The Field-Reversed Configuration (FRC) as a Practical Fusion Reactor Core

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CAP Congress

June 4, 2019

Outline

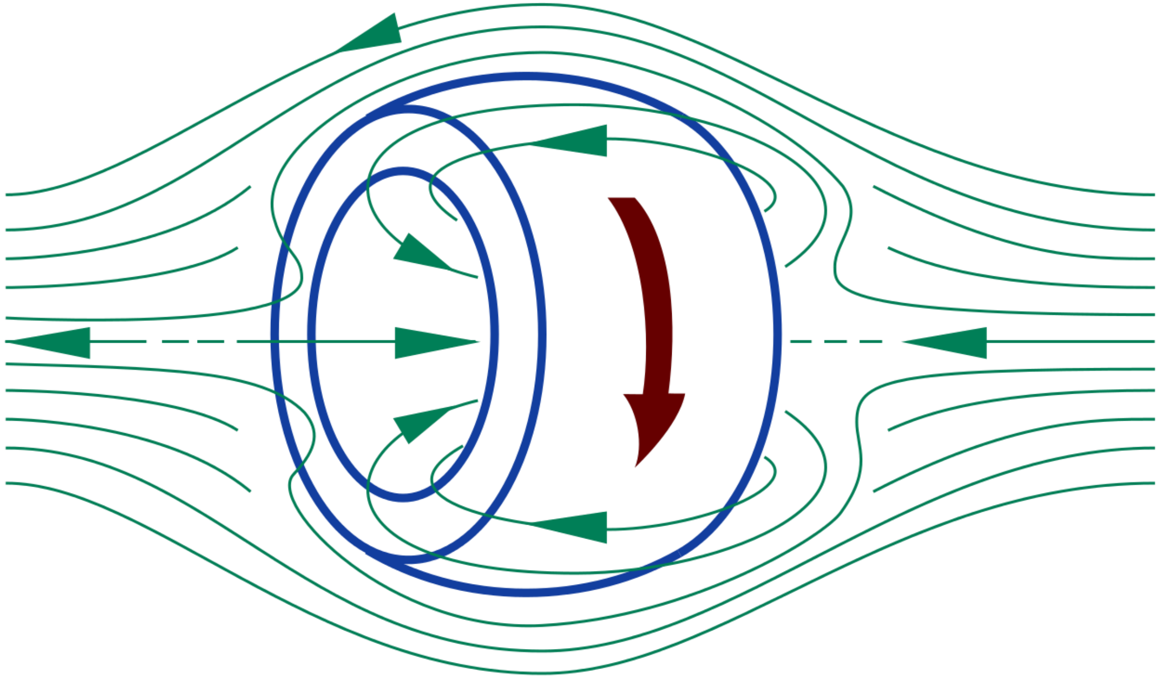


FIG: Conceptual drawing of the field-reversed configuration (FRC)

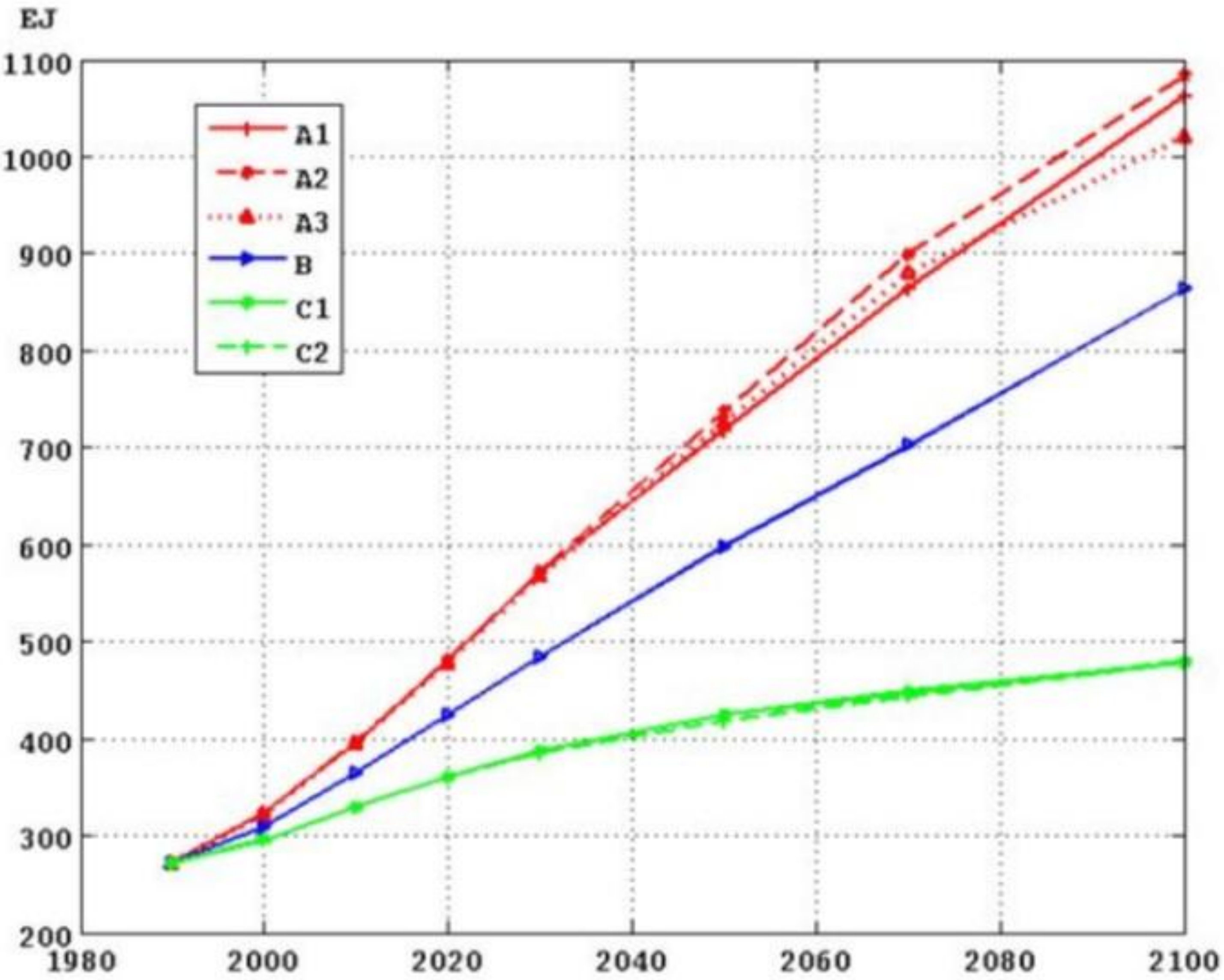
Topics to be discussed

- The case for fusion
- Basic fusion physics
- Basic FRC description
- Brief history of FRC research
- Technical benefits of the FRC
- Results from TAE
- Edge-biasing experiment
- Summary and conclusion

The case for fusion

The world needs energy

Global energy consumption until 2100. IIASA–WEC Study "Global Energy Perspectives"



Worst case

Realistic scenario
"Do nothing"

Best case
$\approx 2 \times$

Kikuchi, M., Lackner, K., and Tran, M. Q. (2012).

