

Alternative Fusion Reactor Concepts

Blair P. Bromley, Chair

Canadian Nuclear Society

Fusion Energy Science and Technology Division

yelmorb7@cnl.ca

Fusion 2030: A Roadmap for Canada

Canadian Nuclear Society Annual Conference

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Introduction

➤ International Context

- What activities are ongoing?
- What are other alternative concepts?

➤ Canadian Context

- Past / Current Experience?
- Future Efforts for Canada?

International Context (1/10)

- **Last ten years have seen a surge in surge in the investigation of alternative approaches and technologies for fusion energy.**
- **Advances in plasma physics, electronics and digital controls, computer simulation, and materials have opened up new avenues for developing fusion power plants.**
- **Building on old concepts originally developed decades ago, but with some modifications and innovations making use of new technologies and new knowledge.**

International Context (2/10)

- **New ideas emerging based on modern understanding of plasma physics.**

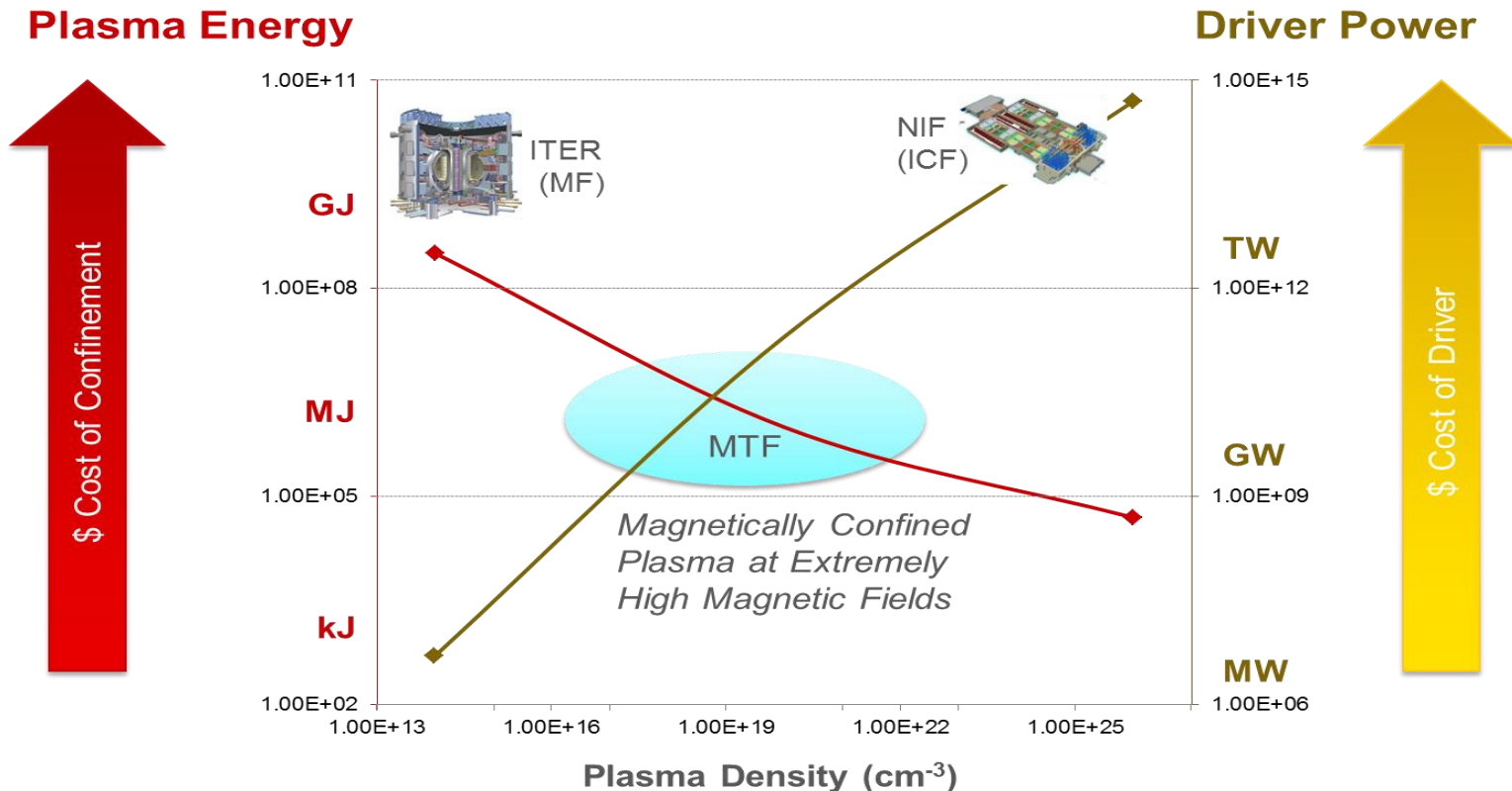
- **New business models and strategies for research and development**
 - **Private companies attracting millions of dollars of investment.**
 - **Building world-class teams and research centers.**
 - **Working closely with publicly-funded institutions.**

International Context (3/10)

- **Magnetized Target Fusion (MTF) / Magneto-Inertial Fusion (MIF)**
 - **Magnetic Fusion (MF) systems**
 - Low density, steady-state systems; c
 - Confine for relatively long period of time.
 - Cost of confining large plasma volumes dominates (field coils).
 - **Inertial Fusion (IFE) systems**
 - High density, pulsed, small plasma volumes
 - Confine for very short period.
 - Cost of the very high power driver systems (such as lasers).
 - **MTF spans the intermediate regime between MF and IFE**
 - Small plasmas (compact torus) confined by magnetic fields.
 - Rapid compression for heating to fusion conditions.
 - Cost of confinement and the compression driver can be dramatically lower.

International Context (4/10)

- **Magnetized Target Fusion / Magneto-Inertial Fusion**
 - **Intermediate region between MF and ICF.**
 - **Potential for lower costs for confinement and driver systems.**



International Context (5/10)

- **Magnetized Target Fusion (MTF) / Magneto-Inertial Fusion (MIF)**
 - **MTF concepts trace back to research first undertaken in the 1970s (LINUS); less explored.**
 - **Recent efforts are aiming to close this gap.**
 - **In Canada, General Fusion, is undertaking pioneering research**
 - **Explore the behaviour of compressed magnetized plasmas.**
 - **In 2015, in the USA:**
 - **DOE Advanced Research Projects Agency for Energy (ARPA-E) launched their ALPHA program,.**
 - **Funding nine different groups pursuing variations of MTF:**
 - **Helion Energy in Seattle,**
 - **Los Alamos National Laboratory**
 - **Swarthmore College, University of California.**
 - **Sandia National Laboratory, Magnetic Liner Inertial Fusion**
 - **China investigating MTF/MIF systems.**
 - **Chinese Academy of Engineering Physics – similar to LANL work.**

International Context (6/10)

- **Other alternative concepts for fusion energy have been proposed periodically over the past decades**
 - **Received much lower support than mainstream concepts.**

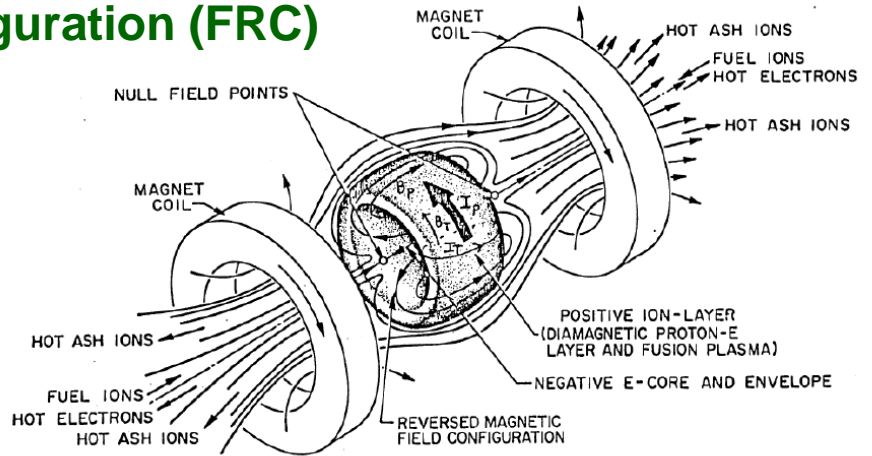
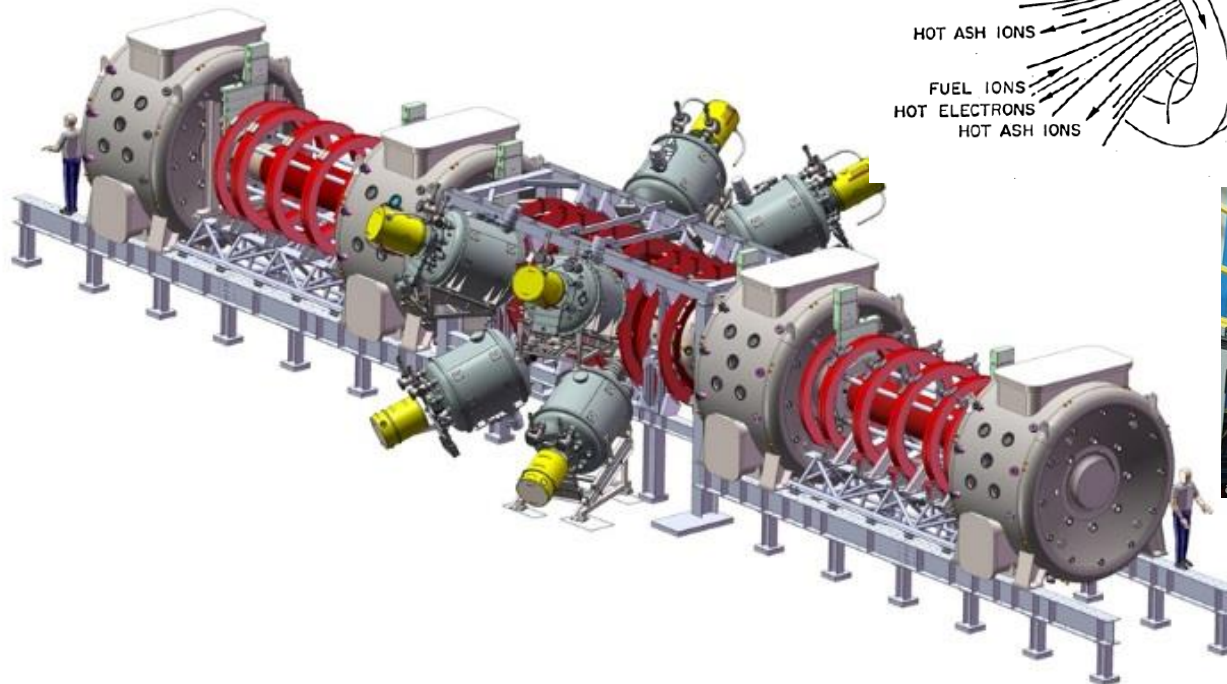
- **Diverse range of fusion concepts have re-emerged**
 - **Attracting investment in both private/public sectors.**
 - **Leveraging funding from various sources.**

- **Alternative concepts share a common themes**
 - **Accepting risk of new science and technology.**
 - **Goal of developing a commercially-viable fusion power plant.**

International Context (7/10)

➤ Tri Alpha Energy (Irvine, California)

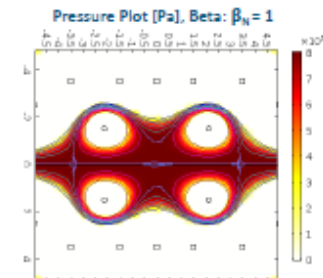
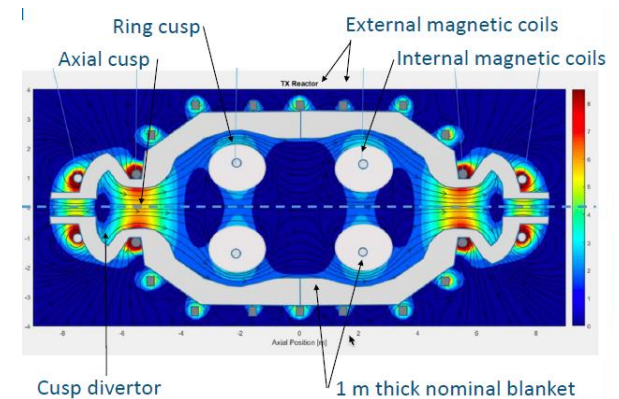
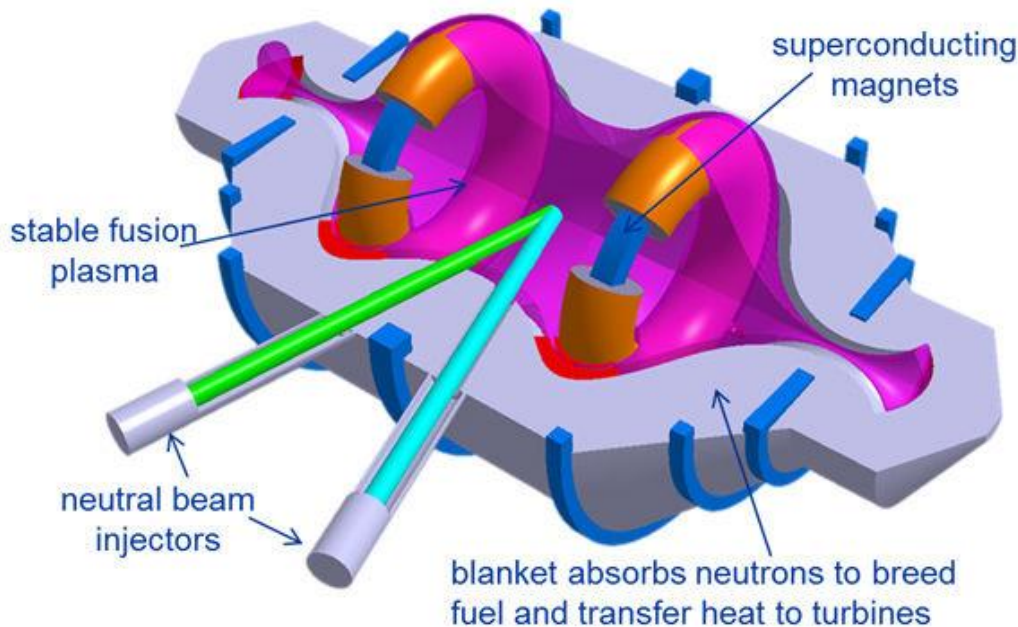
- <https://trialphaenergy.com/>
- Variant of Field-Reversed Configuration (FRC)



International Context (8/10)

