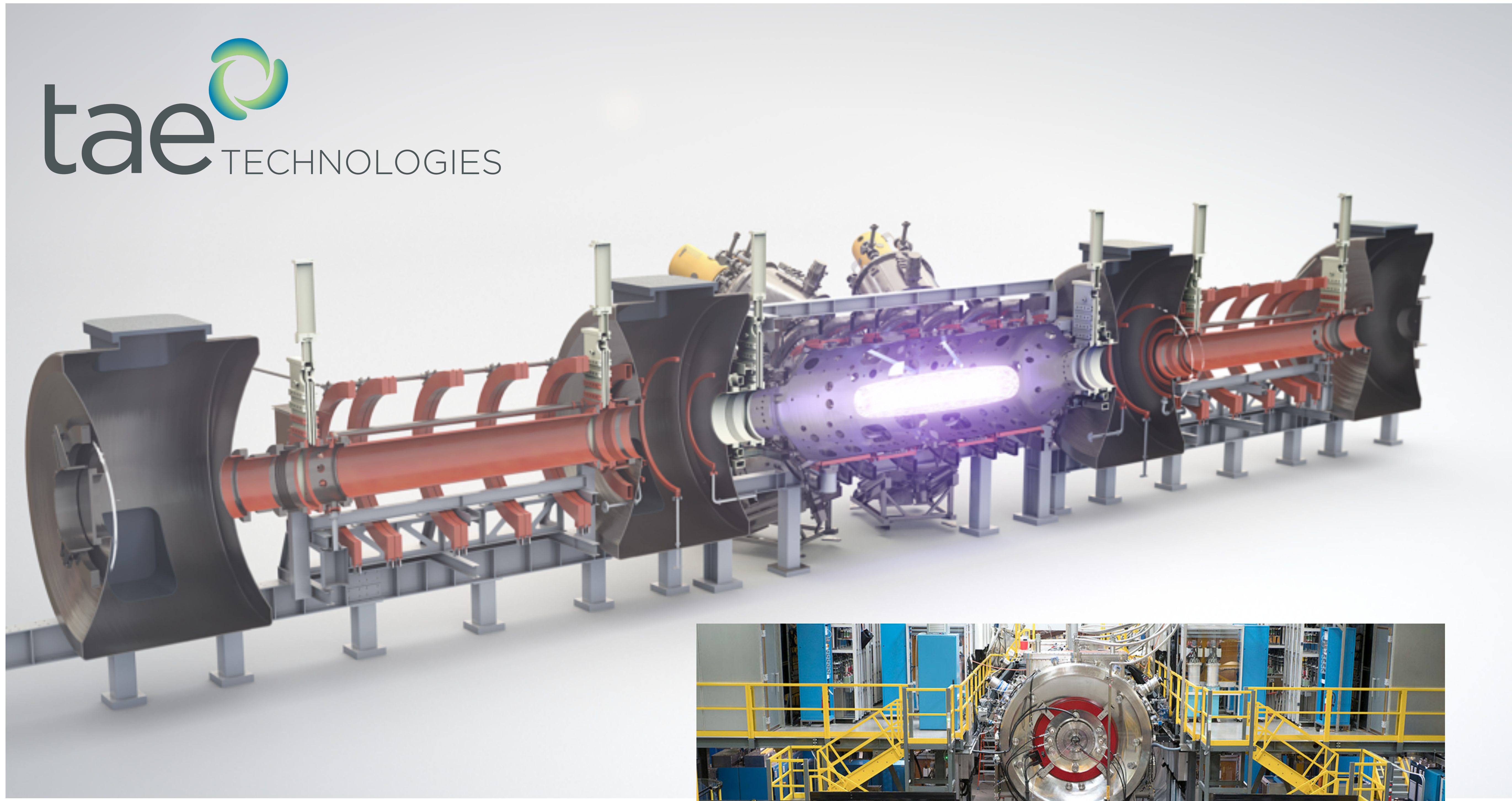
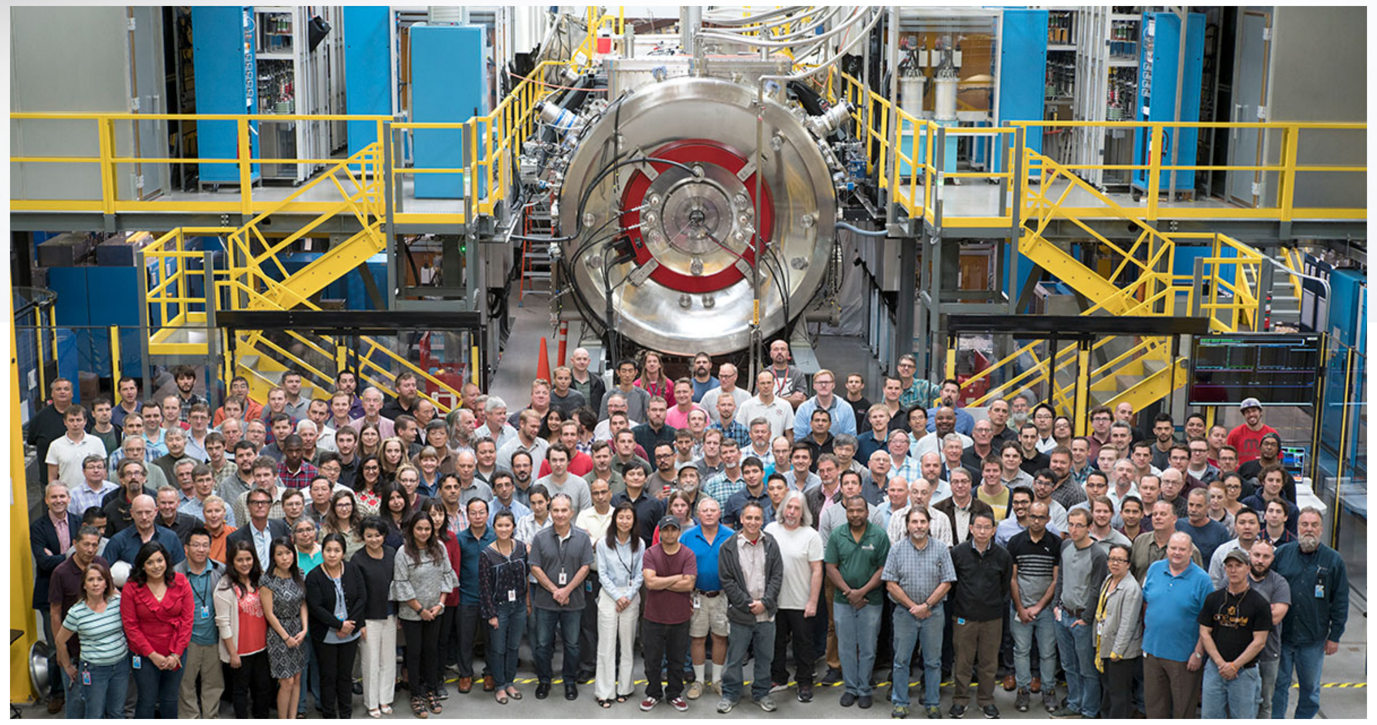