Traditional sources of energy

Fossil fuels are

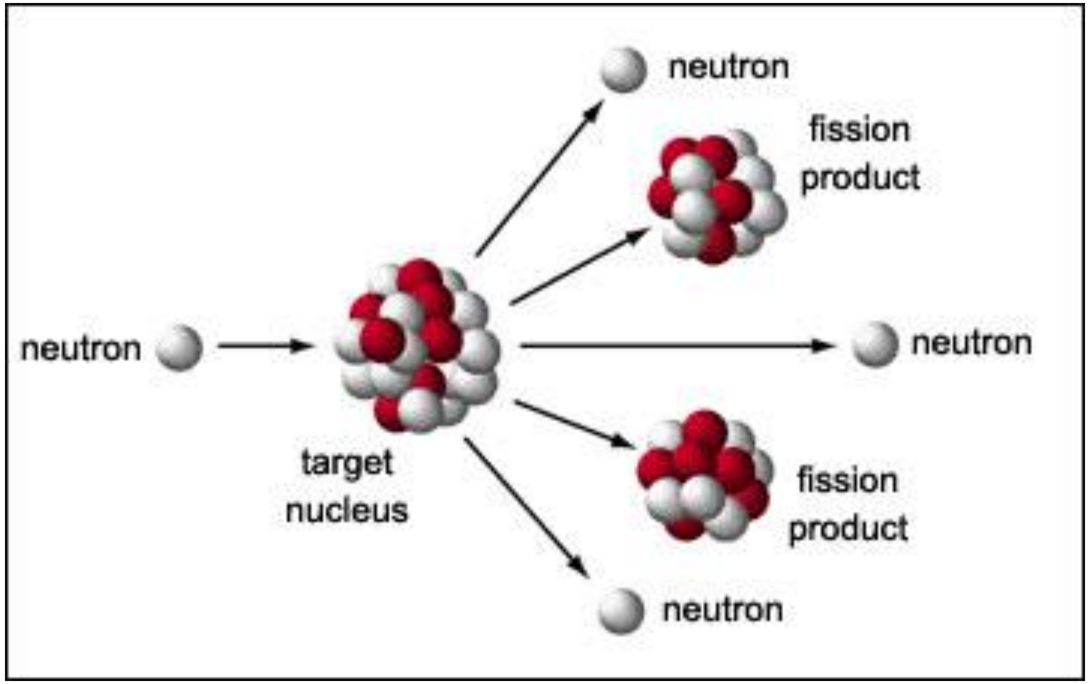
- In limited supply
- Polluting
- Geographically contested
- Archaic

Traditional sources of energy (cont'd.)

Solar and wind are

- Intermittent
- Low density

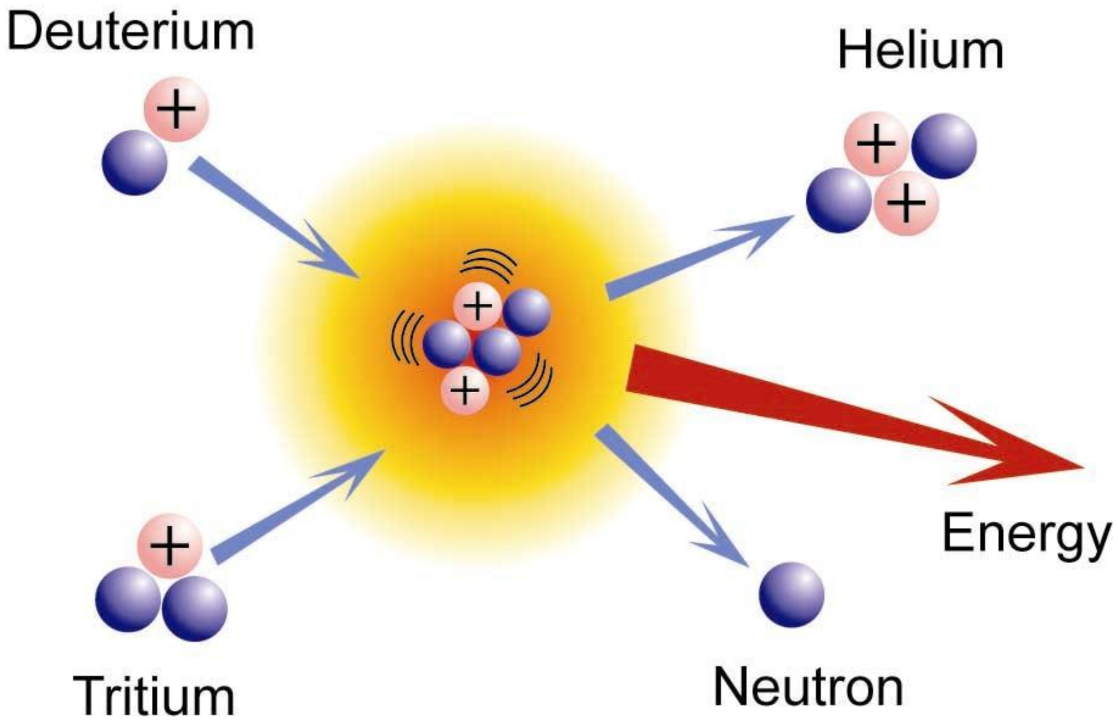
Traditional sources of energy (cont'd.)



Nuclear fission is dangerous

- Radioactive waste
- Meltdown scenarios
- Proliferation of weapons

Nuclear fusion

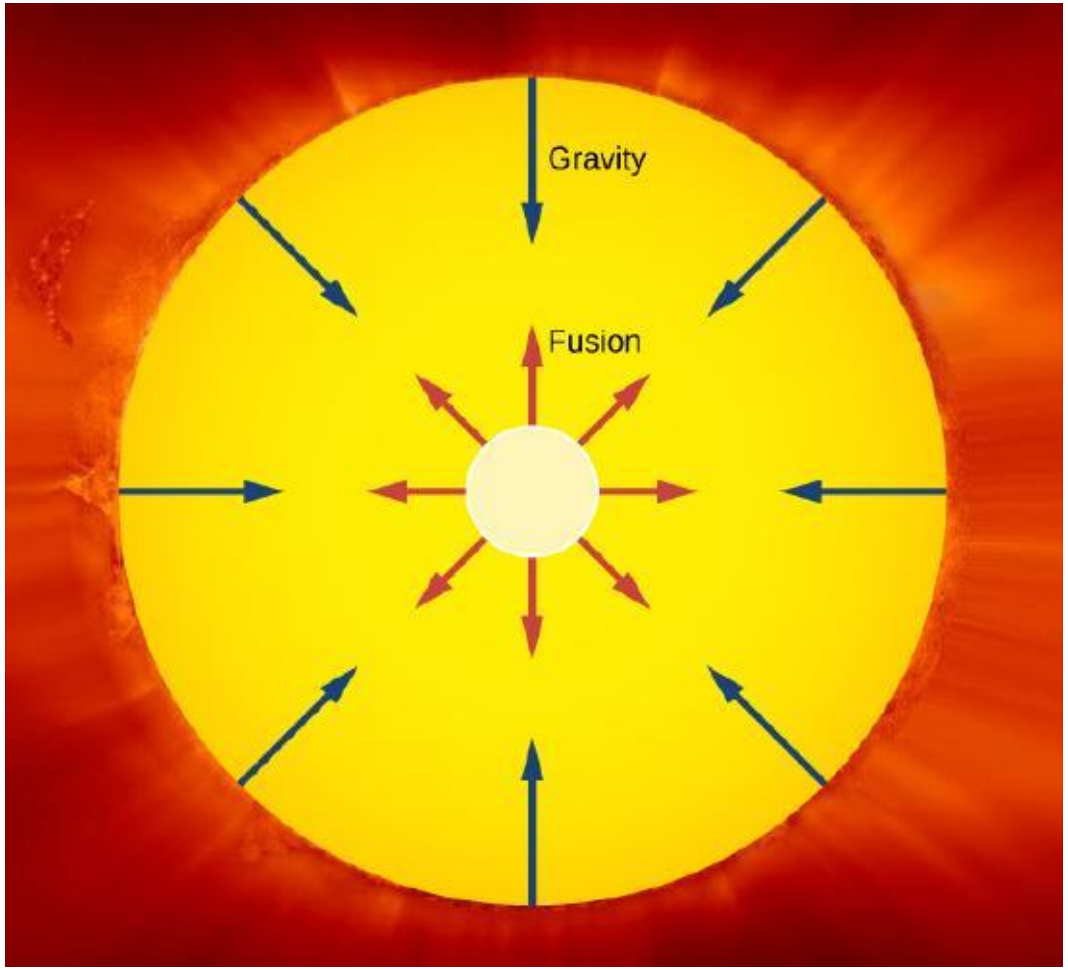


Benefits of nuclear fusion

- Energy dense
- Unlimited, low cost fuel supply
- No proliferation issues
- No possibility of meltdown
- No long-lived radioactive waste
- Thermal or direct energy conversion options