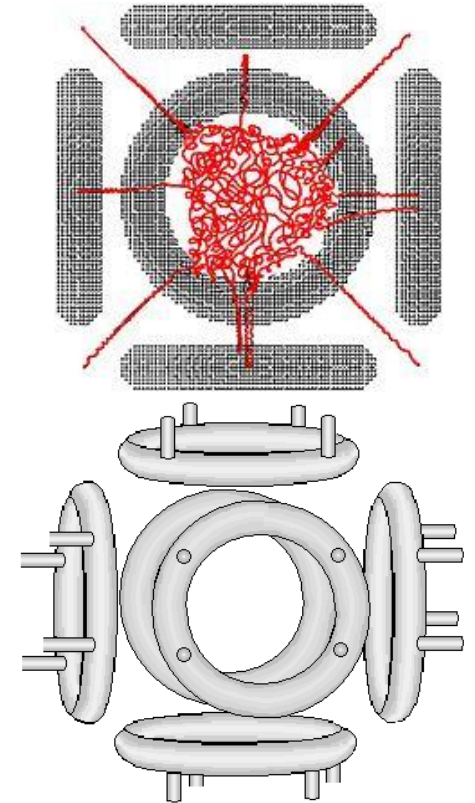
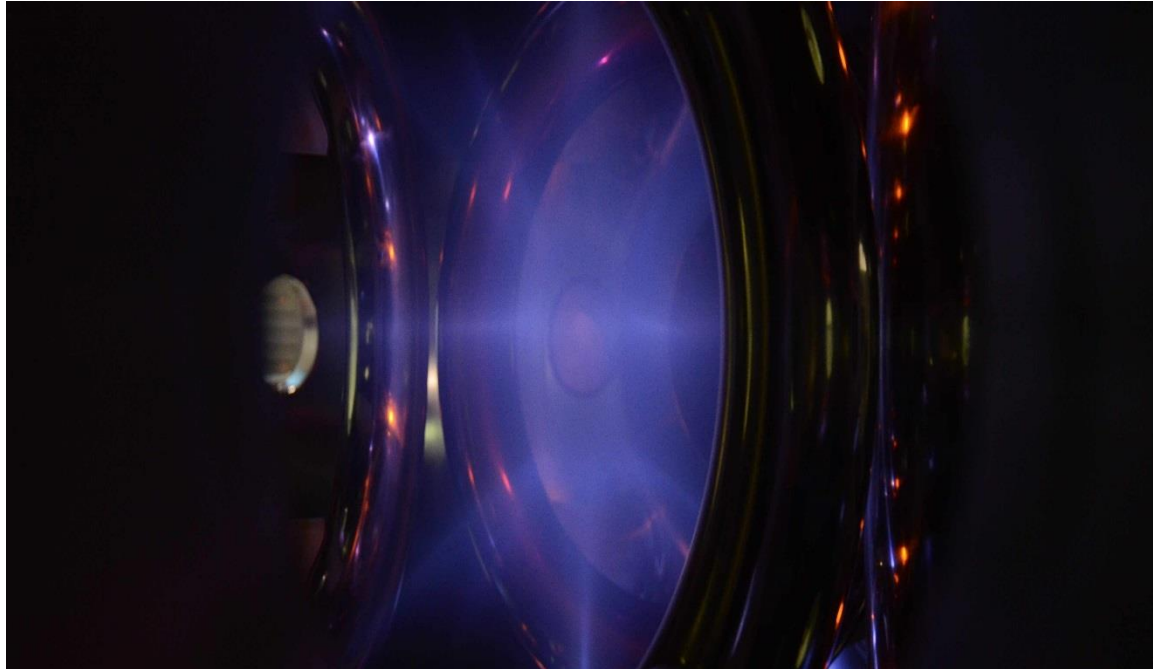
➤ Lockheed Martin's Skunkworks (USA) division

- <http://www.lockheedmartin.com/us/products/compact-fusion.html>
- <http://fusion4freedom.us/pdfs/McGuireAPS.pdf>
- Compact fusion with a new magnetic fusion configuration.
- Combines features of several magnetic confinement approaches.
- Magnetic Mirror / Floating Ring / Multipole / Surmac System



International Context (9/10)

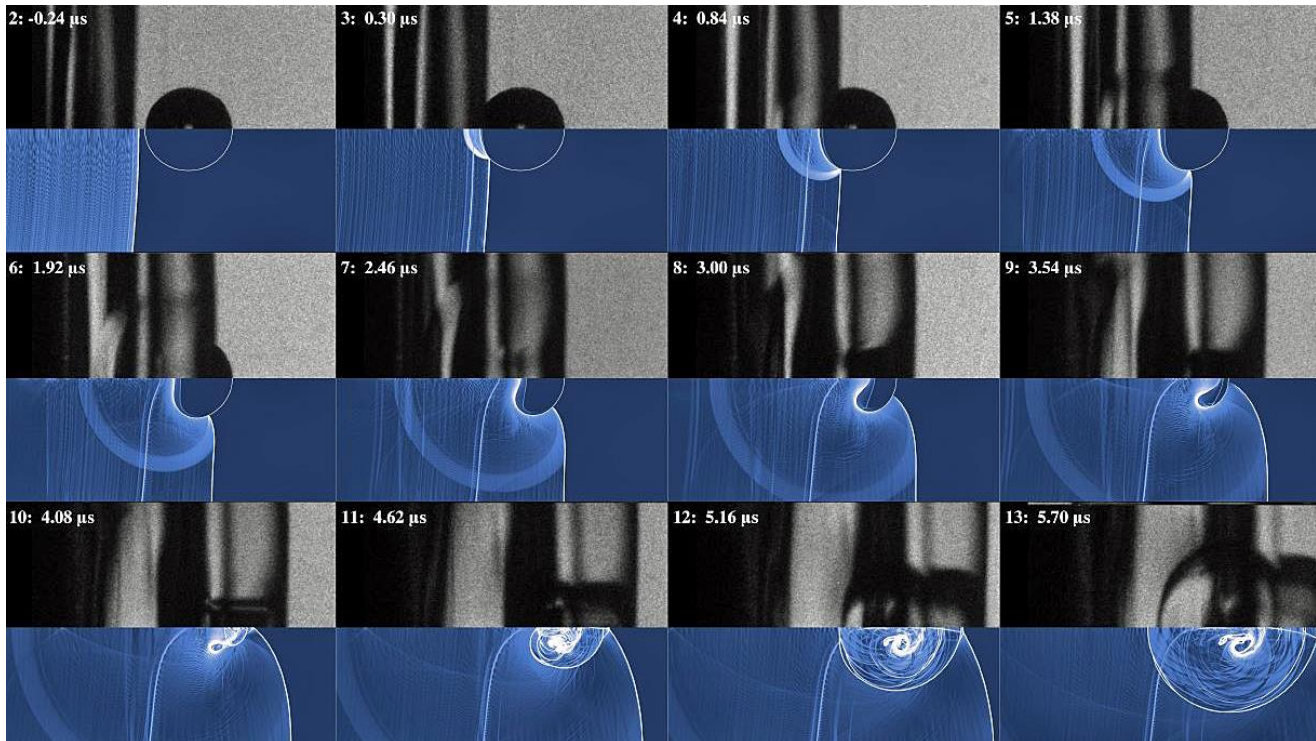
- **EMC2 (USA) <http://www.emc2fusion.org/>**
 - **Multiple intersecting magnetic cusps / Polywell.**
 - **High stability system confines electrons**
 - **Electron cloud electrostatically confine fusion fuel ions (D, T)**



International Context (10/10)

➤ First Light Fusion (UK)

- <http://firstlightfusion.com/>
- Pursuing a new inertial fusion concept.
- Use of shock waves to compress plasma target asymmetrically.
 - High-speed project impacts container of fluid to create shockwave.
 - Cavity collapse method.



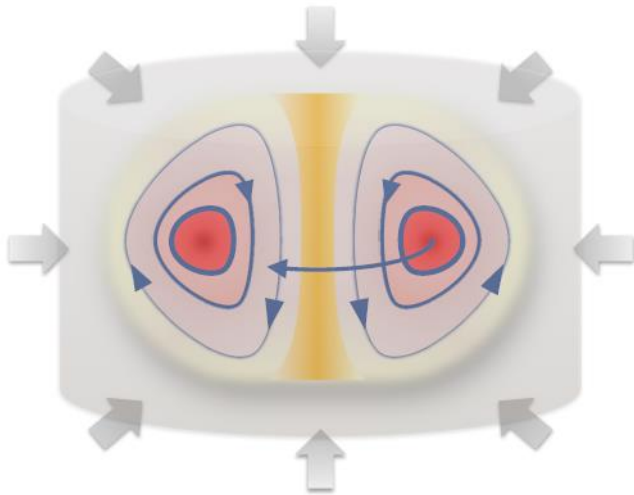
Other Alternative Concepts (25+)

- **Electromagnetic Pinch Devices (Pulsed):**
 - Z-Pinch, Extrap (External Ring Trap) Concept, Dense Plasma Focus (DPF), Linear Theta Pinch, Toroidal Theta Pinch
- **Electrostatic / Magneto-static Confinement Devices**
 - Inertial Electrostatic Confinement (IEC) / Fusors, Penning Traps, Polywells.
- **Magnetic Field Coil Confinement Systems (mostly steady-state)**
 - Magnetic Mirrors, Tandem Magnetic Mirrors, Field-Reversed Configuration (FRC) Mirrors, Ion Ring Compressor (IRC) System – pulsed, Migma System, Magnetic Cusps, Multi-pole and Surmac Systems
- **Magneto-Inertial Fusion Concepts**
 - LINUS Concept, Magnetized Target Fusion (MTF), Acoustically Driven MTF (GF)
- **Large Linear Systems**
 - Laser-heated Solenoid, Cusp-Ended Solenoid Reactor (CESR), Electron beam Heated Multiple Mirror (EBMM) Reactor
- **Large Toroidal Systems**
 - Reversed Field Pinch, ELMO Bumpy Torus.
- **Compact Torus Devices / Compact Tokamak Variants**
 - Spheromak, Spherical Tokamak.

Canadian Context (1/7)

➤ General Fusion (2002-present)

- Private research company in Burnaby, BC.
- 65 employees, more than 50 engineers and scientists.
- Acoustically Driven Magnetized Target Fusion (AD-MTF)
- Compressed gas-driven pistons compress a conductive liquid metal metal chamber; compresses magnetized plasma (compact torus).
- 2nd Largest Private Fusion Research Program in World.



Canadian Context (2/7)

➤ General Fusion (2002-present)

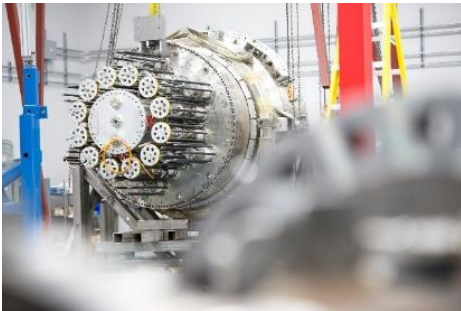
- **Private Investors:**
 - Cleantech venture capital, Cenovus Energy, Jeff Bezos, sovereign wealth funds, with over \$100M invested to date.
- **Government funding: ~\$20M of capital**
 - Sustainable Development Technology Canada (SDTC), Scientific Research and Experimental Development Tax Incentive Program (SR&ED), Industrial Research Assistance Program (NRC-IRAP).
- **University involvement since 2014 (\$350k invested/ \$500k leverage):**
 - U. Saskatchewan, Simon Fraser U., McGill U., U. Sherbrooke, TRIUMF (BC), Princeton U. , Queen Mary U. (London, UK).
- **Other formal and informal research collaborations:**
 - Queen's U., DRDC
 - LANL, LLNL, U. Washington, MIT.



Canadian Context (3/7)

- **GF-MTF Plasma Formation: Enabling Long Lifetimes**
- **Achieved 2700 μ s plasma lifespan in 38 cm diameter Generation 2 “SPECTOR” plasma injectors, with temperatures of 500 eV**
- **Transferring Gen 2 small plasma injector technology to Gen 3 large injectors. First plasma on Gen 3 “PI3” injector in December 2016.**

Generation 1



2011-2014

Generation 2



2015-2017

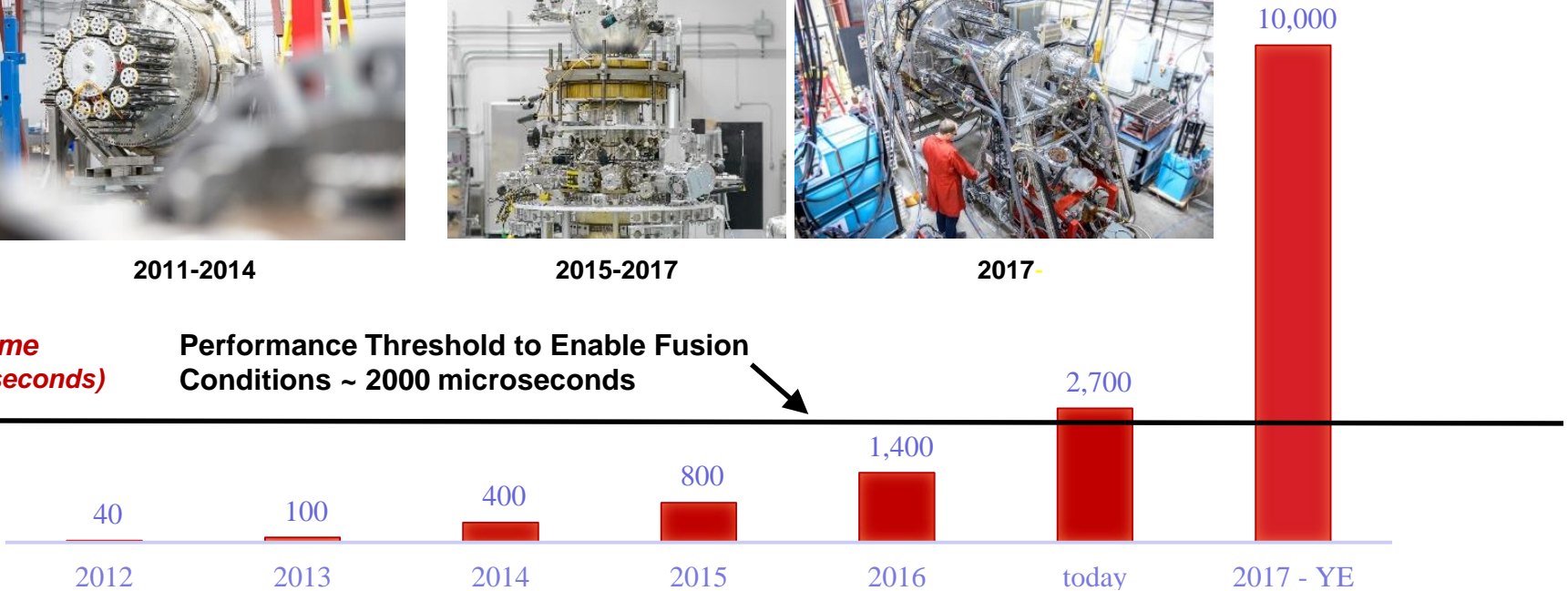
Generation 3



2017-

Time
(microseconds)