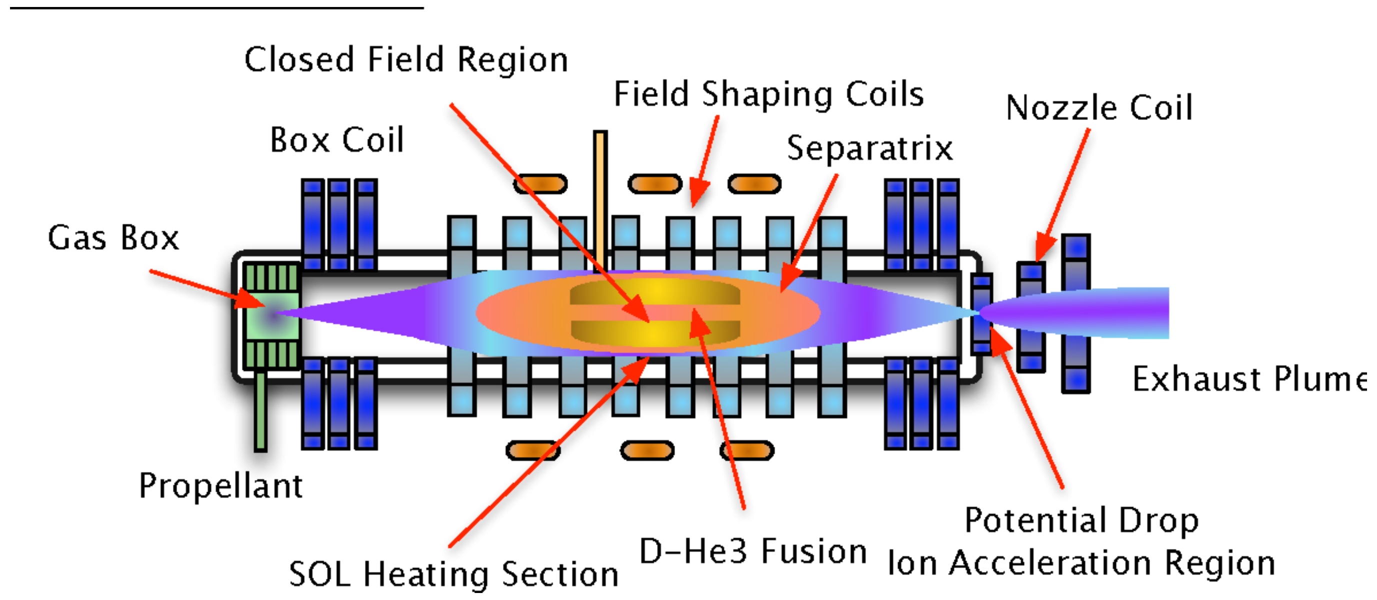
Figure: PPPL, FESAC Toroidal Alternates Panel (2008).