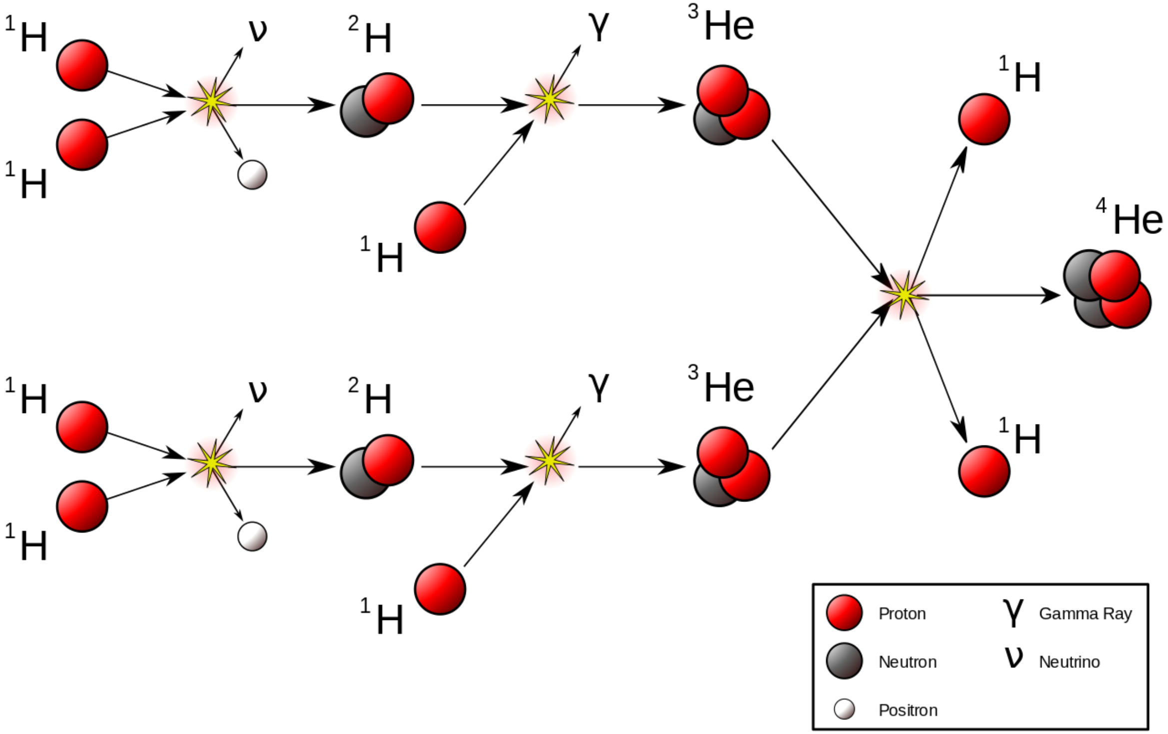
Basic fusion physics

Fusion in the sun



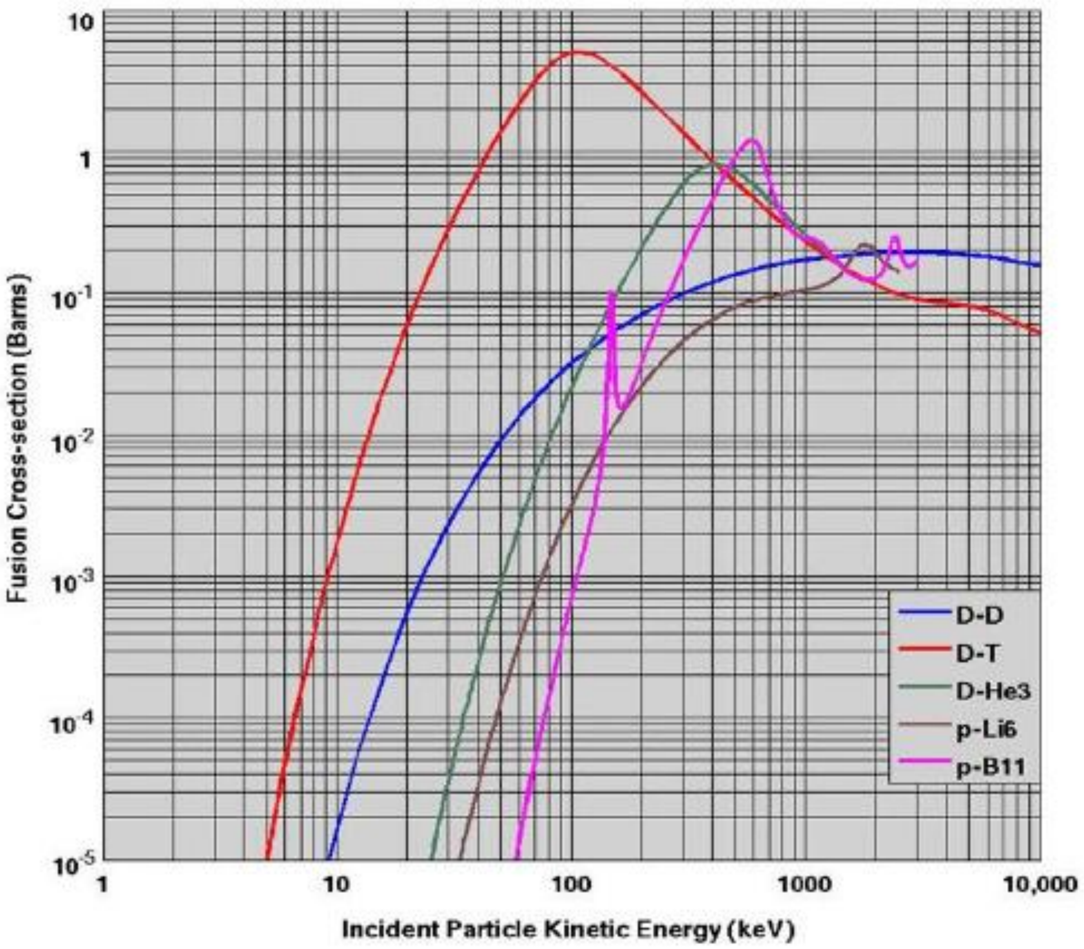
Proton-proton chain reaction

$$4p \rightarrow \ {}^{4}He + 2e^{+} + 2\nu_e$$



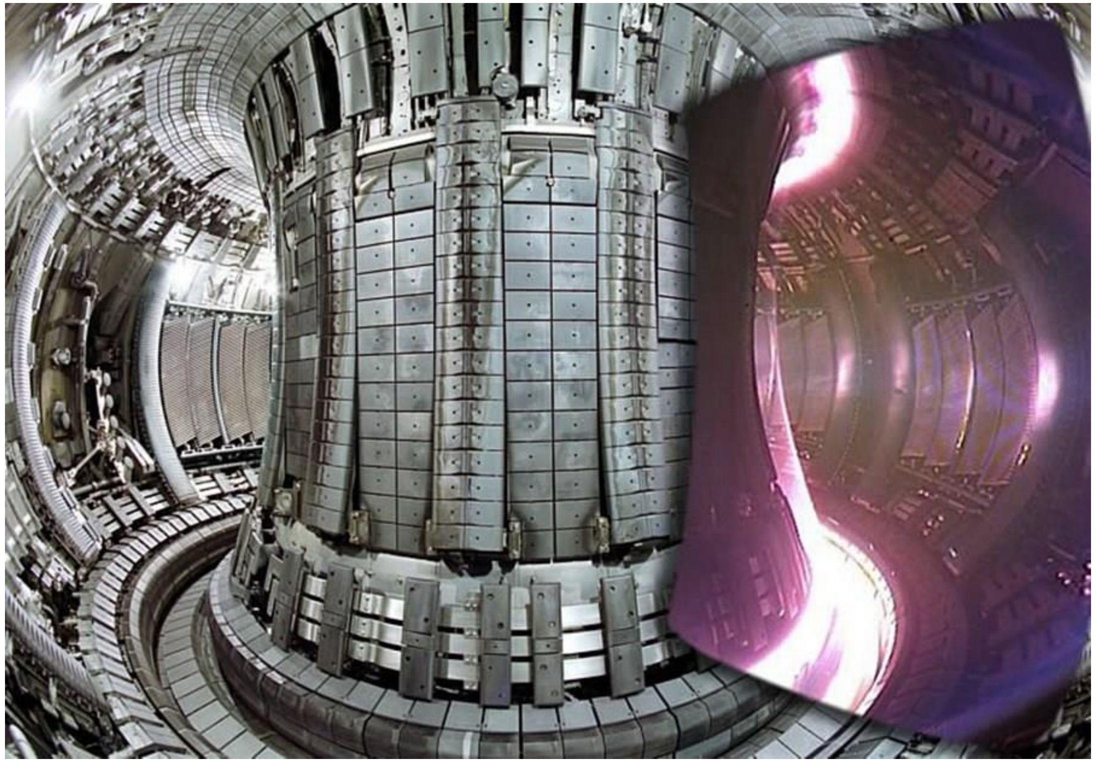
Fusion fuel

$$D + T \rightarrow \alpha + n + 17.6\,\text{MeV}$$
$$D + D \rightarrow {}^3\text{He} + n + 3.27\,\text{MeV}$$
$$D + D \rightarrow T + p + 4.05\,\text{MeV}$$