Performance Threshold to Enable Fusion
Conditions ~ 2000 microseconds

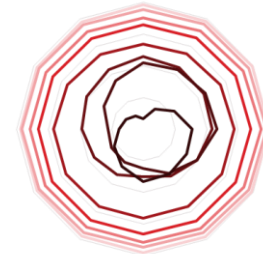


70x improvement over 5 years

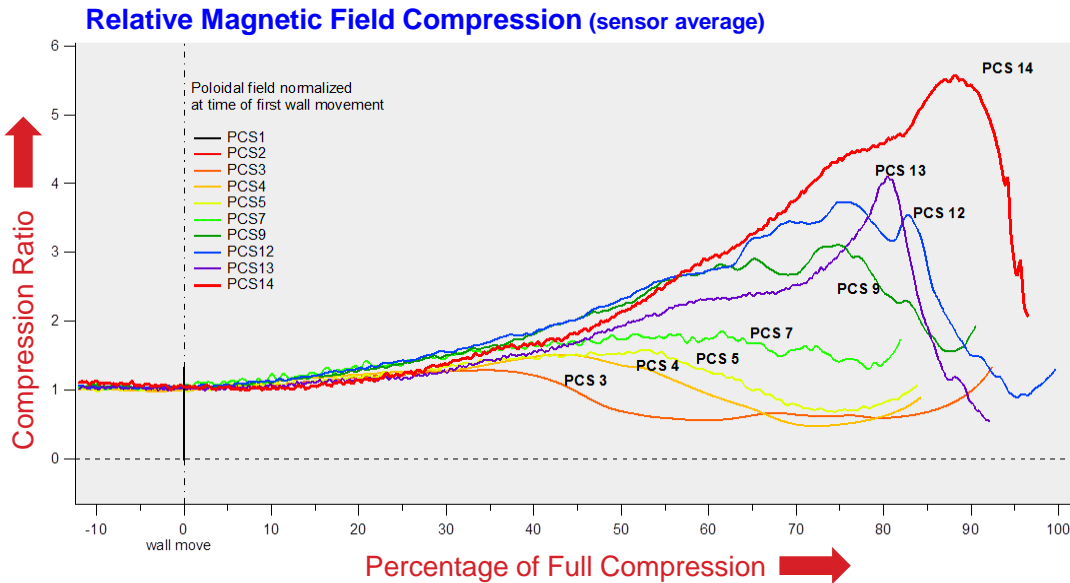
Canadian Context (4/7)

- **GF-MTF Plasma Stability During Compression**
- **PCS14 (February, 2017): Latest test results achieved higher and deeper compression**
- **Why? Changes made prevented the magnetic instabilities seen in previous tests**

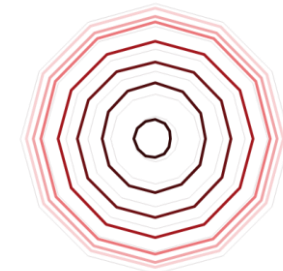
**Unstable Magnetic Symmetry
Late in Compression
PCS13**



EVOLUTION OF PLASMA STABILITY CONTROL

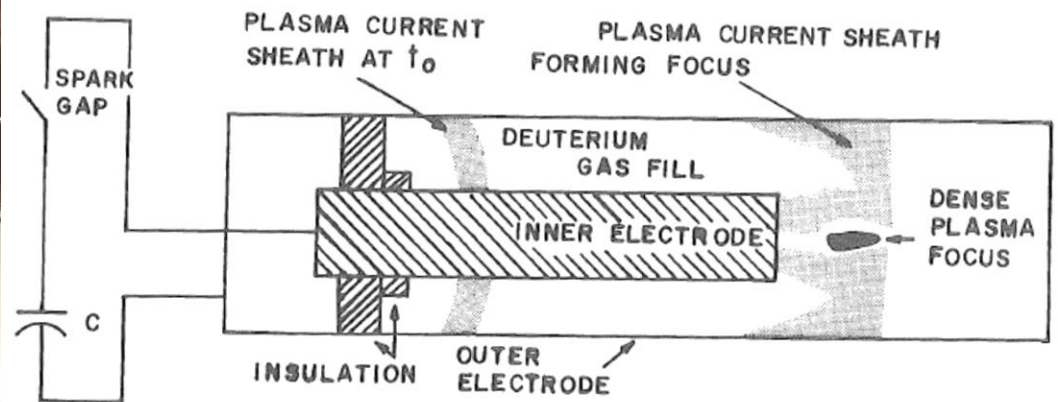
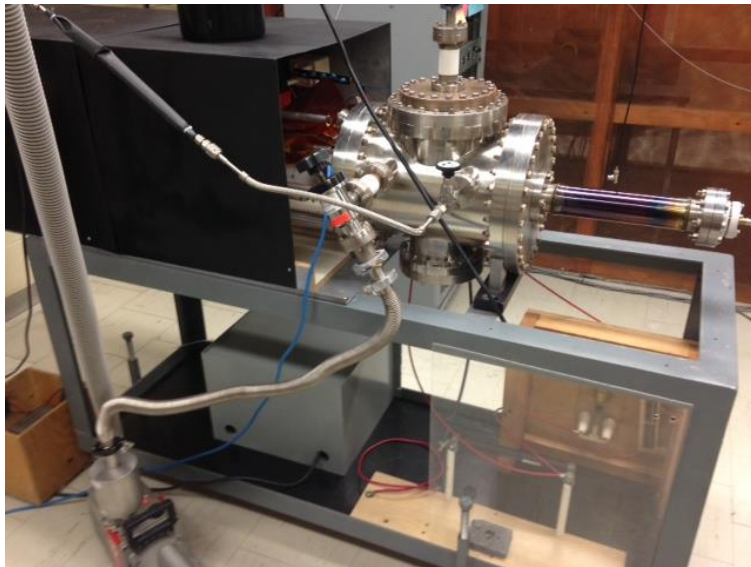
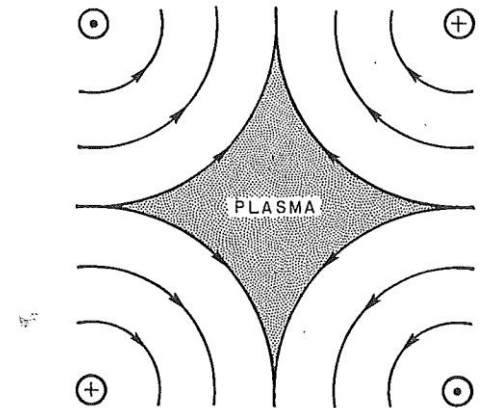


**Stable Magnetic Symmetry
Throughout Compression
PCS14**



Canadian Context (5/7)

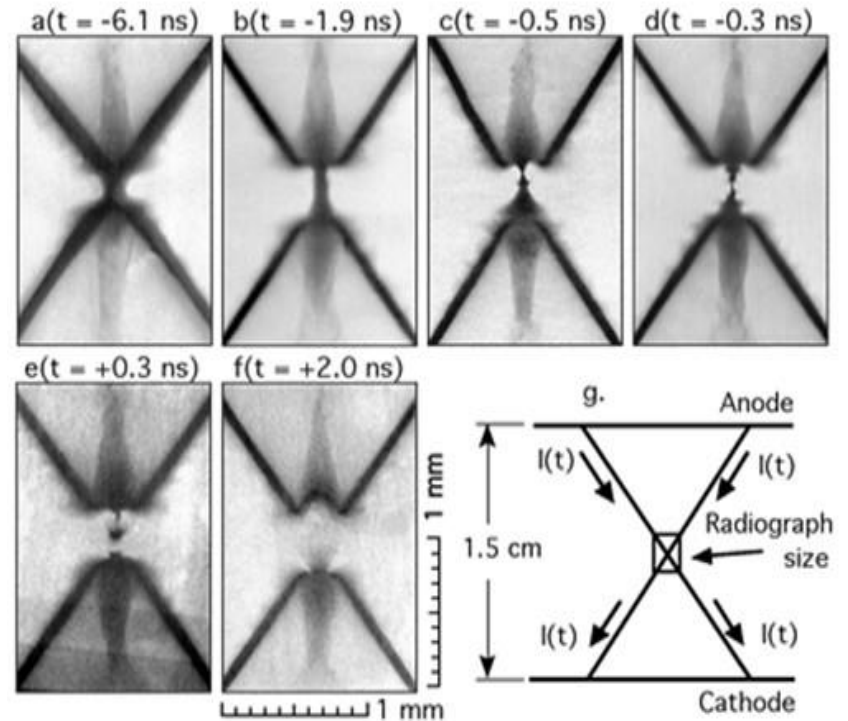
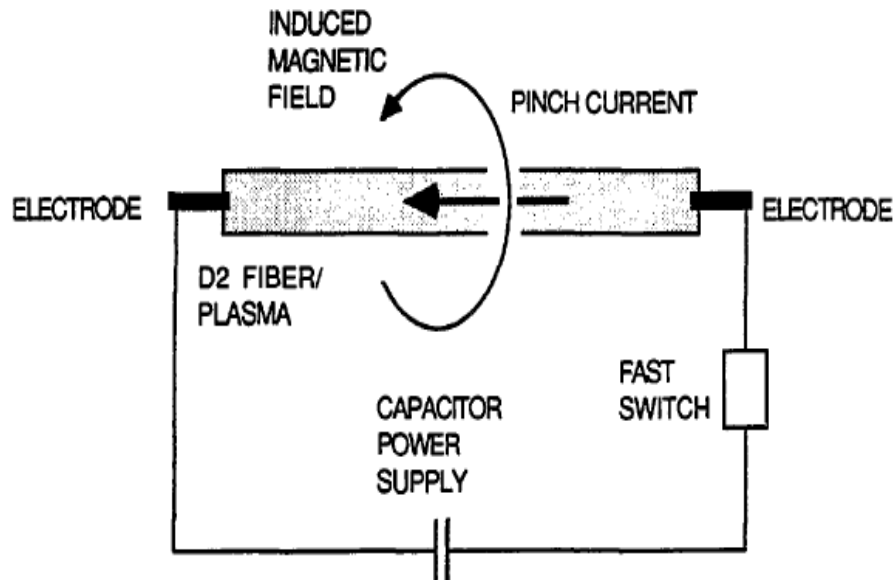
- **U. Quebec at Montreal (1970s)**
 - **Magnetic Cusp ; stable, but leaky.**
- **U. Saskatchewan (2013+)**
 - **Dense Plasma Focus (DPF)**
 - **2-kJ prototype; 20-kJ under development.**
 - **Potential to use $p\text{-}^{11}\text{B}$ aneutronic fuel.**
 - **Scaling laws suggest 300-MJ device required.**



Canadian Context (6/7)

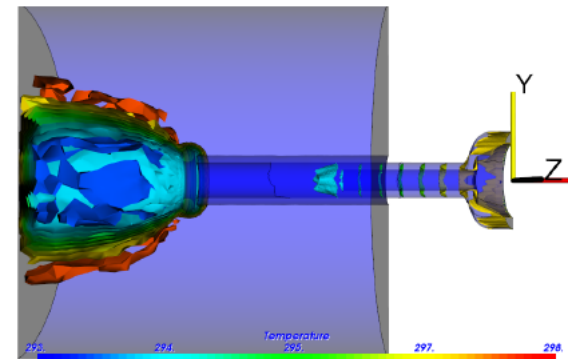
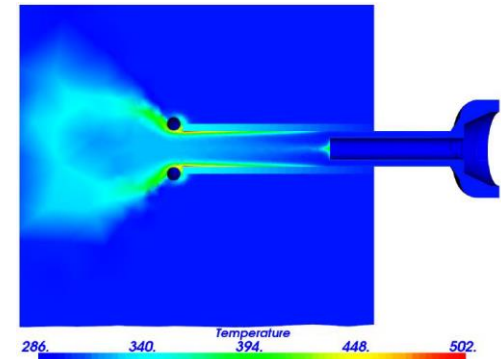
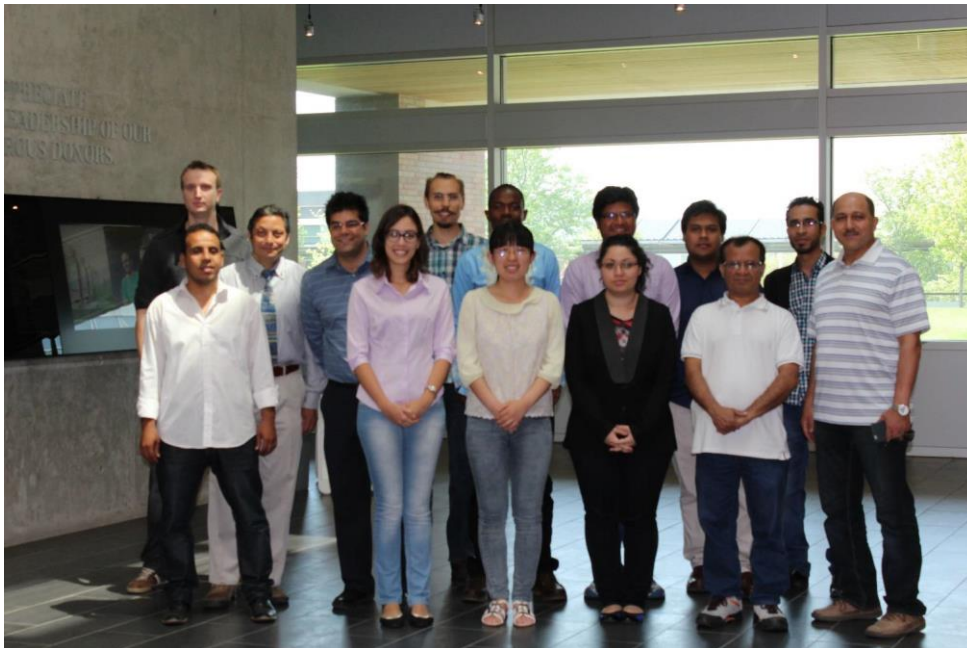
➤ HOPE Innovations (2011)

- Private research company (Mississauga).
- Investigating variants of X-Pinch, Z-Pinch Devices.
- Intersections of plasma beams.
- Preliminary experiments.