Two steady-state FRC fusion companies/collaborations focused on aneutronic fusion fuels





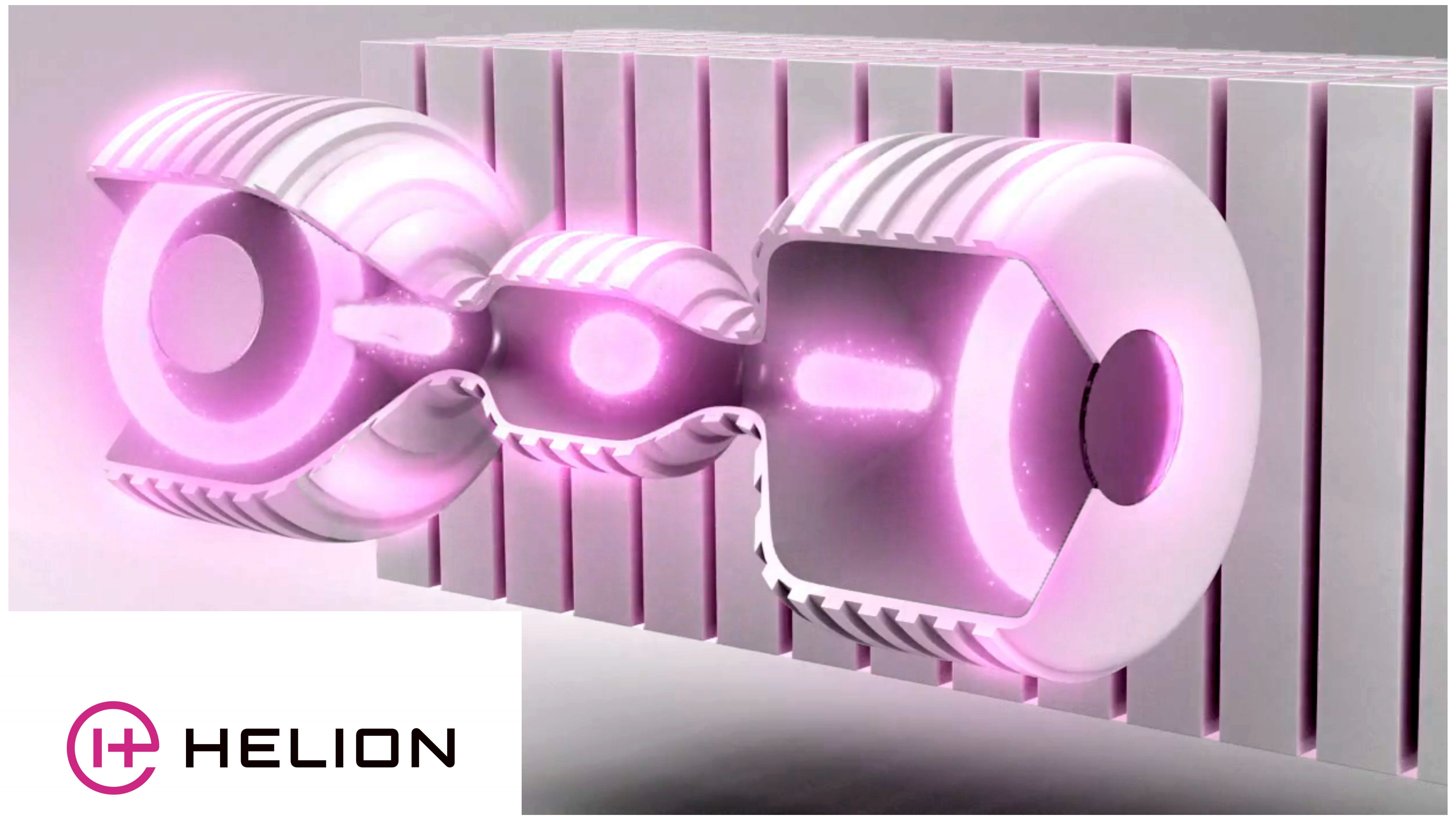
* Logo and Images from TAE Technologies



* Logos and Images from PSS & PPPL

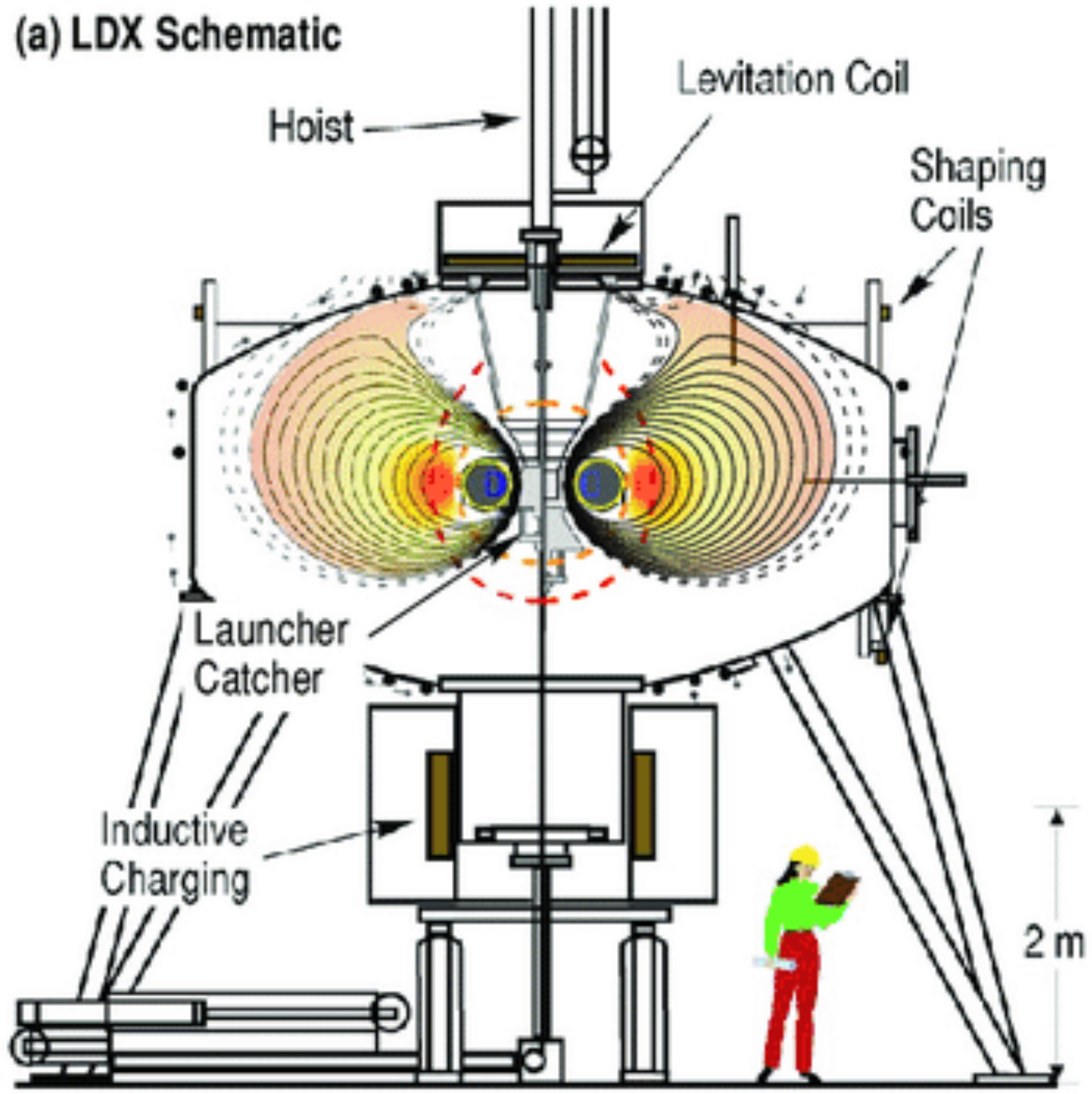
Helion Energy is developing a pulsed FRC fusion generator and aims to use D-^{3}He fusion fuel - a form of magneto-inertial fusion (MIF)