$$D + {}^3\text{He} \rightarrow \alpha + p + 18.34\,\text{MeV}$$
$$D + {}^6\text{Li} \rightarrow 2\alpha + 22.4\,\text{MeV}$$
$$p + {}^7\text{Li} \rightarrow 2\alpha + 17.2\,\text{MeV}$$
$$p + {}^6\text{Li} \rightarrow \alpha + {}^3\text{He} + 4.0\,\text{MeV}$$
$$p + {}^{11}\text{B} \rightarrow 3\alpha + 8.7\,\text{MeV}$$



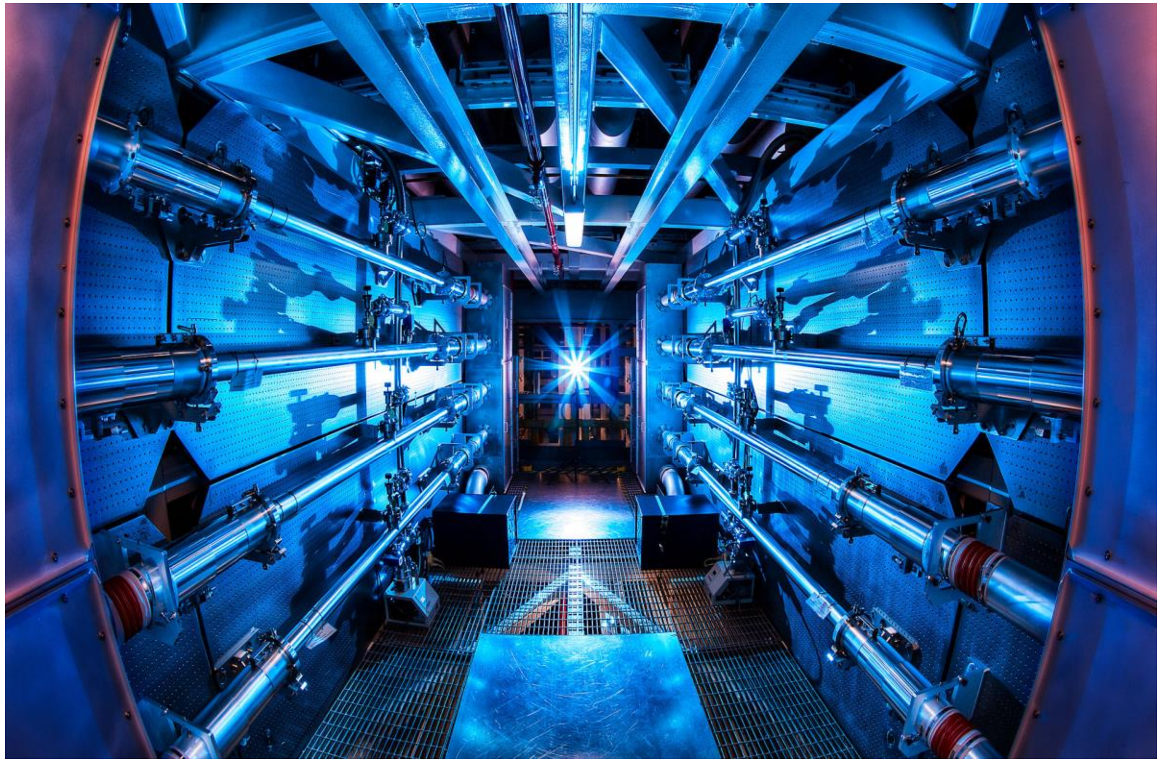
Kikuchi, M., Lackner, K., and Tran, M. Q. (2012).