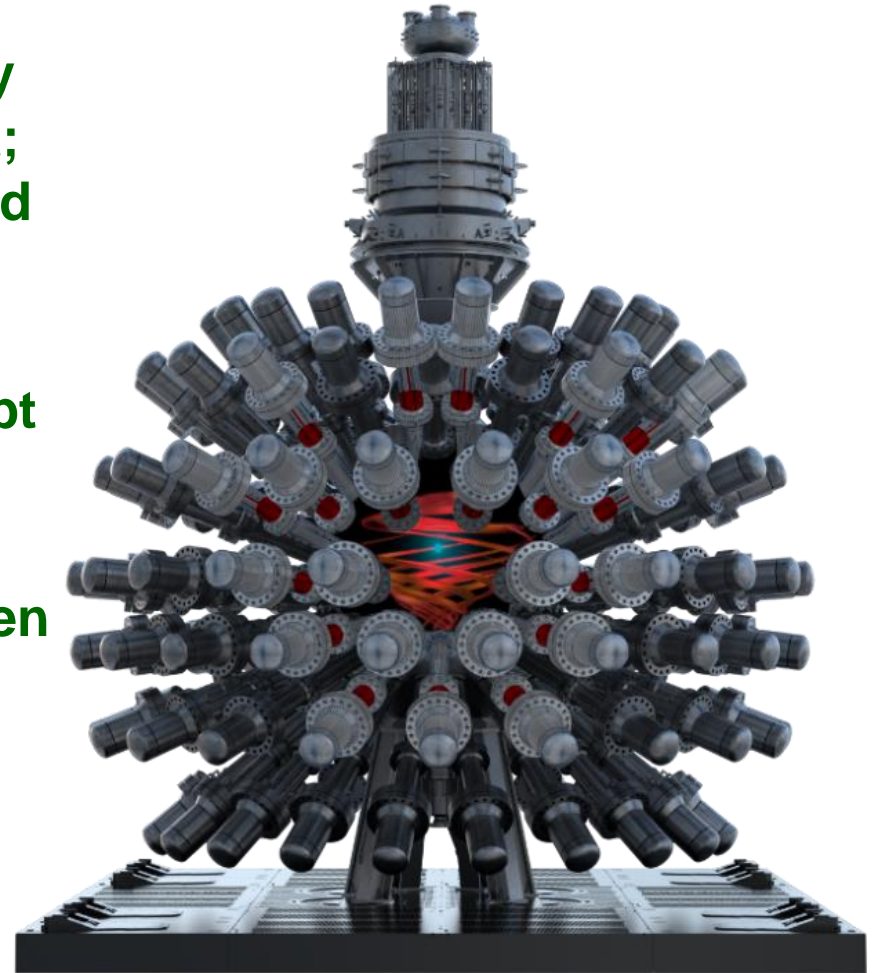
Canadian Context (7/7)

- **University of Ontario Institute of Technology (UOIT)**
 - **Advanced Plasma Engineering Lab (APEL)**
 - **Plasma generation devices.**
 - **Plasma simulation studies.**
 - **Study of control systems.**
 - **Since 2013**



Future Canadian Efforts (1/4)

- **Moving to Integrated GF-MTF Prototype:**
- **2016/17: inflection point in all key areas of technology development; confidence to construct integrated prototype**
- **Pre-conceptual design now underway, detailed design concept toward year-end.**
- **Prototype goal: achieving fusion conditions (10 keV), sub-breakeven**
- **Will operate at low rep-rate (one shot per day)**



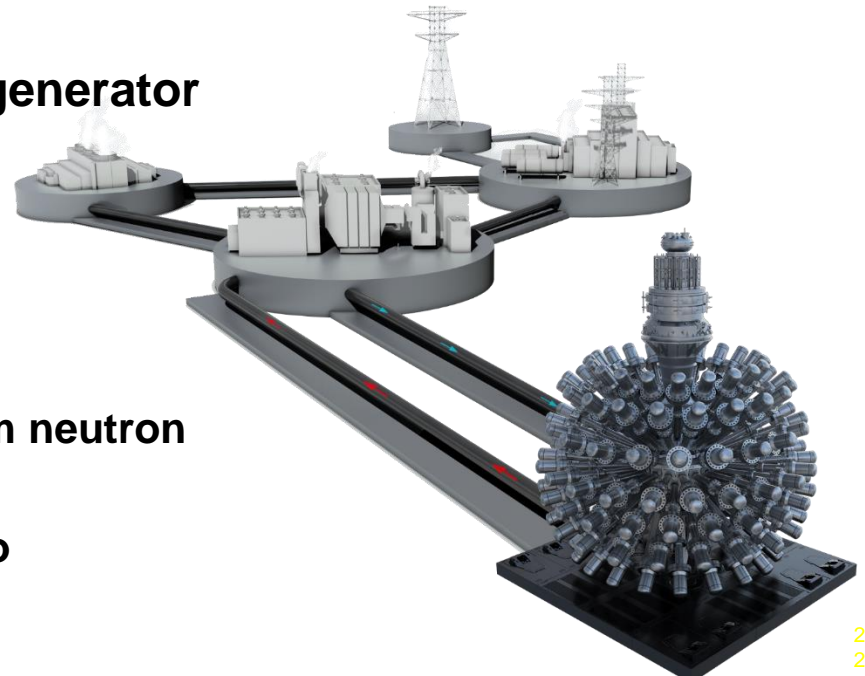
Future Canadian Efforts (2/4)

General Fusion MTF Power Plant Operation

- 3 meter diameter compression vessel filled with liquid lead-lithium, circulated to form a cavity in the center.
- Plasma injector forms plasma into the cavity.
- 200 piston drivers symmetrically collapse the cavity
 - Compressing and heating the plasma
- Plasma ignites and fusion energy is absorbed into surrounding lead-lithium
- Hot lead-lithium transfers energy
 - Standard Rankine steam cycle and generator

~100 MWe net output

- Compressed gas driver relatively low cost
- Thick liquid metal wall shields structure from neutron damage, breeds tritium, extracts energy
- Pulsed approach with plasma-only target (no manufactured consumables)



Future Canadian Efforts (3/4)

- **Other Alternative Fusion Concepts:**
- **Construction / operation of smaller-scale devices**
 - **University, government, private-sector laboratories.**
 - **Magnetized Target Fusion (see previous presentation).**
 - **Dense Plasma Focus, Z-Pinch / X-Pinch**
 - Pulsed systems.
 - **Other alternative concepts**
 - IEC Devices, Polywells, Magnetic Mirrors, Multi-poles, other variants.
 - Steady-state systems.
 - **Operate with hydrogen, deuterium.**
 - Operating with tritium will have special and extra licensing requirements.
 - **Use for testing equipment and components.**
 - Instrumentation, refuelling, plasma heating, field coils.
 - **Use measurements also for benchmarking simulation tools.**

Future Canadian Efforts (4/4)

- **Computer simulation of alternative fusion devices**
 - **Feasible/suitable for university/academic activities.**
 - Physics, electrical engineering, applied mathematics.
 - **Develop capability to simulate wide variety of devices.**
 - Test scaling, test viability.
 - Design tool.
 - **Plasma physics, electro-magnetics, control systems.**
 - Direct simulation of plasma behavior (particle-in-cell methods).
 - Use of high-speed computing facilities.
 - **Plasma-material interactions.**
 - **Compare results with peers in international community.**
 - Expand knowledge base.
 - Verify/assess claims made by various groups.

Summary

- **Opportunity for Canada to work on alternative fusion reactor concepts.**
 - **Support and complement international efforts.**
 - **Pursue alternative concepts domestically.**
- **Key areas for Canada to take leading contributing role:**
 - **Magnetized Target Fusion**
 - Effort lead by General Fusion
 - Support by other institutions in Canada and abroad.
 - **Smaller-scale experiments for alternative concepts.**
 - Test component technologies, instrumentation.
 - Data to benchmark simulation tools.
 - **Computer simulations.**
 - Test behavior and viability of alternative concepts.
 - Modified earlier concepts, innovative new concepts.

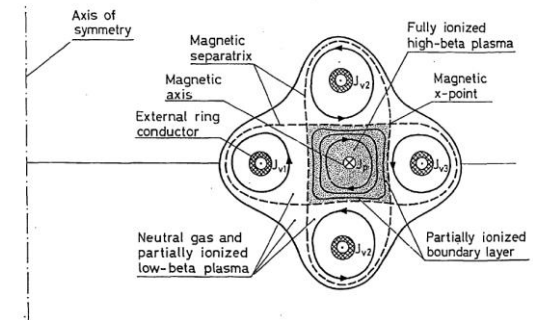
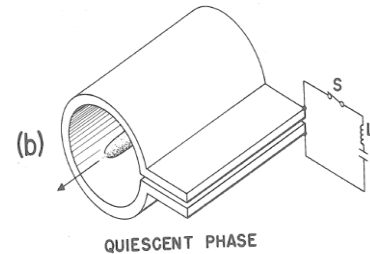
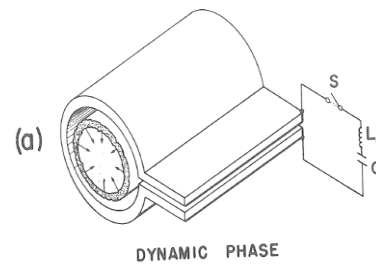
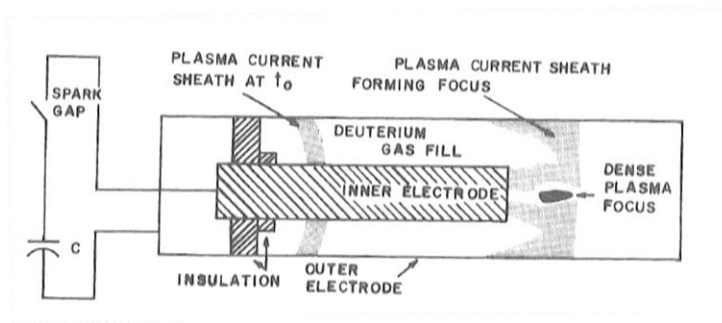
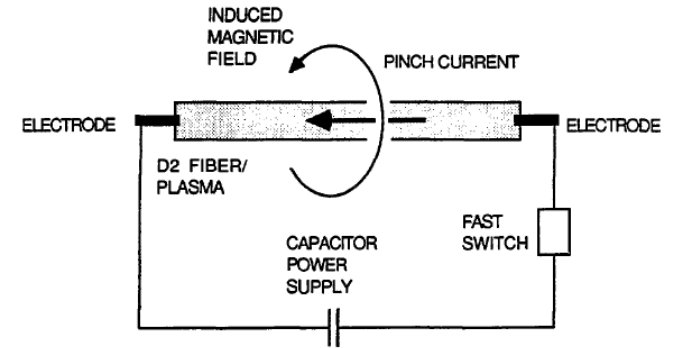
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Supplementary Slides

Other Alternative Concepts (1/12)

➤ Electromagnetic Pinch Devices (Pulsed):

- **Z-Pinch**
- **Extrap (External Ring Trap) Concept**
- **Dense Plasma Focus (DPF)**
- **Linear Theta Pinch**
- **Toroidal Theta Pinch**



Other Alternative Concepts (2/12)

- **Electrostatic / Magnetostatic Confinement Devices**
 - **Inertial Electrostatic Confinement (IEC) / Fusors**
 - **Penning Traps**
 - **Polywells (multiple magnetic cusps)**