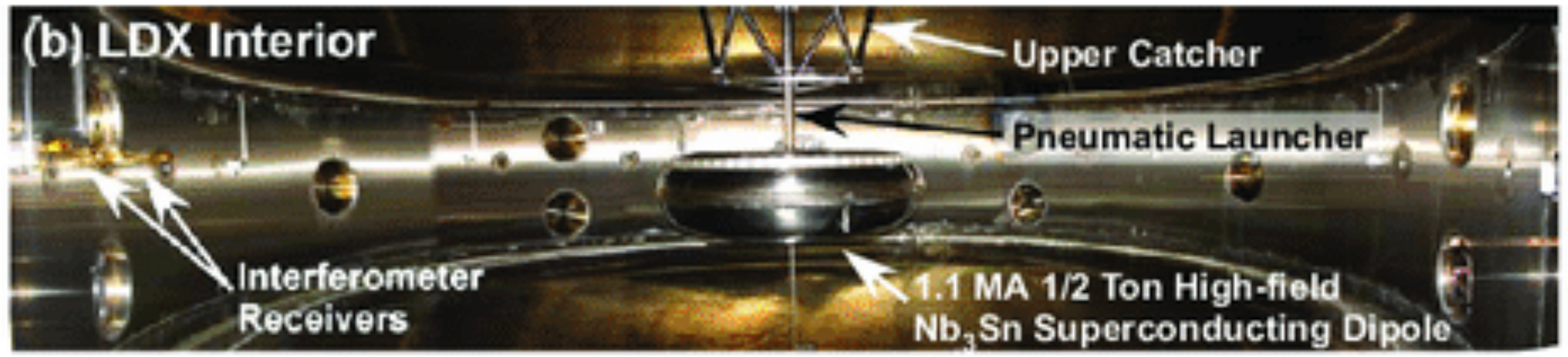
- Formation of two D-^{3}He FRCs that are accelerated and merged into one
- Kinetic energy is converted to thermal energy during merging
- Single FRC is then compressed to much higher plasma pressures by ramping up a large axial magnetic field quickly
- Fusion occurs and plasma expands, “pushing against” the magnetic flux that was used to compress the FRC
- Change in magnetic flux induces an electric field in surrounding coils that can drive electrons — direct energy capture
- Production of naturally scarce ^{3}He is required, similar to making tritium for DT fusion power plants with Li-6