Main approaches to fusion on Earth



https://www.iter.org/

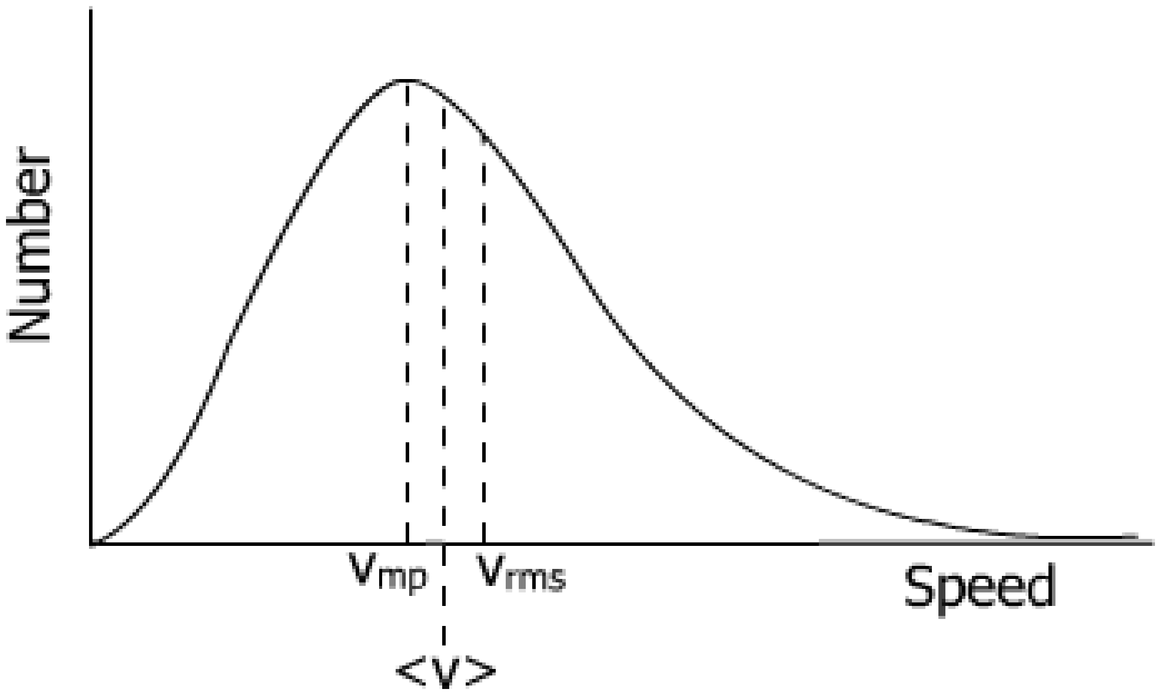
Magnetic confinement fusion

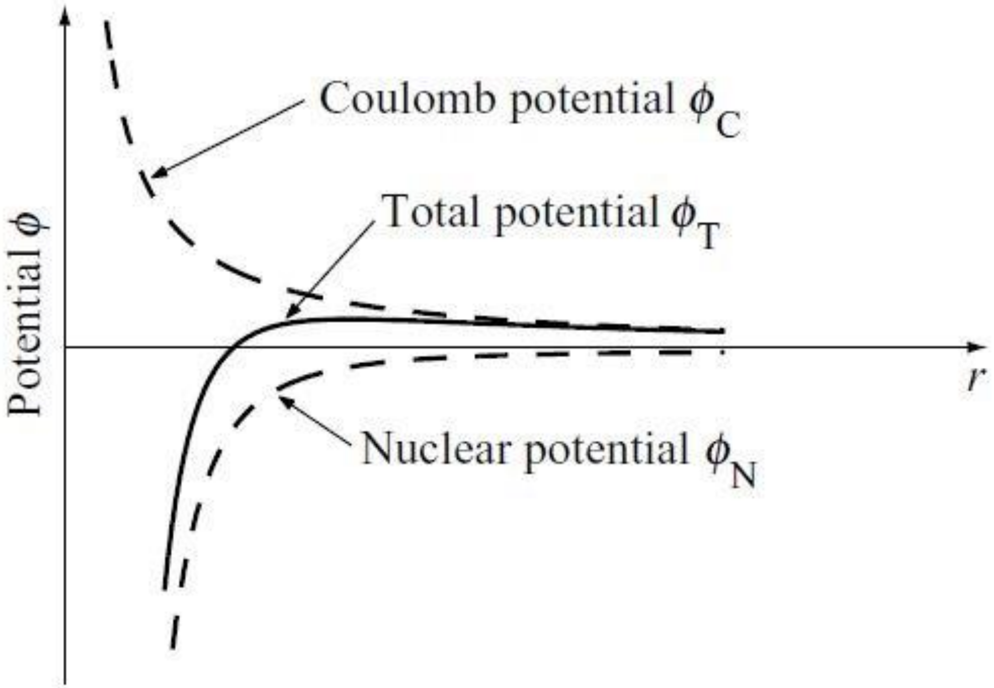


https://lasers.llnl.gov/

Inertial confinement fusion

Maxwell-Boltzmann and nuclear potential





Chen, F. F. Introduction to plasma physics and controlled fusion, volume 3. Springer, (2015).

Alternative approaches to fusion

- Magnetic confinement
  - Toroidal system
    - Axially symmetric
      - Tokamak
      - Reversed field pinch
      - Spheromak
    - Axially asymmetric
      - Stellarator system
      - Heliac
      - Bumpy torus
  - Open end system
    - Mirror, Tandem mirror
    - Field reversal configuration
    - Cusp
- Inertial confinement
  - Laser
  - Ion beam, Electron beam

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generalfusion

Chen, F. F. Introduction to plasma physics and controlled fusion, volume 3. Springer, (2015).

Basic FRC description

FRC formation and structure

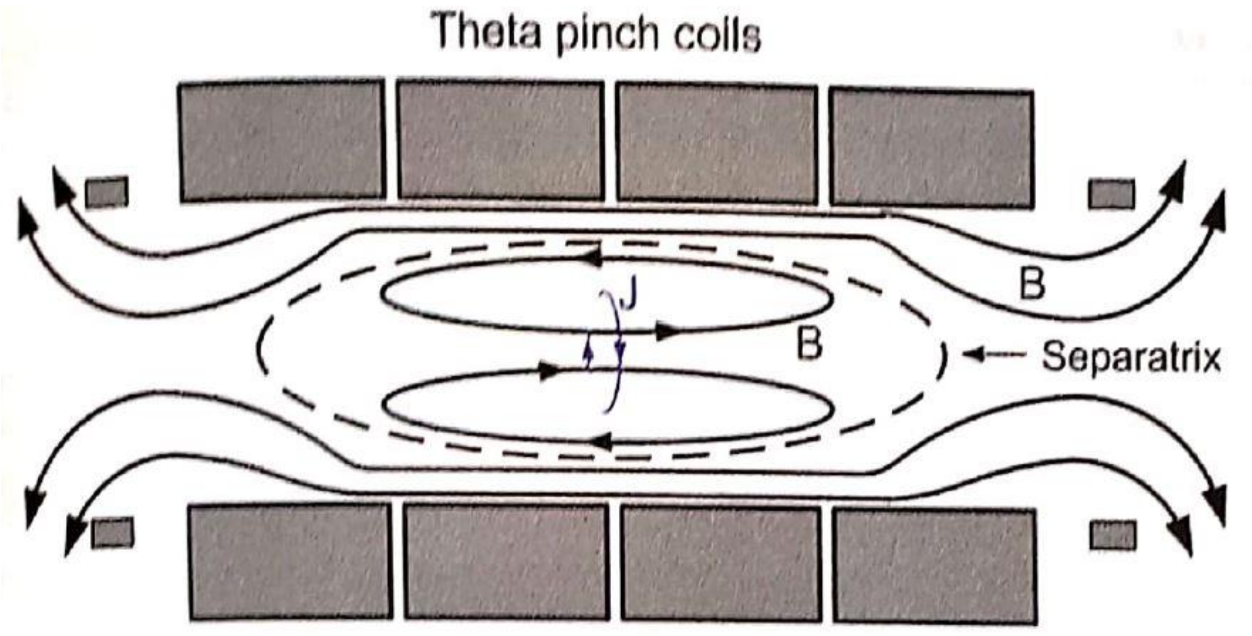


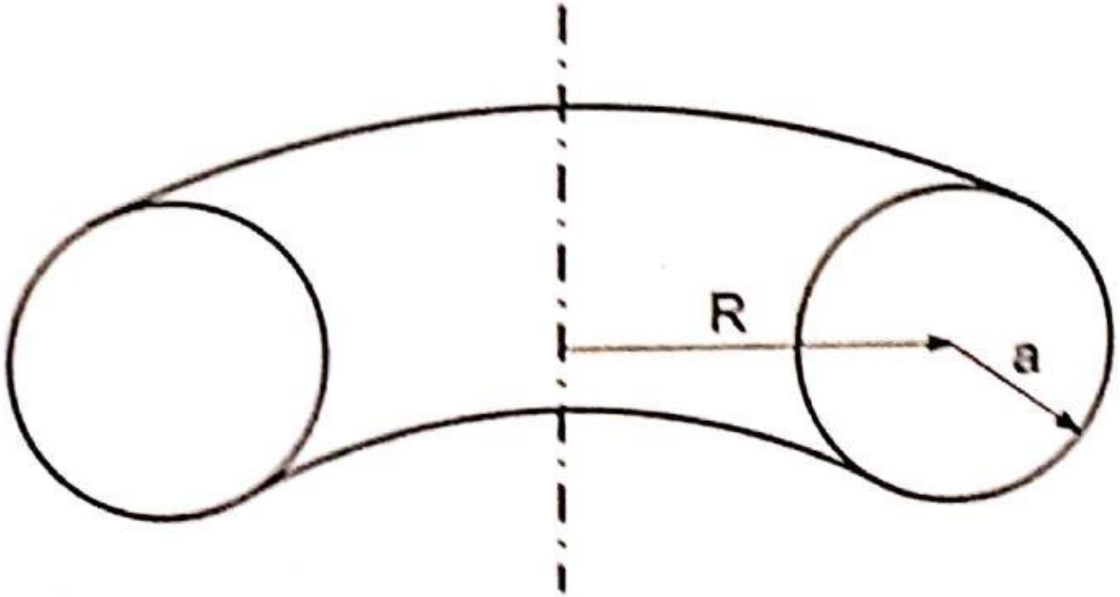
FIG: FRC formation in theta-pinch coils

Steps of theta-pinch formation

1. Pre-ionization
2. Field reversal
3. Radial compression and field line connection
4. Axial contraction
5. Equilibrium

Chen, F. F. Introduction to plasma physics and controlled fusion, volume 3. Springer, (2015).