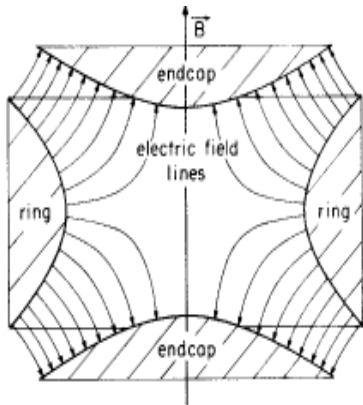
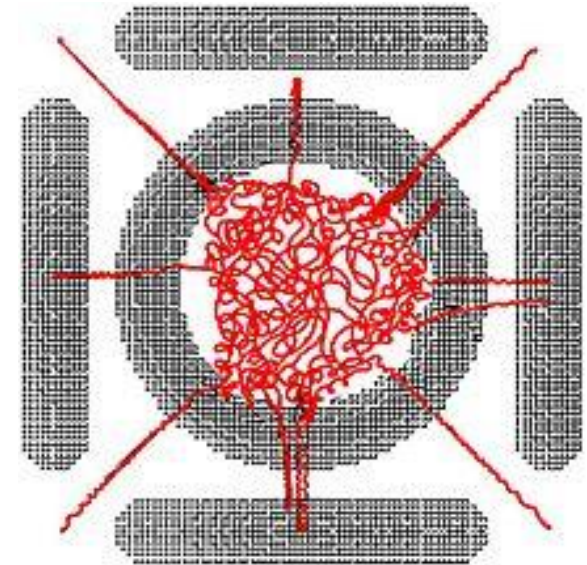
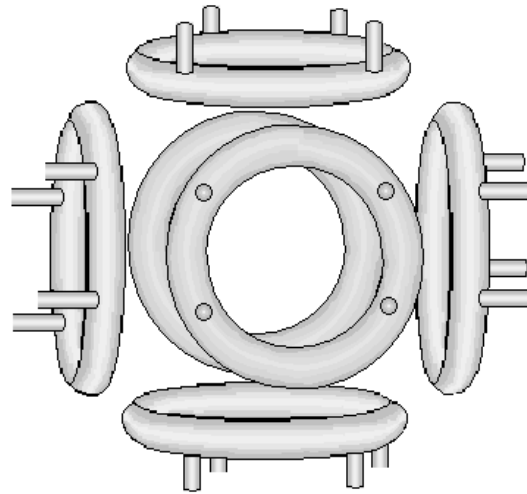
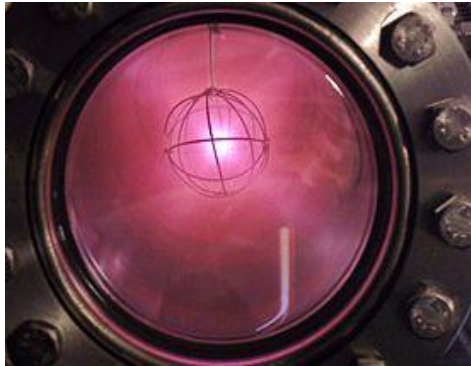
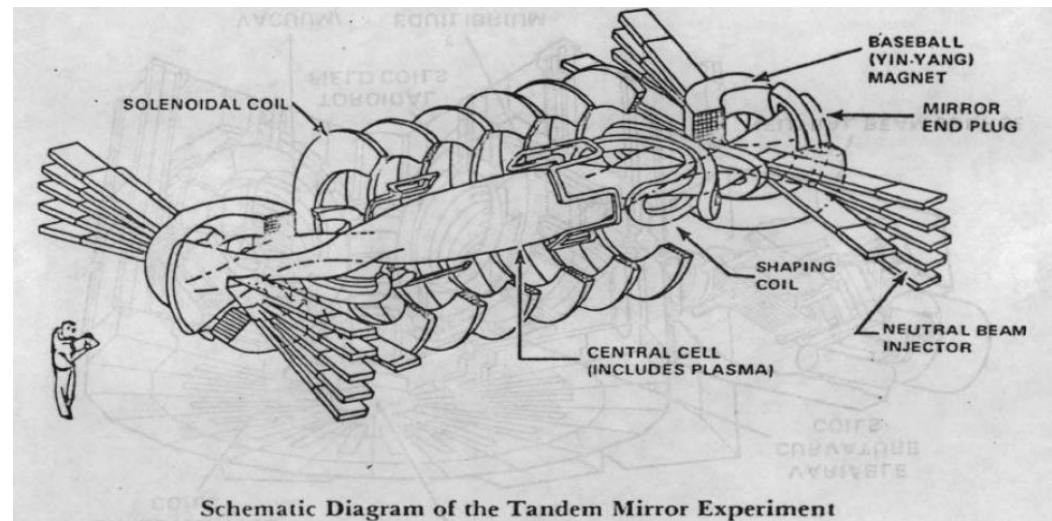
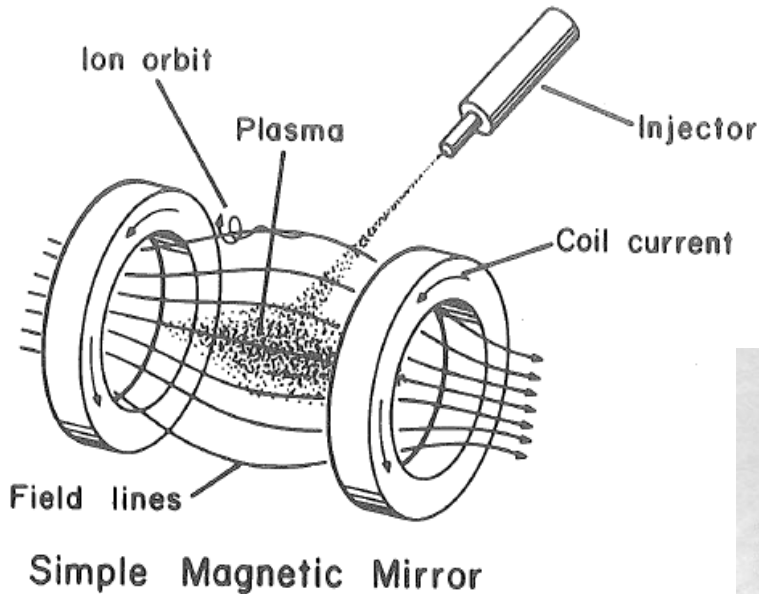


FIG. 2. Electric and magnetic field configurations of the Penning trap.

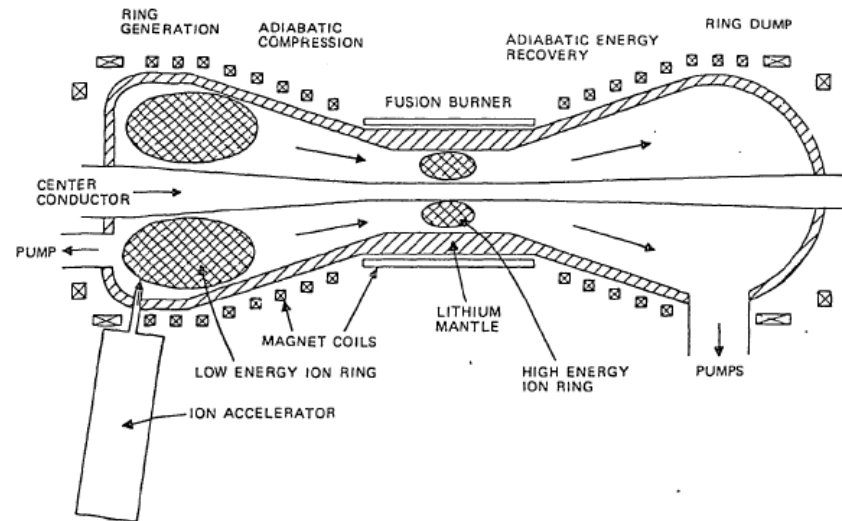
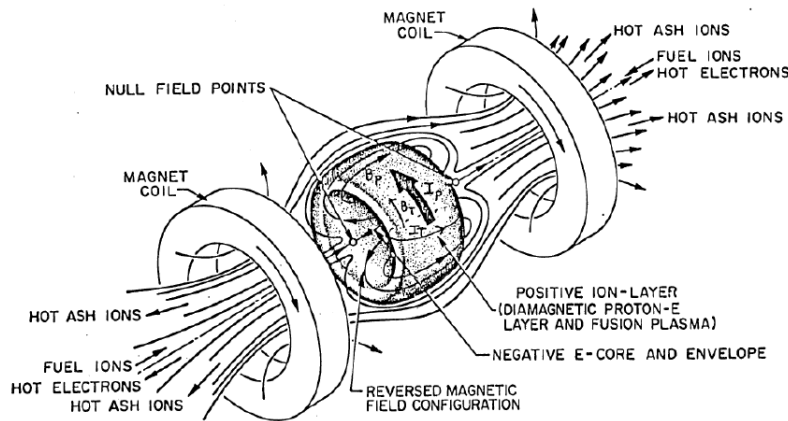
Other Alternative Concepts (3/12)

- **Magnetic Field Coil Confinement Systems (mostly steady-state)**
 - **Magnetic Mirrors**
 - **Tandem Magnetic Mirrors**



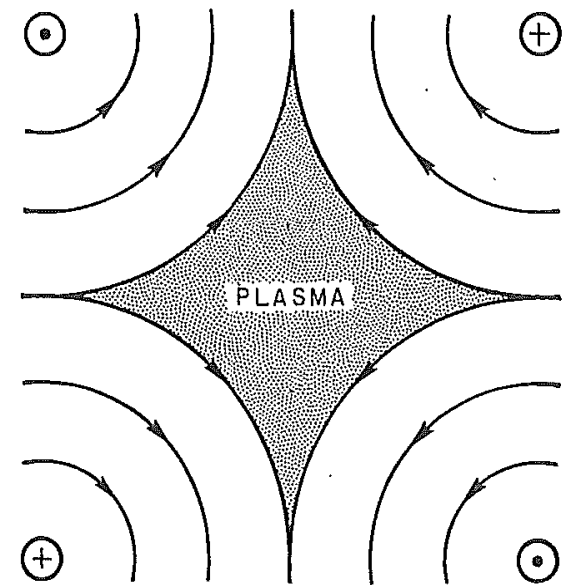
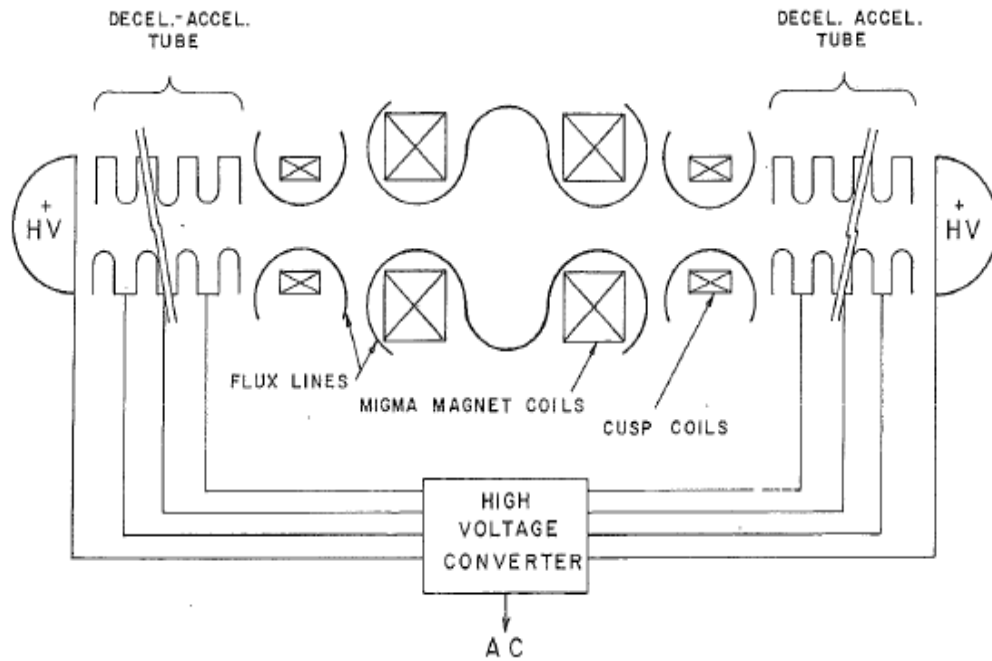
Other Alternative Concepts (4/12)

- **Magnetic Field Coil Confinement Systems (mostly steady-state)**
 - **Field-Reversed Configuration (FRC) Mirrors –**
 - **Ion Ring Compressor (IRC) System – pulsed**



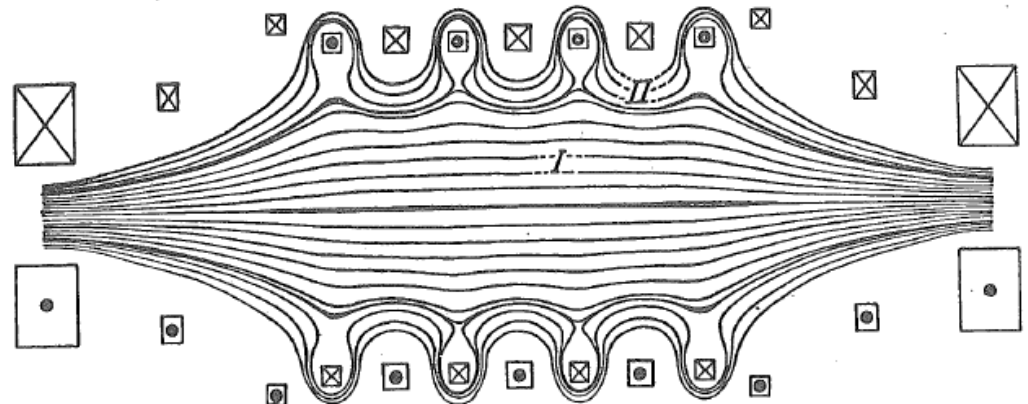
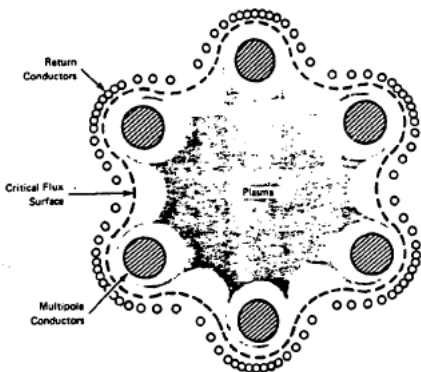
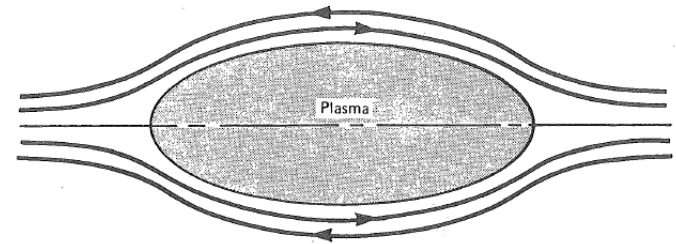
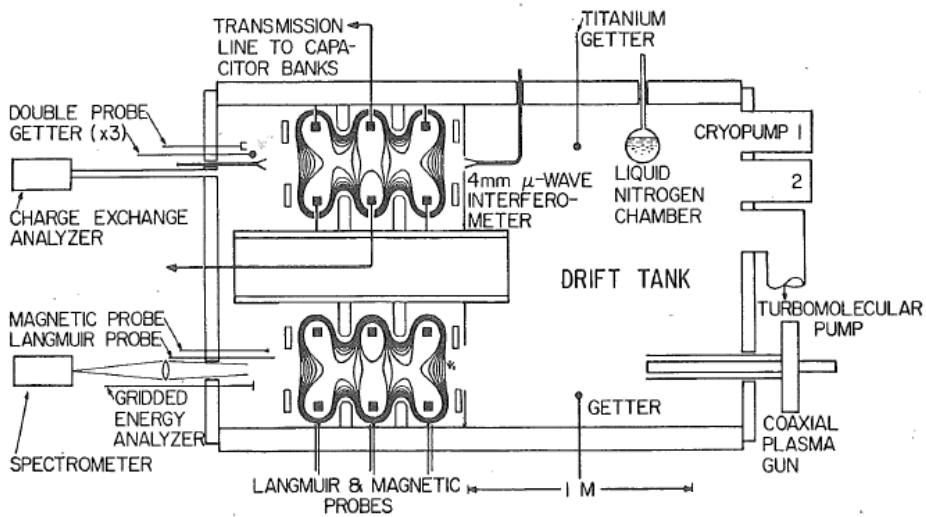
Other Alternative Concepts (5/12)

- **Magnetic Field Coil Confinement Systems (mostly steady-state)**
 - **Migma System**
 - **Magnetic Cusps**



Other Alternative Concepts (6/12)