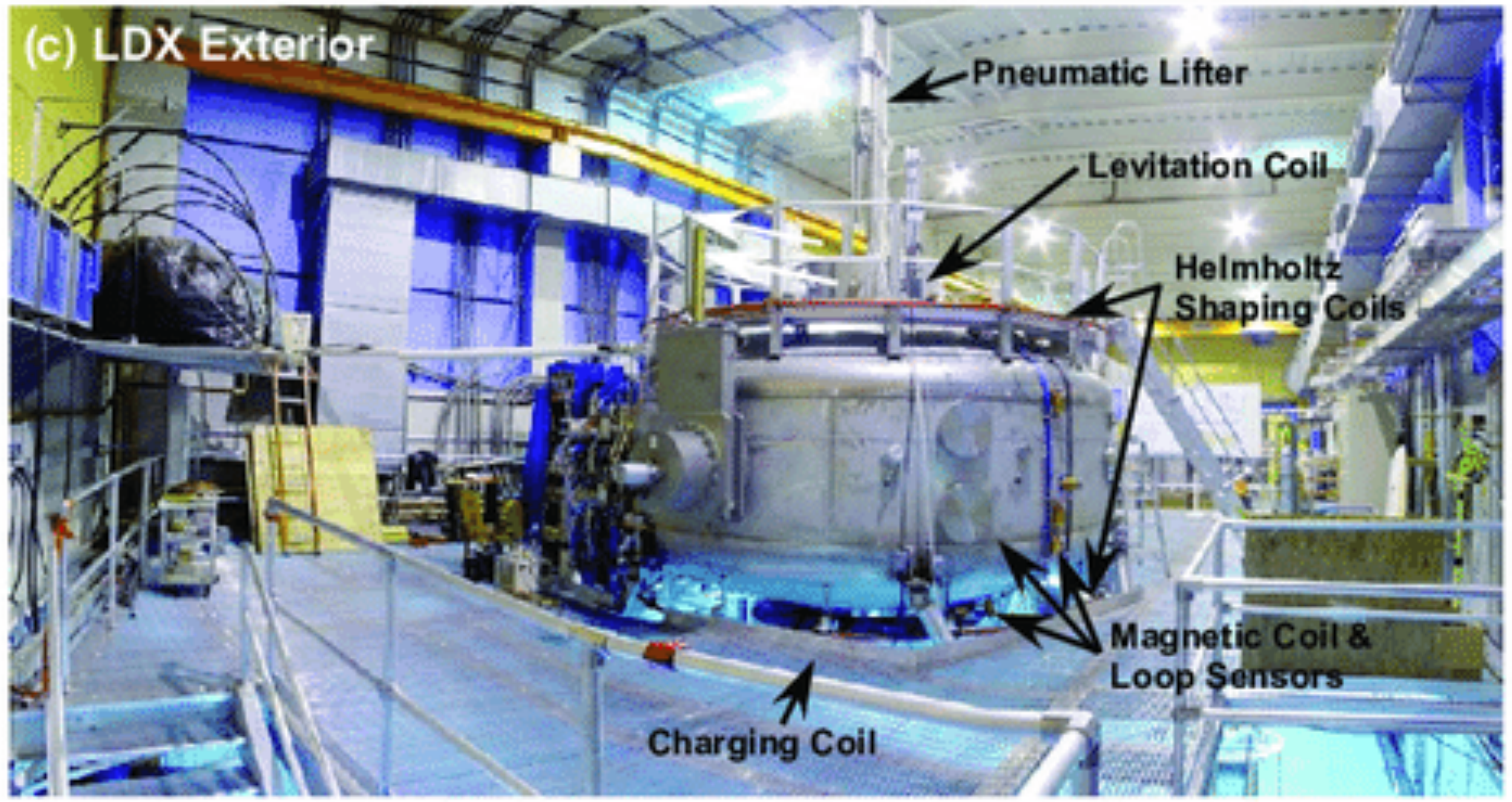


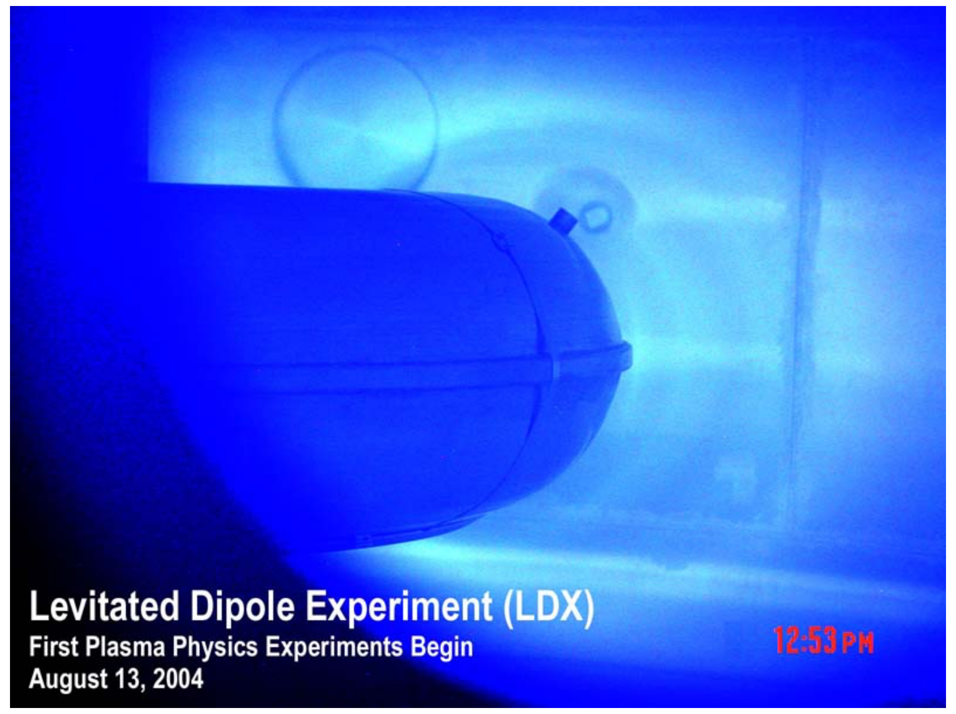
* Logo and images from Helion Energy

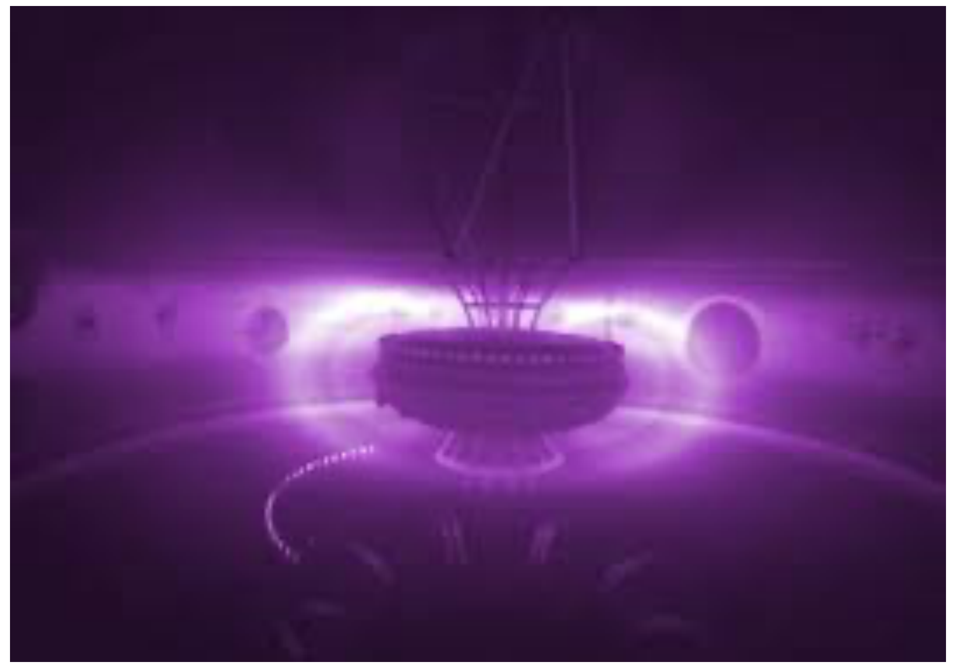
Levitated dipole is a unique fusion concept that uses a floating superconducting coil to generate poloidal fields for plasma confinement