Compact toroid



$$Aspect\ ratio = \frac{R}{a}$$

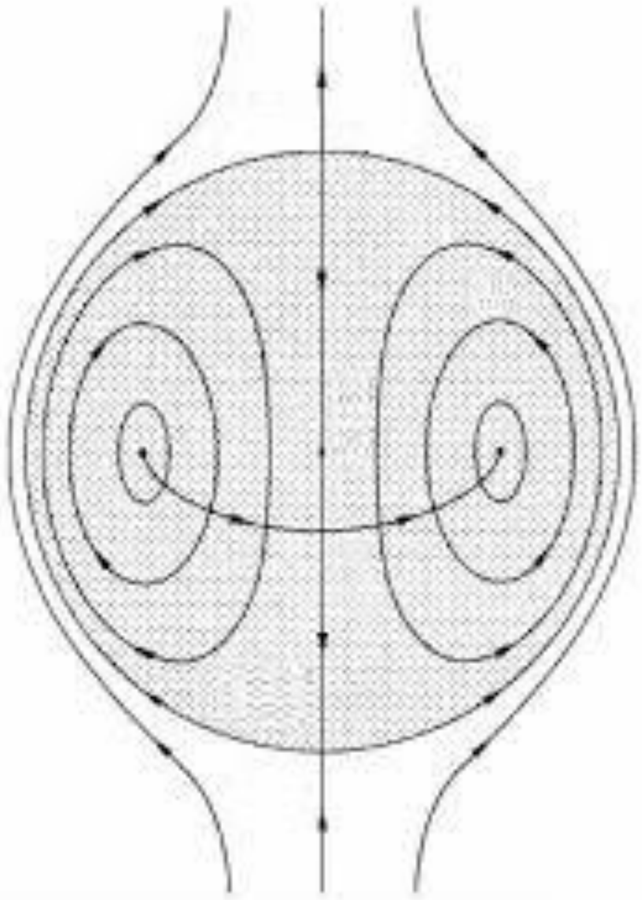


FIG: Schematic diagram of a spheromak

Chen, F. F. Introduction to plasma physics and controlled fusion, volume 3. Springer, (2015).

Comparison to Tokamak and Stellarator

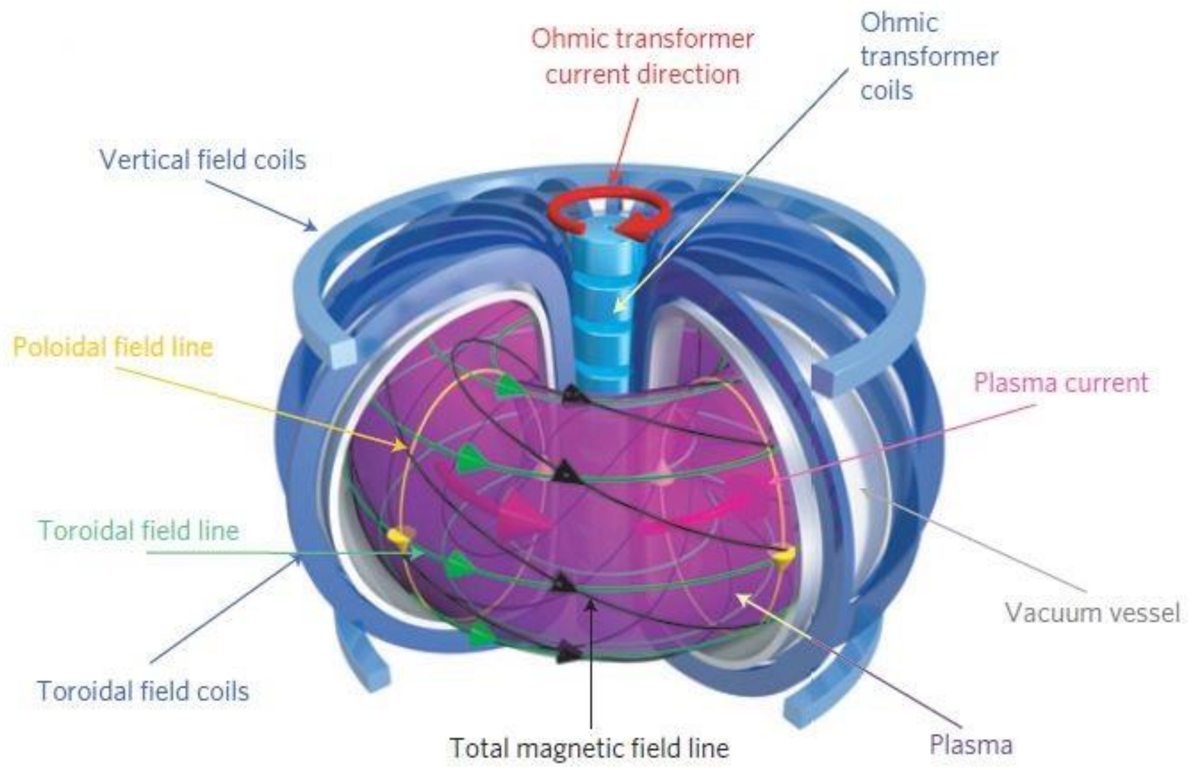


FIG: Artist rendering of the ITER tokamak

FIG: Artist rendering of Wendelstein-7x stellarator

Ongena, J., Koch, R., Wolf, R., and Zohm, H. Nature Physics **12**, 398 EP – May (2016).

Brief history of FRC research

Early FRC research era

Pioneering experiments

FIELD MIXING AND ASSOCIATED NEUTRON PRODUCTION IN A PLASMA*

A. C. Kolb and C. B. Dobbie
United States Naval Research Laboratory, Washington, D. C.

Field-reversed experiments (FRX) on compact toroids

W. T. Armstrong, R. K. Linford, J. Lipson, D. A. Platts, and E. G. Sherwood

Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545
(Received 9 June 1980; accepted 12 August 1981)

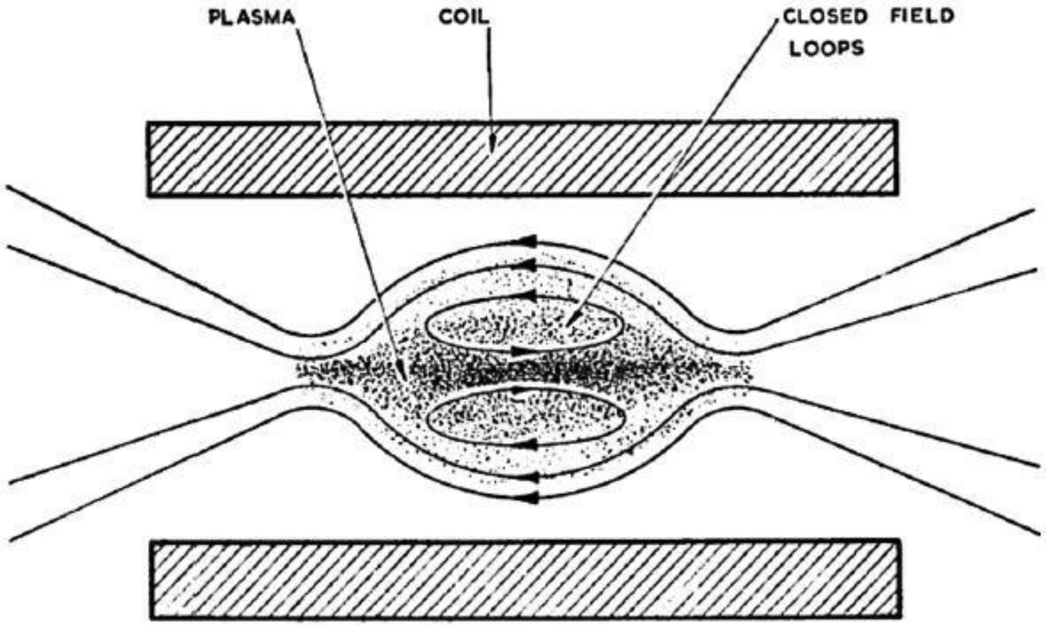


FIG: Early FRC schematic

Early FRC research era (cont'd.)