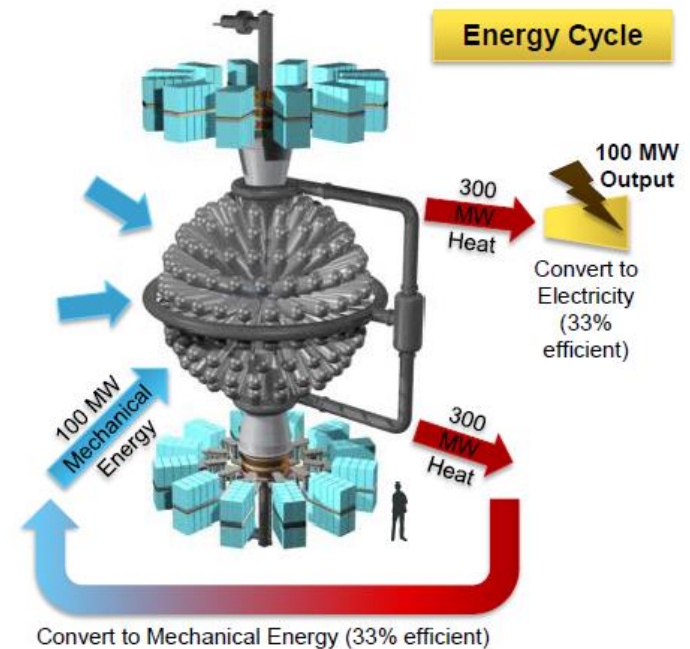
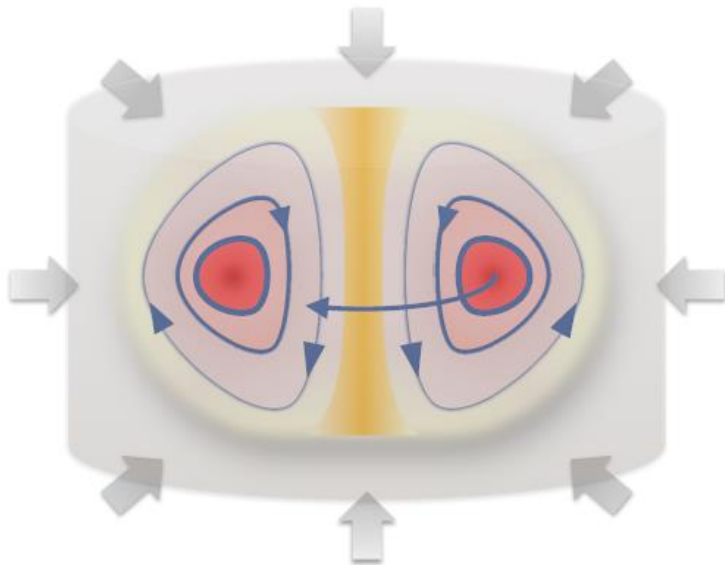
- **Magnetic Field Coil Confinement Systems (mostly steady-state)**
 - **Multi-pole and Surmac Systems**



Other Alternative Concepts (7/12)

➤ Magneto-Inertial Fusion Concepts

- **LINUS Concept**
- **Magnetized Target Fusion (MTF)**
- **Acoustically Driven MTF (General Fusion)**
 - See earlier presentation.



Other Alternative Concepts (8/12)

➤ Large Linear Systems

- Laser-heated Solenoid
- Cusp-Ended Solenoid Reactor (CESR)
- Electron beam Heated Multiple Mirror (EBMM) Reactor

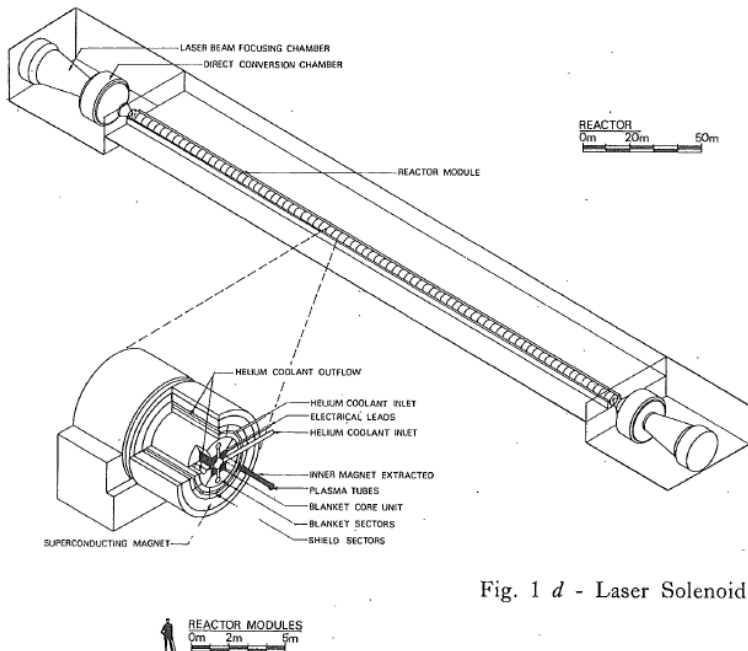


Fig. 1 d - Laser Solenoid Reactor

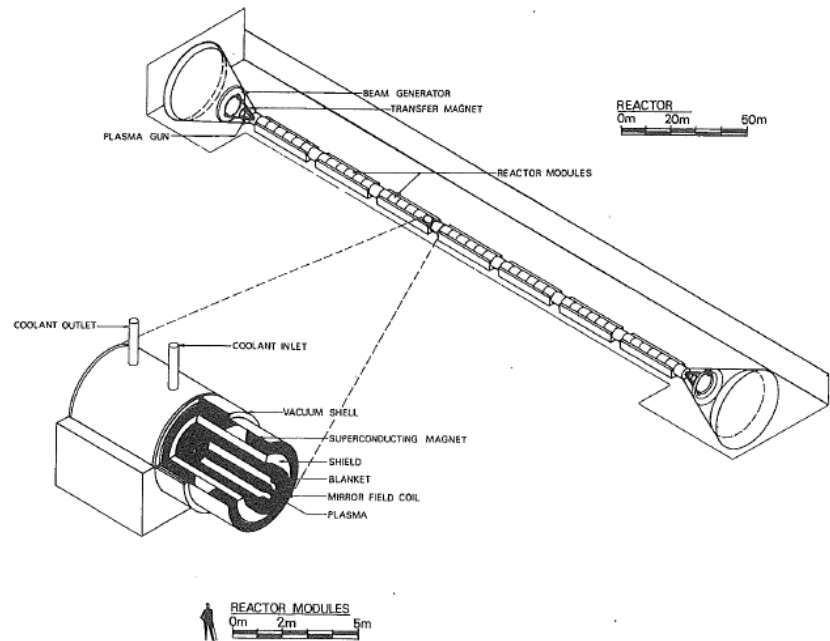
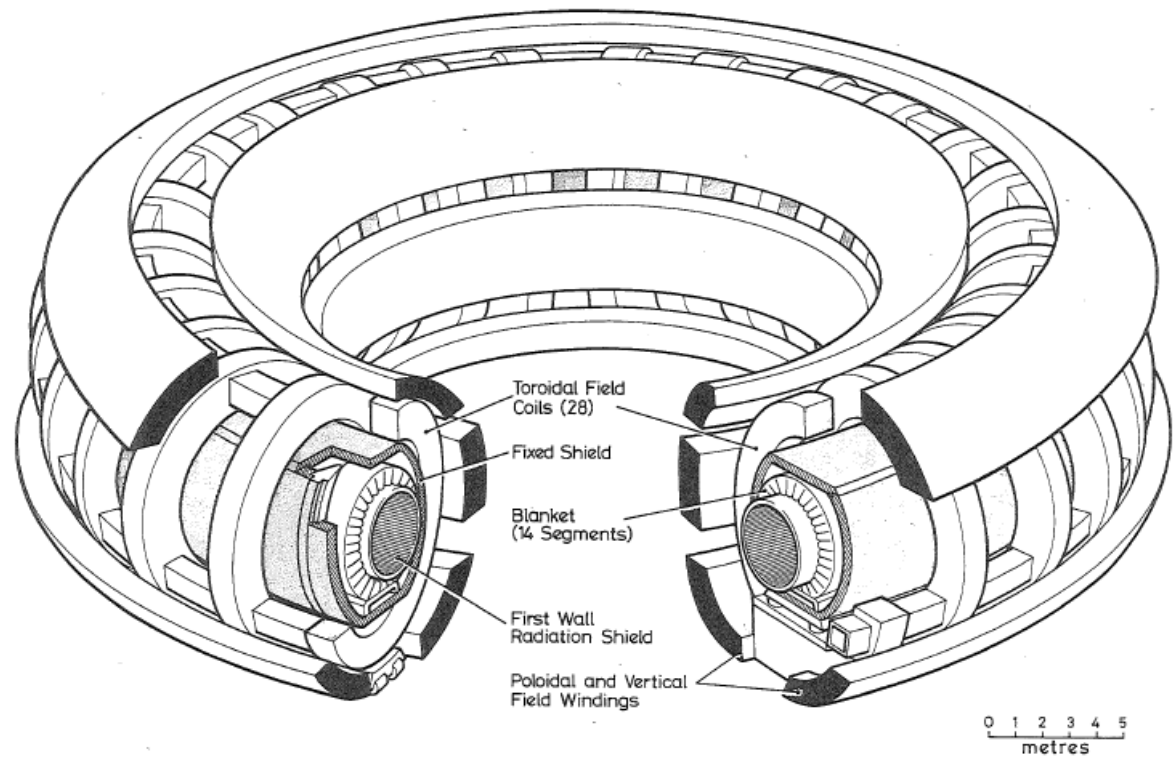
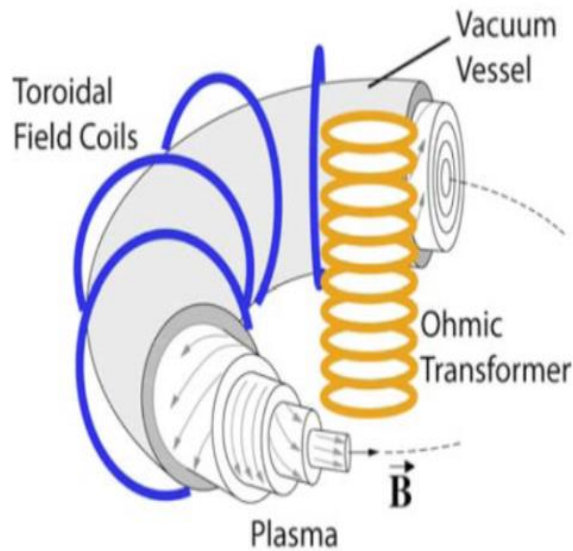


Fig. 1 a - Electron-Beam-Heated Solenoid Reactor

Other Alternative Concepts (9/12)

- Large Toroidal Systems
 - Reversed Field Pinch – pulsed.



Other Alternative Concepts (10/12)

➤ Large Toroidal Systems

- **ELMO Bumpy Torus (steady state).**

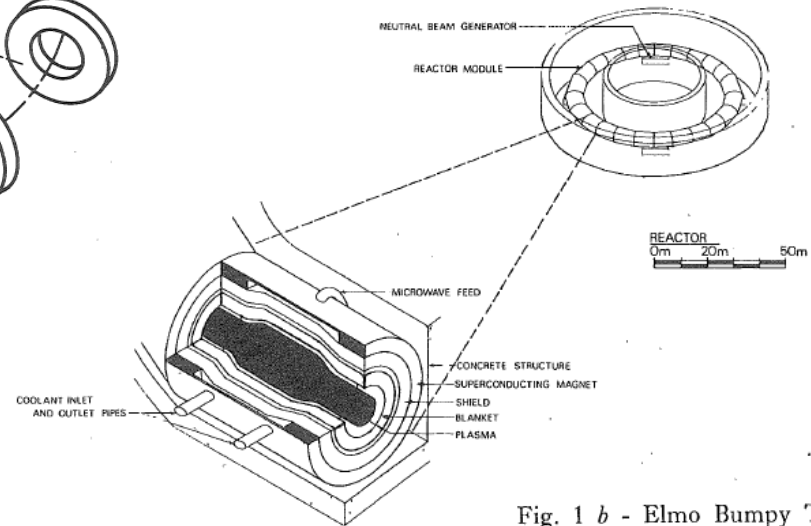
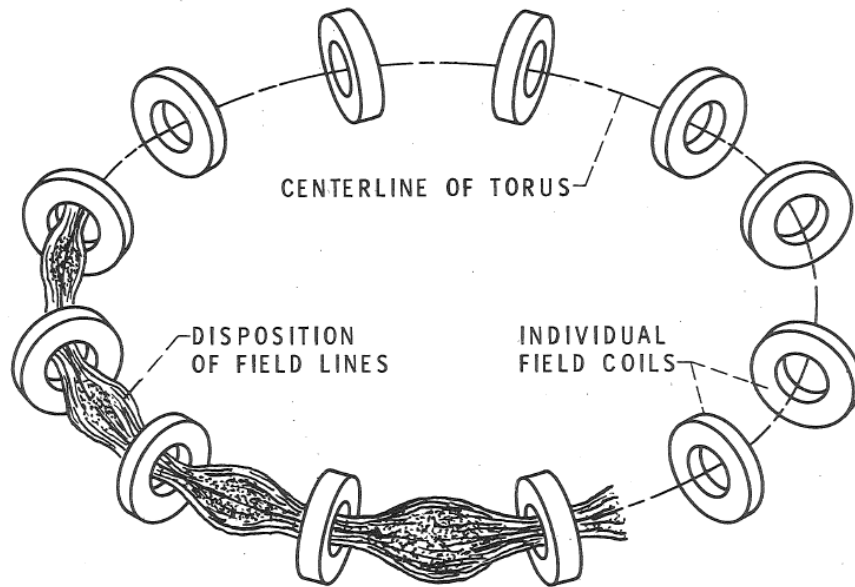
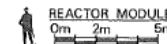