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

Outline

Introduction and overview

Linear fusion configurations

- Z-pinch, θ-pinch, screw pinch
- Magnetic mirrors

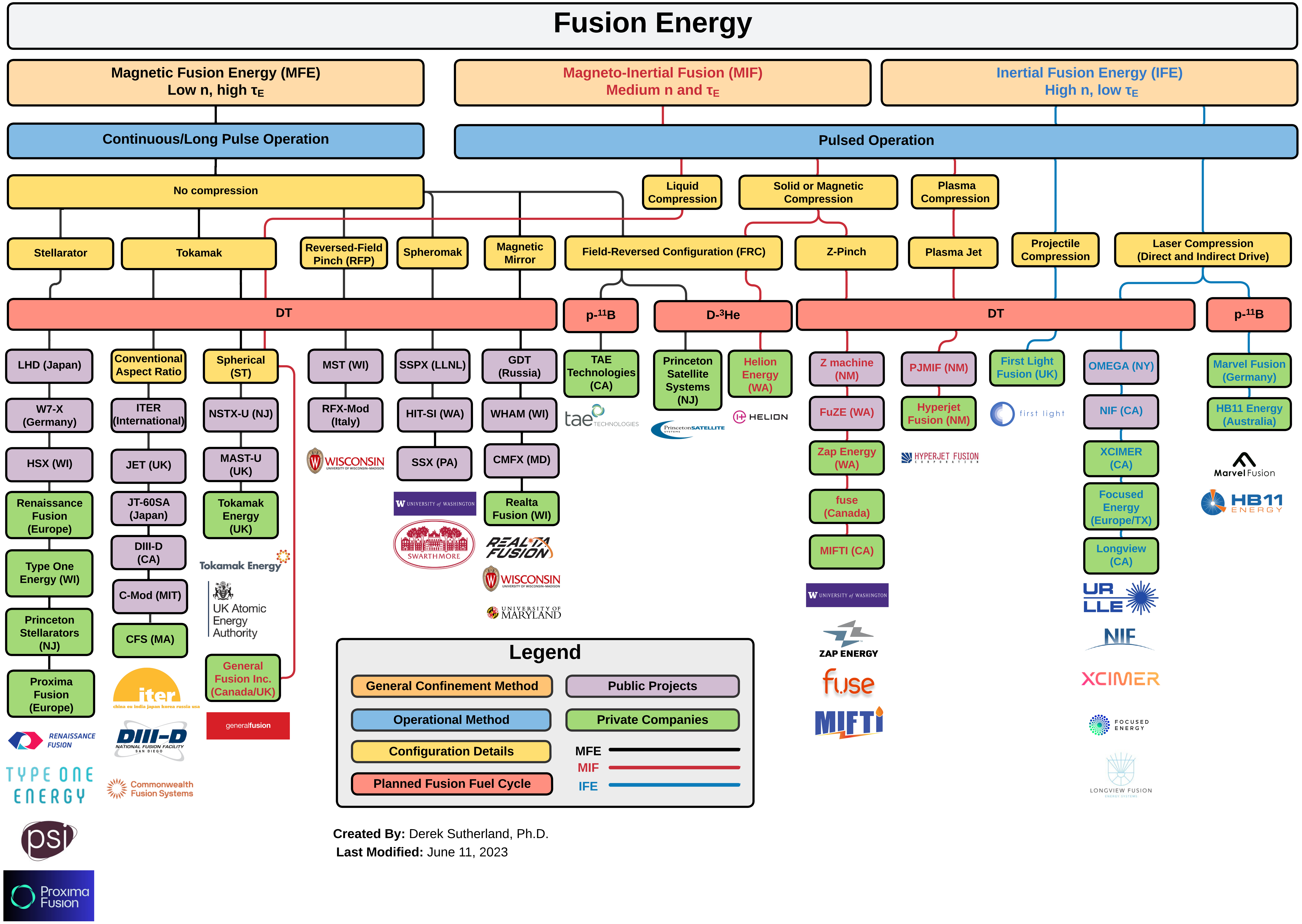
Toroidal fusion configurations

- Reversed field pinch (RFP), Spheromak
- Field-reversed configuration (FRC)
- Levitated Dipole