Mitigation of the rotational instability

THE ORIGIN OF ROTATION IN FIELD-REVERSED CONFIGURATIONS+

D.S. HARNED*, D.W. HEWETT**
Los Alamos National Laboratory,
Los Alamos, New Mexico,
United States of America

Quadrupole Stabilization of the $n=2$ Rotational Instability of a Field-Reversed Theta-Pinch Plasma

S. Ohi, T. Minato, Y. Kawakami, M. Tanjyo, S. Okada, Y. Ito, M. Kako, S. Gotô, T. Ishimura, and H. Itô
Plasma Physics Laboratory, Faculty of Engineering, Osaka University, Suita, Osaka 565, Japan
(Received 28 February 1983)

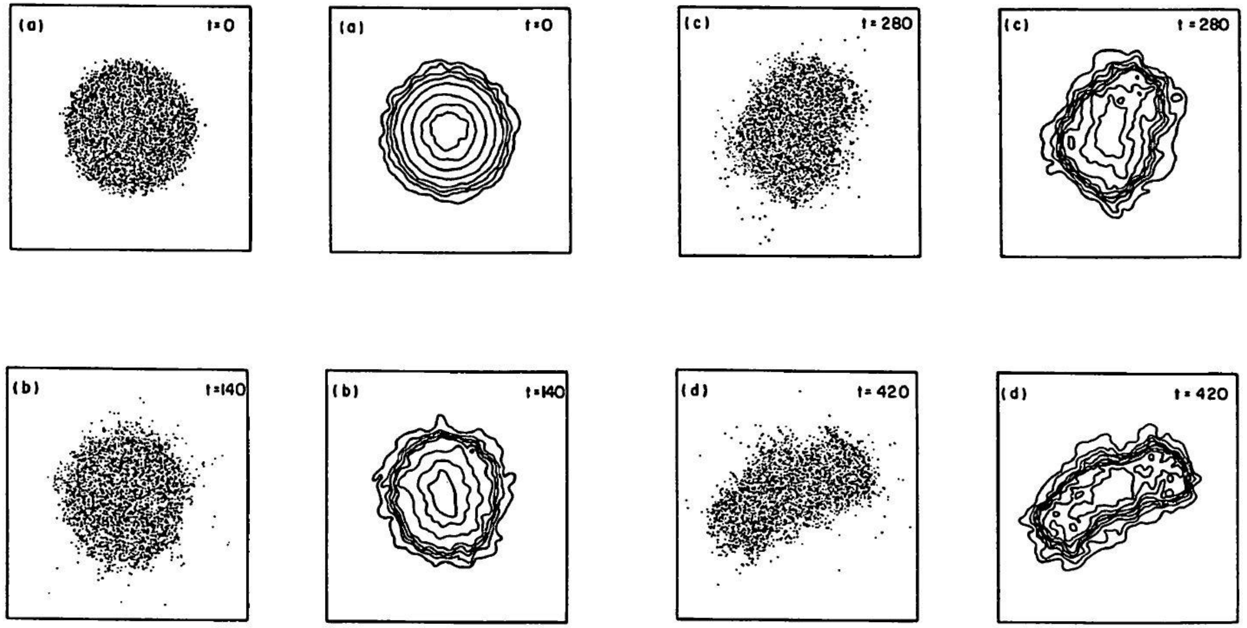


FIG: Elliptical deformation of FRC due to onset of rotational instability

Modern FRC research era

FIELD REVERSED CONFIGURATIONS

M. TUSZEWSKI
Los Alamos National Laboratory,
University of California,
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United States of America

Review of field-reversed configurations

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Department of Aeronautics and Astronautics, University of Washington, Seattle, Washington 98195, USA

(Received 15 March 2011; accepted 11 May 2011; published online 26 July 2011)

Facility	Type	Institution
Tokyo Spheromak-3		
TS-3	merging-spheromak	Univ. Tokyo
Nihon University Compact Torus Experiment-III		
NUCTE-III	θ-pinch	Nihon Univ.
*FRC Injection eXperiment**		
FIX	translation-trapping	Osaka Univ.
Magnetic Reconnection eXperiment		
MRX	spheromak merging	Princeton Plasma Phys. Lab.
*Translation Confinement Sustainment**		
TCS	rotating magnetic fields	Univ. Washington
Swarthmore Spheromak eXperiment		
SSX	merging-spheromak	Swarthmore Coll.
Field-Reversed eXperiment-Liner		
FRX-L	θ-pinch	Los Alamos Natl. Lab.
Tokyo Spheromak-4		
TS-4	merging-spheromak	Univ. Tokyo
*Translation Confinement Sustainment-Upgrade**		
TCS-U	rotating magnetic fields	Univ. Washington
Princeton Field Reverse eXperiment		
PFRC	rotating magnetic fields	Princeton Plasma Phys. Lab.
Plasma Liner Compression		
PLC	translation-trapping	Mathematical Sci. Northwest
Inductive Plasma Accelerator		
IPA	collision-merging	Mathematical Sci. Northwest
Colorado	spheromak merging	Univ. Colorado
Irvine Field-Reversed Configuration		
IFRC	coaxial source	Univ. California Irvine
C-2	collision-merging	Tri Alpha Energy

Modern FRC research era (cont'd.)

2018 US – Japan Workshop on Compact Tori:

Improved confinement and novel applications of compact tori

Nov. 2nd – 4th, 2018
Hosted by CTFusion at the
Crowne Plaza Portland-Downtown Convention Center Hotel
1441 NE 2nd Avenue, Portland, Oregon, 97232, United States of America

Program Committee:

Michiaki Inomoto, Professor
The University of Tokyo

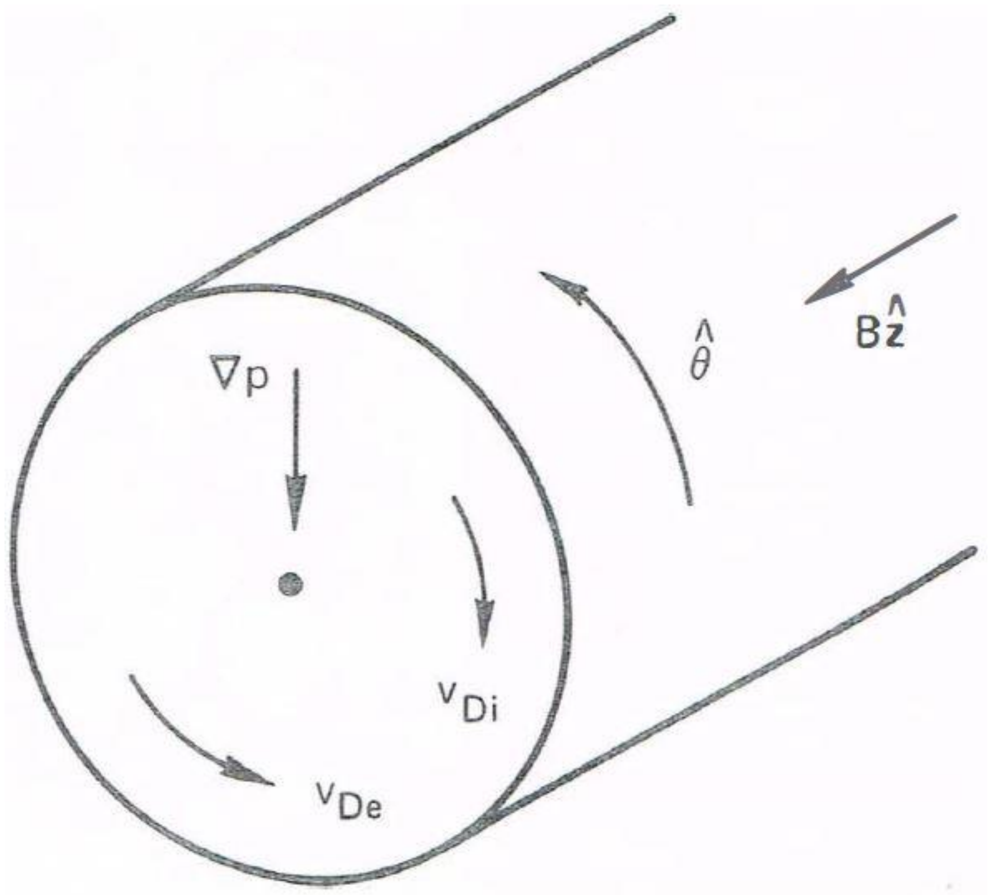
Thomas Jarboe, Professor
University of Washington