Fig. 1 b - Elmo Bumpy Torus Reactor

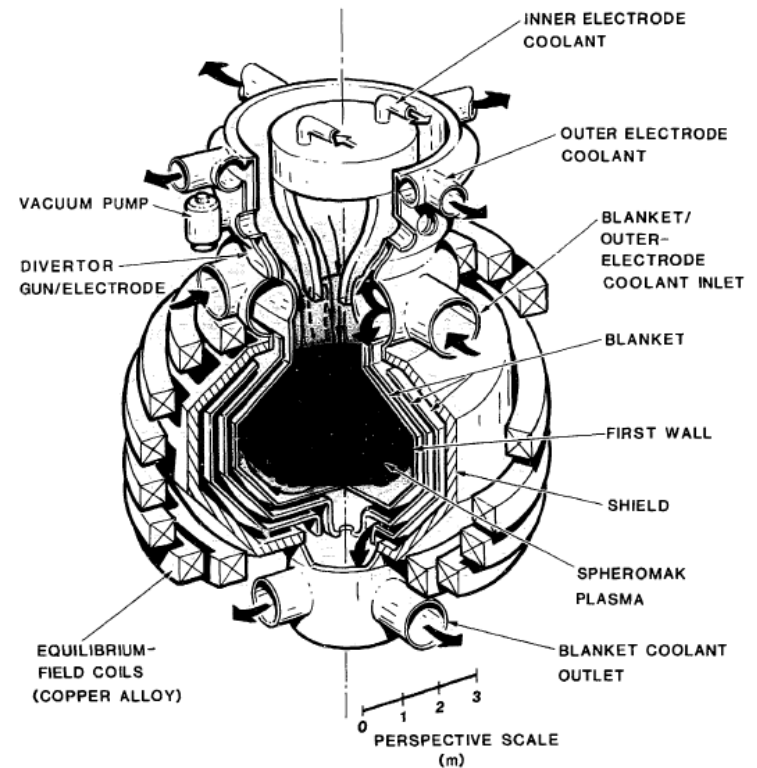
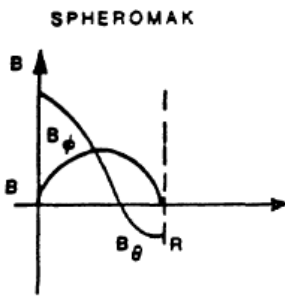
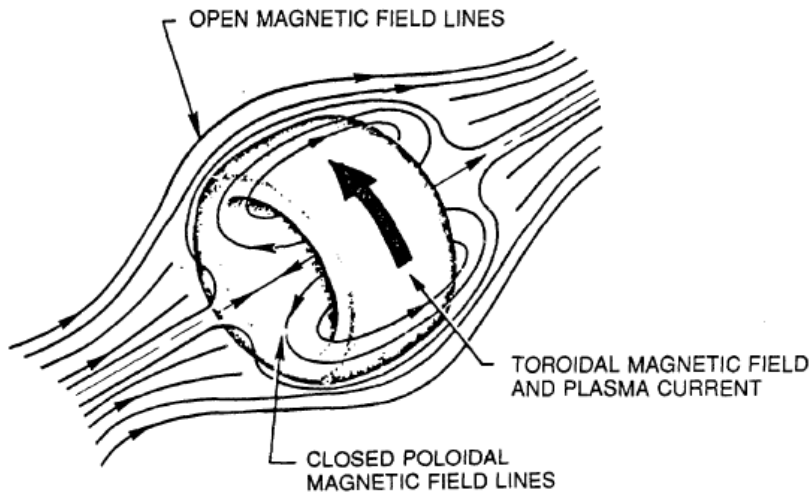


Other Alternative Concepts (11/12)

➤ Compact Torus Devices / Compact Tokamak Variants

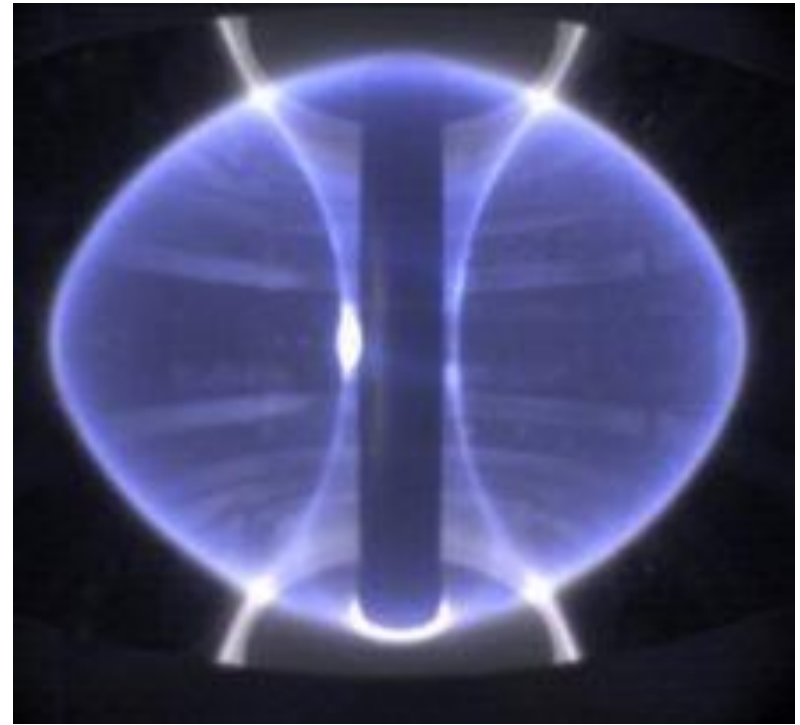
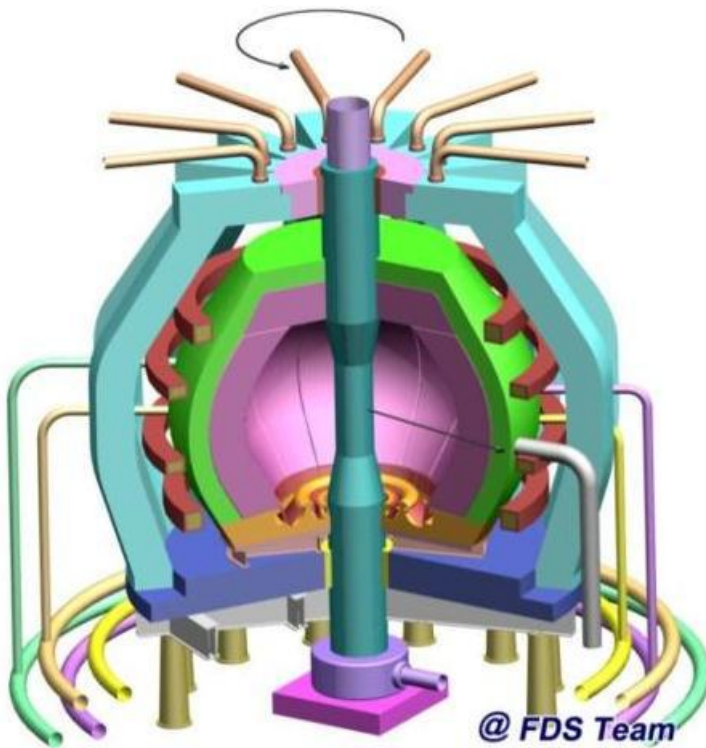
- **Spheromak**

- Pulsed (steady state maybe possible).



Other Alternative Concepts (12/12)

- Compact Torus Devices / Compact Tokamak Variants
 - Spherical Tokamak.



Supplementary Info

- ***FYI – Govt of Canada is seeking public input on the future of science and “innovation”. Feel free to contribute! These are the two links for the government consultations:***
 - ***1. Canada’s Fundamental Science Review:***
 - ***<http://www.examenscience.ca/eic/site/059.nsf/frm-eng/RVOT-AASJLL>***
 - ***2. Innovation Agenda consultation:***
 - ***<http://www.ic.gc.ca/eic/site/062.nsf/eng/home>***
- ***The first one is the one that the submissions will be private (public cannot see them and has a expert panel). For the second one the submissions are public and less technical.***

CNS-FESTD

- **Visit:**
- **<https://cns-snc.ca/home>**
- **<https://cns-snc.ca/CNS/fusion/>**

- **Join the Canadian Nuclear Society (CNS).**
- **<https://cns-snc.ca/cns/membership/>**

- **Join the Fusion Energy Science and Technology Division (FESTD)**

General Fusion

- Private research company in Burnaby, BC
- 65 employees, more than 50 engineers and scientists
- Pursuing Acoustic Magnetized Target Fusion (MTF)
- Compressed gas driven pistons compress magnetized plasma within a conductive metal chamber of liquid metal



Approaches to Fusion



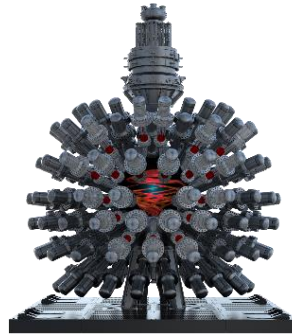
Magnetic Confinement

Plasma confinement using large magnetic coils

Low density:

$\sim 10^{14}$ ions/cm³

Continuous operation
(ITER)



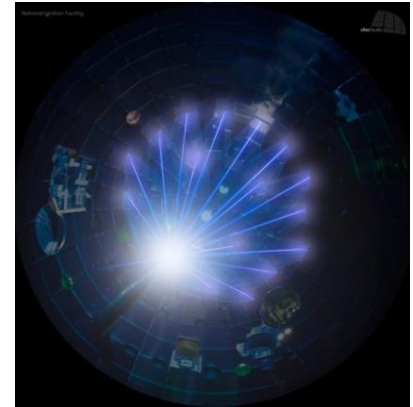
Magnetized Target Fusion (MTF)

Combination of compression and magnetic confinement

Medium density:

$\sim 10^{20}$ ions/cm³

Pulsed: ~ 10 μ s
(General Fusion)



Inertial Confinement (ICF)

Very fast compression using high power lasers or ion beams

Extreme density:

$\sim 10^{26}$ ions/cm³

Pulsed: < 1 ns
(NIF)

GF-MTF Power Plant Concept

General Fusion Plant Operation

1. 3 meter diameter compression vessel filled with liquid lead-lithium, circulated to form a cavity in the center.
2. Plasma injector forms plasma into the cavity
3. 200 piston drivers symmetrically collapse the cavity, compressing and heating the plasma
4. Plasma ignites and fusion energy is absorbed into surrounding lead-lithium
5. Hot lead-lithium transfers energy to a standard rankine steam cycle and generator



~100 MWe net output

Compressed gas driver relatively low cost

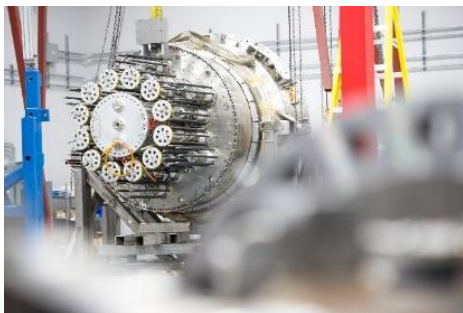
Thick liquid metal wall shields structure from neutron damage, breeds tritium, extracts energy

Pulsed approach with plasma-only target (no manufactured consumables)

GF-MTF Plasma Formation: Enabling Long Lifetimes

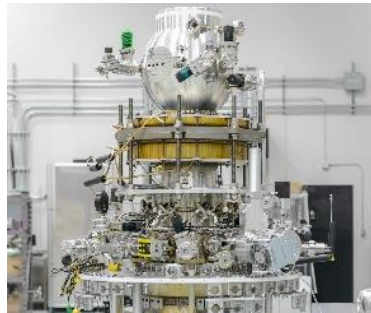
- Achieved 2700 μ s plasma lifespan in 38 cm diameter Generation 2 “SPECTOR” plasma injectors, with temperatures of 500 eV
- Transferring Gen 2 small plasma injector technology to Gen 3 large injectors. First plasma on Gen 3 “PI3” injector in December 2016.

Generation 1



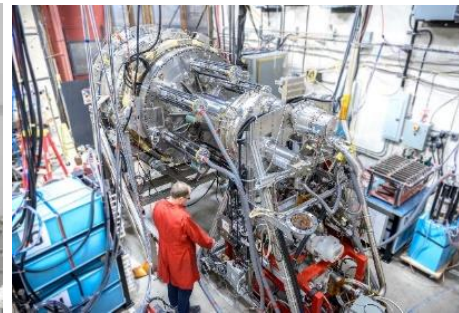
2011-2014

Generation 2



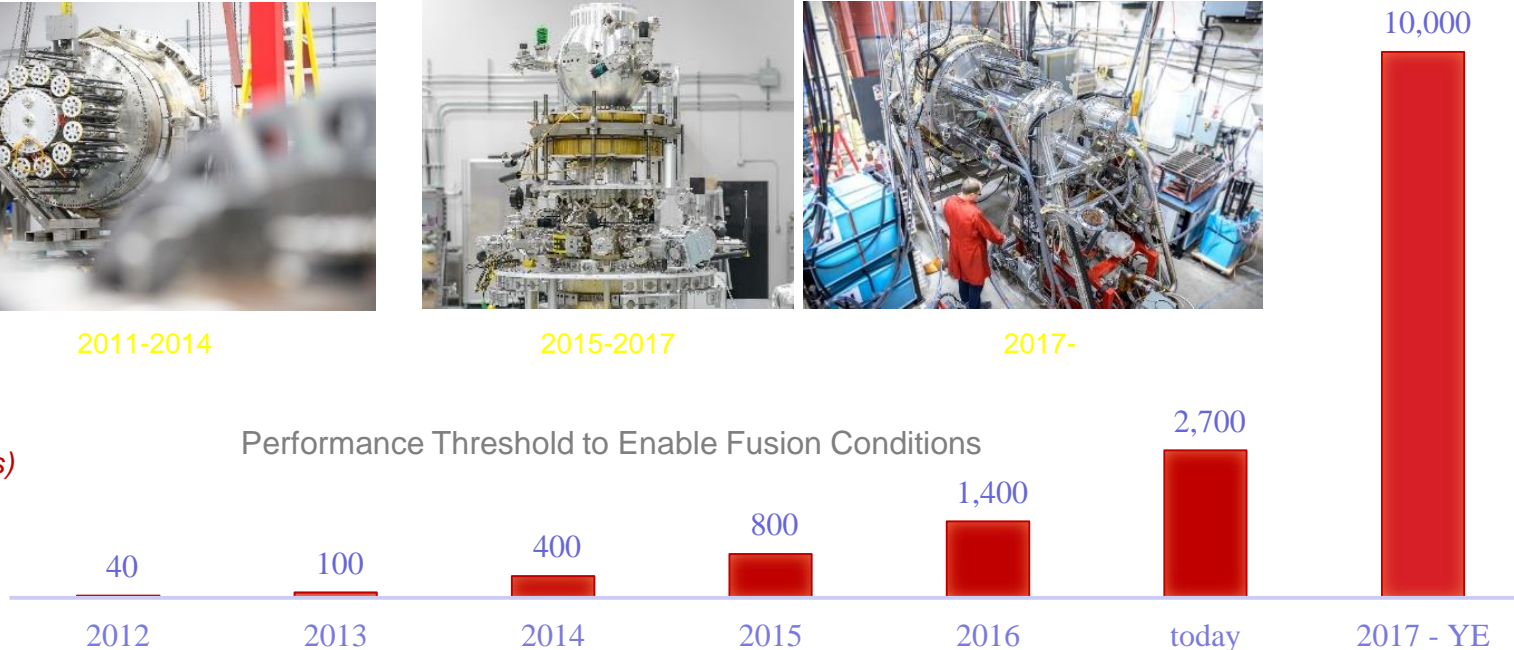
2015-2017

Generation 3



2017-

Time
(microseconds)