The growing fusion energy landscape

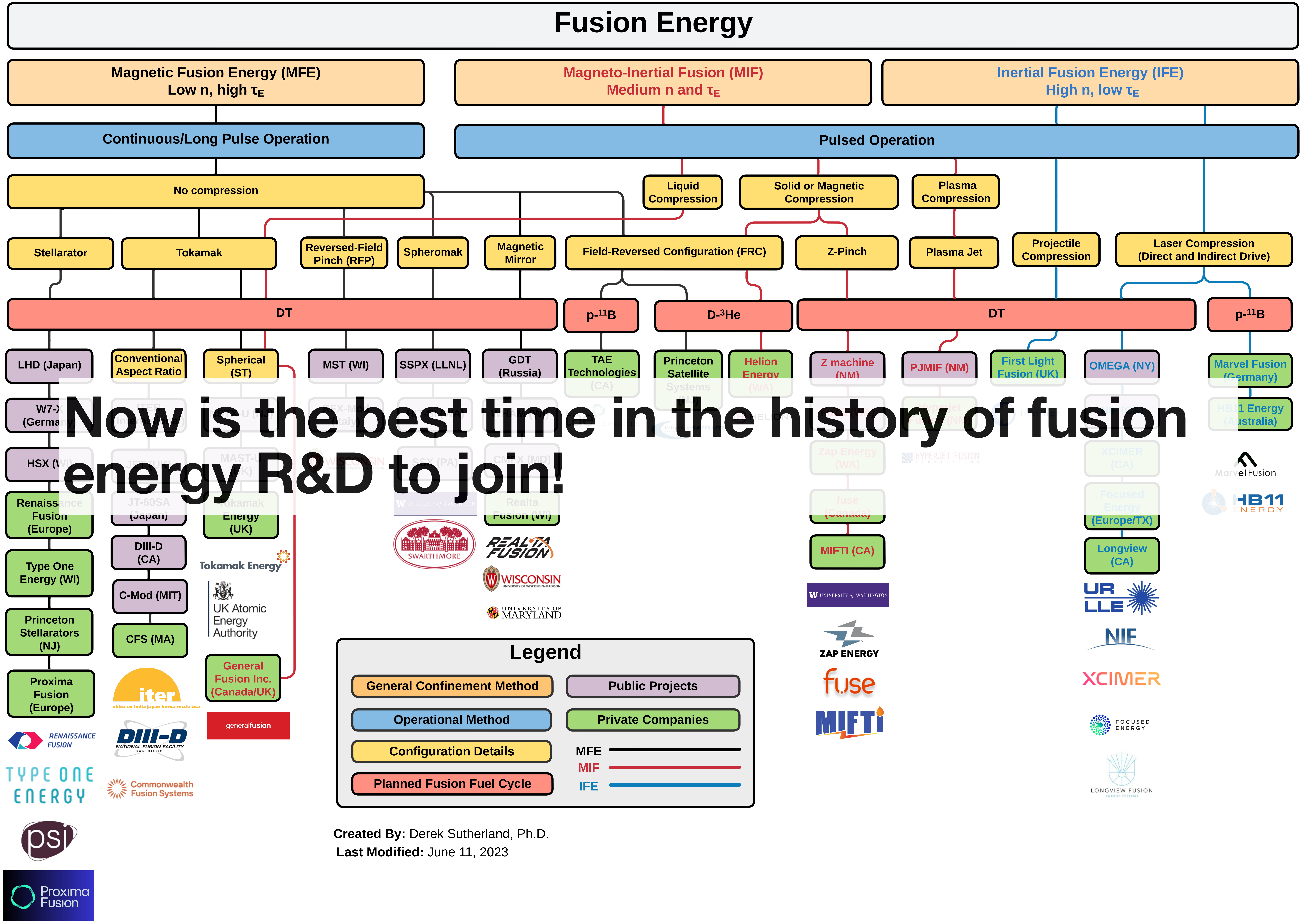
Summary and resources

A partial fusion energy landscape shows the growing diversity of the field!



Created By: Derek Sutherland, Ph.D.
Last Modified: June 11, 2023

A partial fusion energy landscape shows the growing diversity of the field!



Now is the best time in the history of fusion energy R&D to join!

Outline

Introduction and overview

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- Levitated Dipole

The growing fusion energy landscape

Summary and resources

Summary

- Alternative fusion approaches generally are the “non-mainline” fusion concepts
- There are various approaches to reach net-gain fusion energy production organized into three main camps of fusion: MFE, MIF, and IFE
- Linear fusion concepts are used as a building blocks of toroidal fusion concepts with shared physics foundations
- Now is the best time in history to join the fusion field — tons of activity across the entire fusion space both in the public and private sectors!
- Check out the Fusion Industry Association for the latest on the private fusion industry!

Resources

Check out the NRL and MIT plasma formularies:

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

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