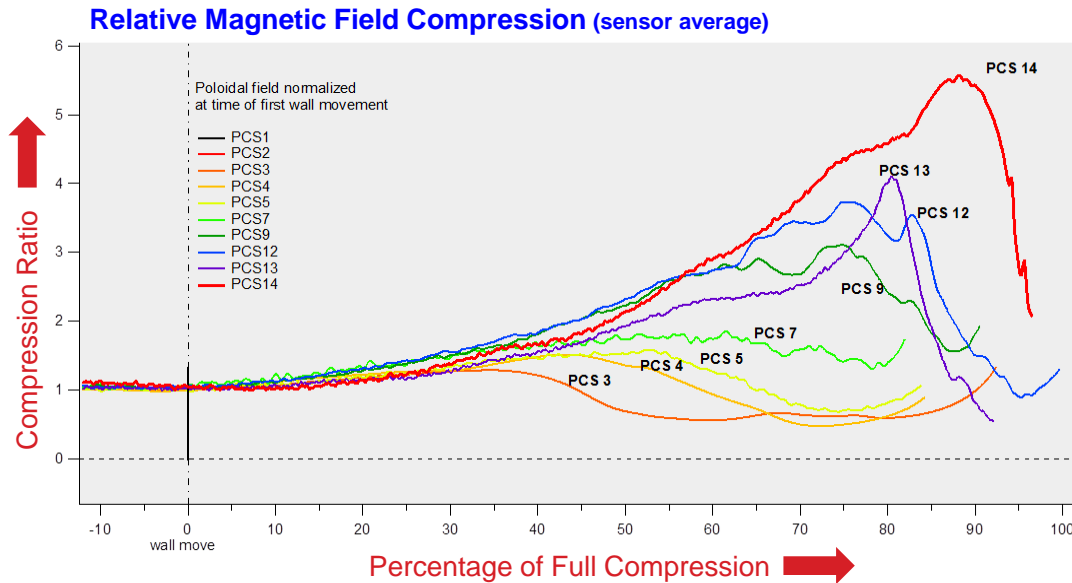


70x improvement over 5 years

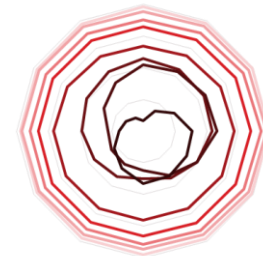
GF-MTF Plasma Stability During Compression

- PCS14 (February, 2017): Latest test results achieved higher and deeper compression
- Why? Changes made prevented the magnetic instabilities seen in previous tests

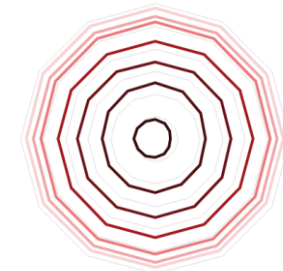
EVOLUTION OF PLASMA STABILITY CONTROL



**Unstable Magnetic Symmetry
Late in Compression
PCS13**

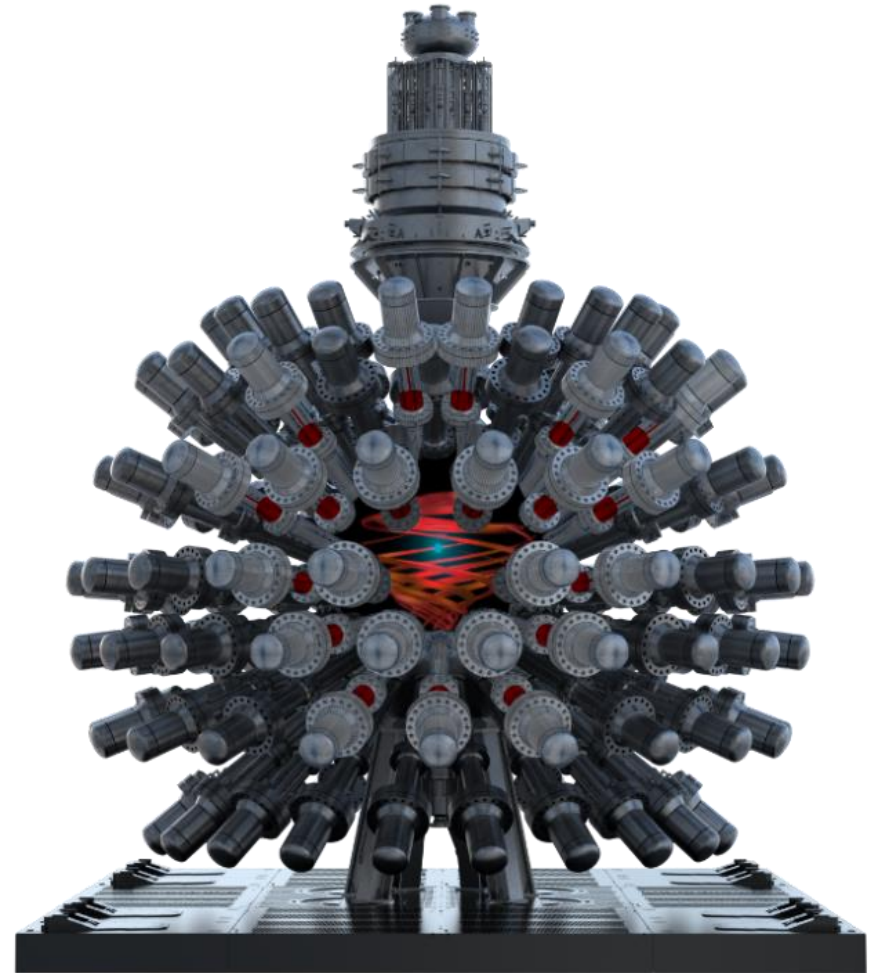


**Stable Magnetic Symmetry
Throughout Compression
PCS14**



Moving to Integrated GF-MTF Prototype

- 2016/17 has been an inflection point in all key areas of technology development and has given confidence to construct integrated prototype
- Pre-conceptual design now underway, detailed design concept toward year-end
- Prototype goal is achieving fusion conditions (10 keV), sub-breakeven
- Will operate at low rep-rate (one shot per day)



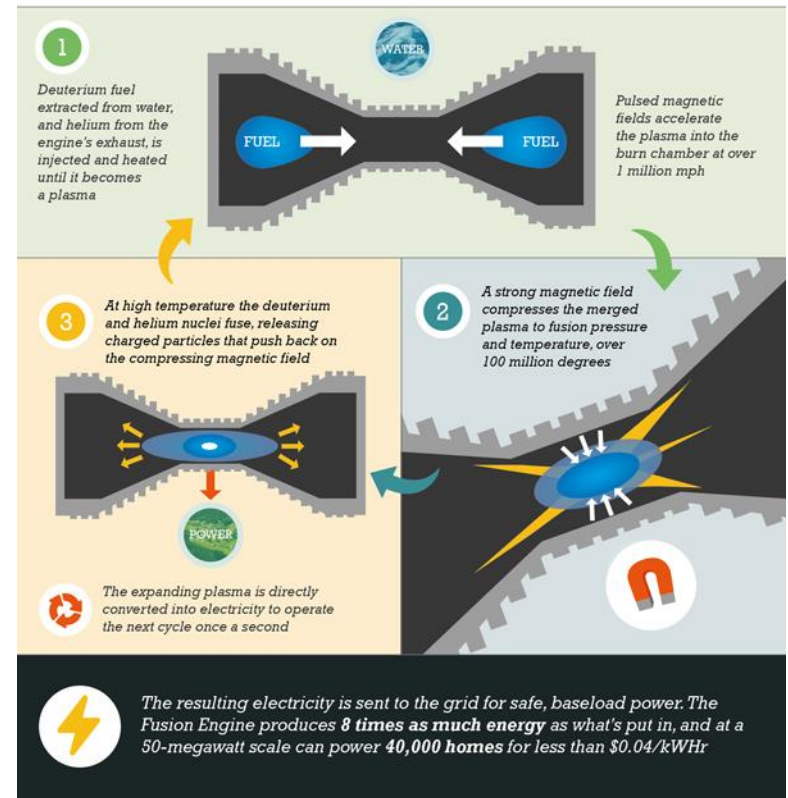
More Alternative Concepts (1/4)

➤ Helion

- **Magnetic compression of merged FRCs**
- <http://www.helionenergy.com/>
- <https://arpa-e.energy.gov/?q=site-page/2016-alpha-annual-meeting>
- <https://www.arpa-e.energy.gov/?q=slick-sheet-project/compression-frc-targets-fusion>



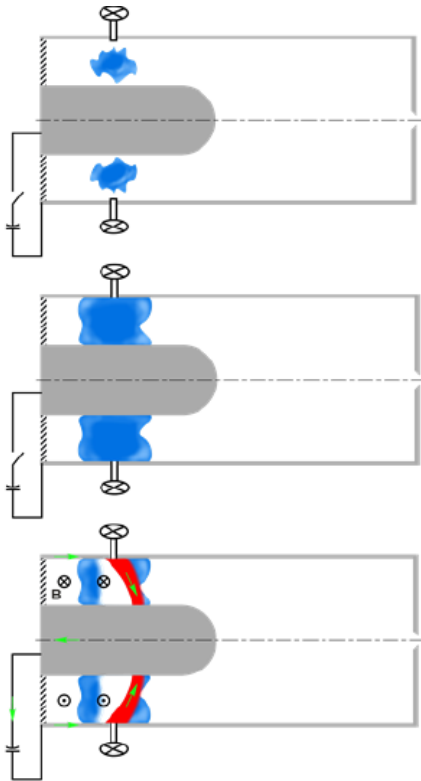
This truck-sized engine can power the grid using fuel that is easy to obtain and plentiful, its exhaust being ordinary helium gas. It's one of the safest and cleanest technologies around, and this is how it works



More Alternative Concepts (2/4)

➤ U. Washington – Shear-Flow Stabilized Z-Pinch

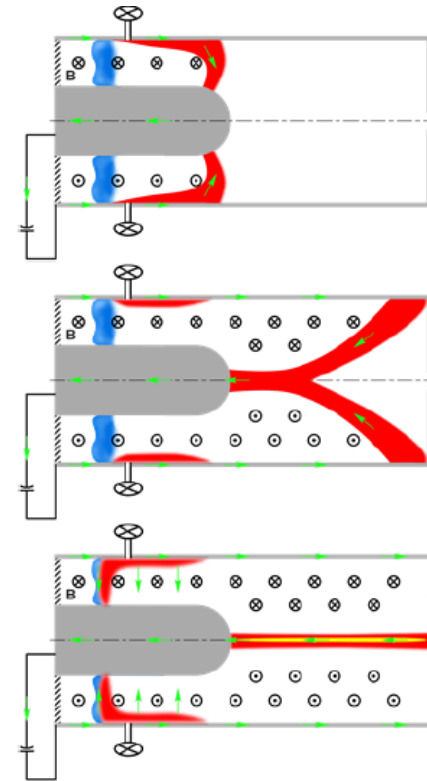
- <https://www.arpa-e.energy.gov/?q=slick-sheet-project/flow-z-pinch-fusion>
- http://www.iccworkshops.org/epr2016/uploads/417/nelson_epr16_zap_fuze_talk.pdf
- <http://plasma.physics.wisc.edu/uploadedfiles/journal/Shumlak928.pdf>
- **Similarities to Dense Plasma Focus**
- **Cooperation with Lawrence Livermore National Laboratory**



Gas is injected and capacitor is discharged.

Plasma accelerates down the coaxial accelerator until it assembles into a Z-pinch plasma along the axis.

Inertia and gun currents maintain the flowing plasma state until the accelerator plasma empties or current diminishes.



More Alternative Concepts (3/4)

➤ Dynamak Concept / University of Washington

- **Advanced Spheromak Concept**
- **Dynamo current drive.**
- <http://www.sciencedirect.com/science/article/pii/S0920379614002518>

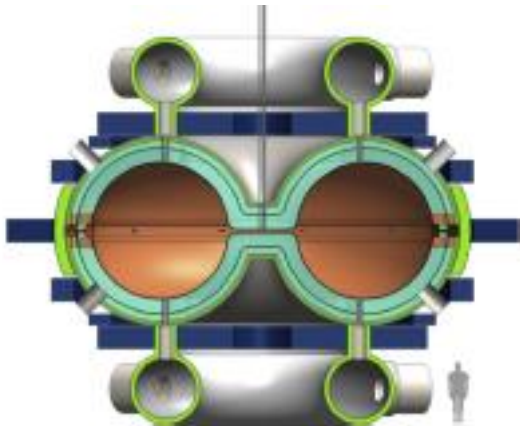


Fig. 1. A sliced rendering of the dynamak reactor concept, excluding the second: power conversion cycle.

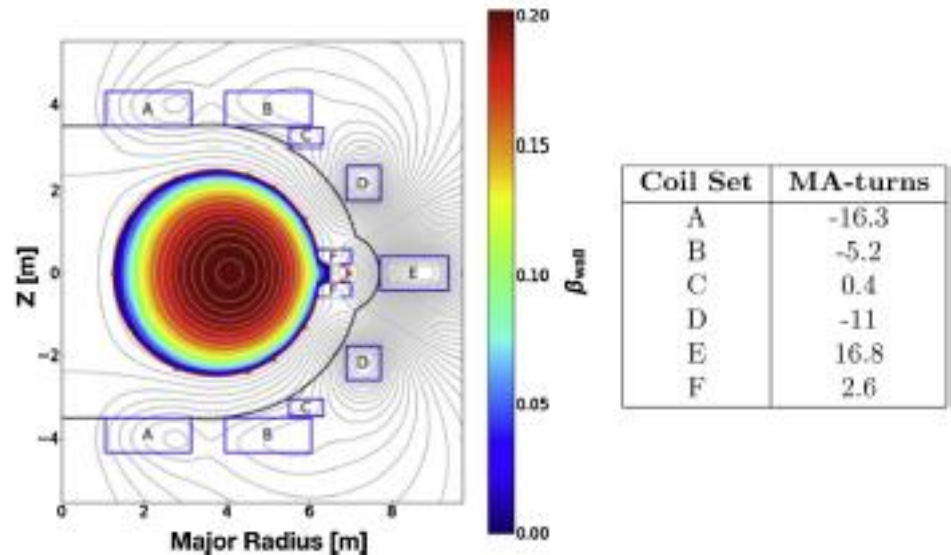


Fig. 2. Grad-Shafranov equilibrium with corresponding coil set and currents.

More Alternative Concepts (4/4)

➤ Plasma Liner Experiment (PLX)

- Los Alamos National Laboratory
- Magneto-inertial fusion (MIF) with plasma guns (Ar/Xe)
- Spherical imploding plasma liner on magnetized plasma target (DT)
- http://fire.pppl.gov/fpa10_LANL_Wurden.pdf
- <http://wsx.lanl.gov/talks/FPA2012-Fusion-Research-at-LANL-Wurden-talk.pdf>