Local Organizer:

Aaron Hossack, Chief Technology Officer,
CTFusion, ahossack@ctfusion.net

Technical benefits of the FRC

Simple linear geometry



Physics of FRC geometry

- Axial magnetic field
- Radial pressure gradient
- Azimuthal plasma rotation

$$v_{\perp} = \frac{E \times B}{B^2} - \frac{\nabla p \times B}{qnB^2}\ \hat{\theta}$$

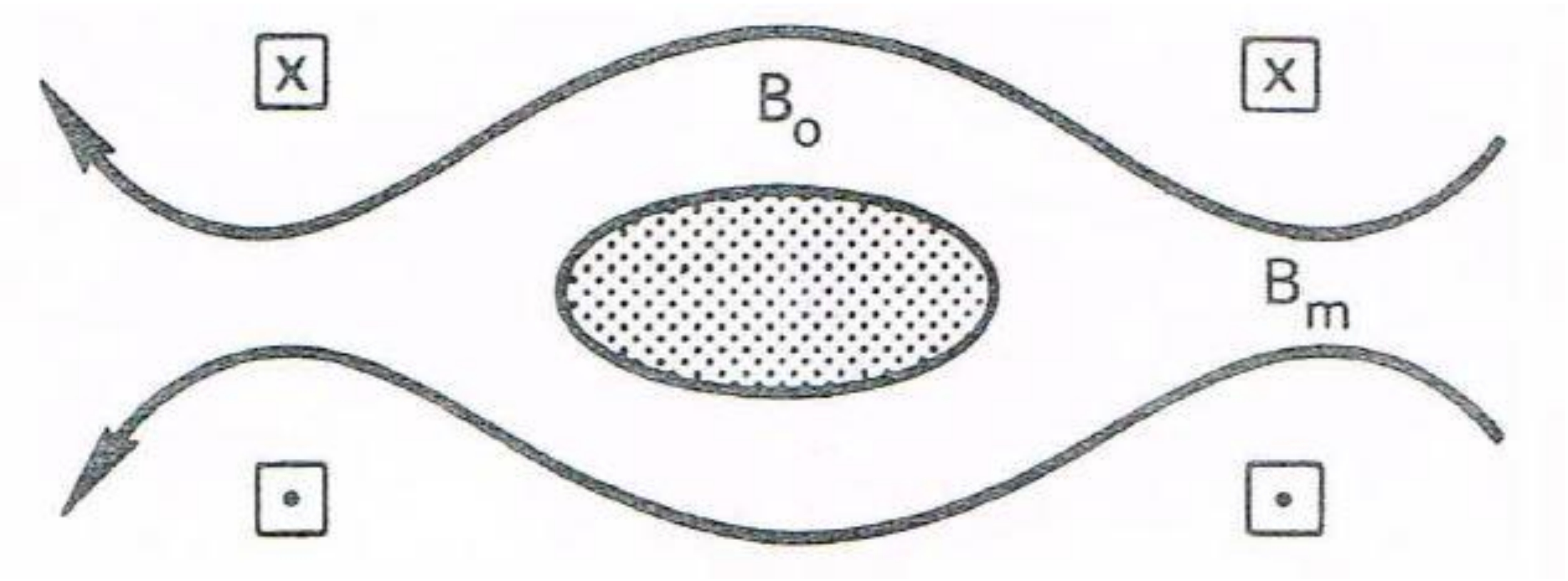
- Diamagnetic current

$$j_D = ne\left(v_{D_i} - v_{D_e}\right)$$

Chen, F. F. Introduction to plasma physics and controlled fusion, volume 3. Springer, (2015).

Simple magnetic topology

Magnetic mirrors



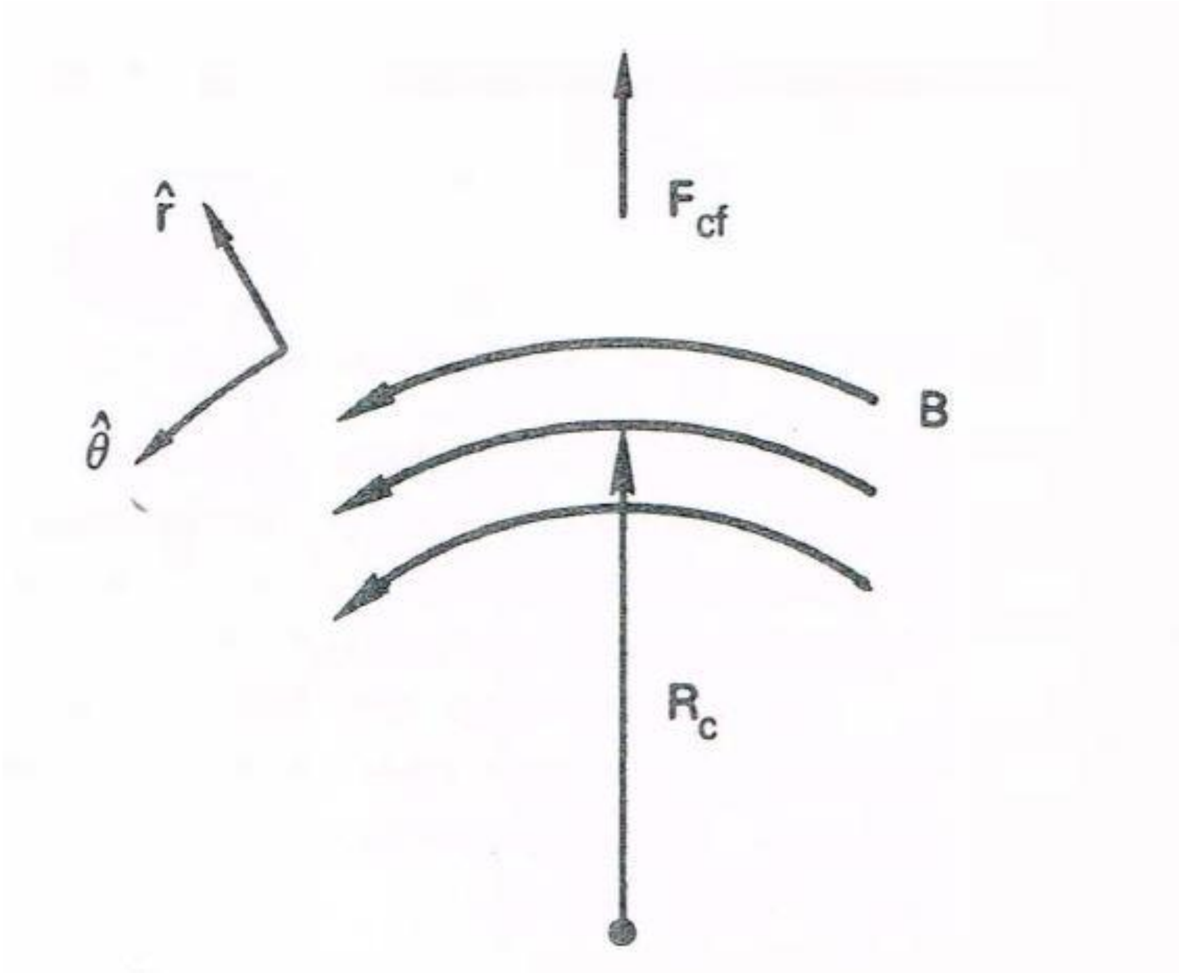
Grad-B drift

$$v_{\nabla B} = \pm \frac{1}{2} v_\perp r_L \frac{B \times \nabla B}{B^2}$$

Chen, F. F. Introduction to plasma physics and controlled fusion, volume 3. Springer, (2015).

Simple magnetic topology

Curvature drift



Curved vacuum field

$$v_R + v_{\nabla B} = \frac{m}{q}\left(v_\parallel^2 + \frac{1}{2}v_\perp^2\right)\frac{R_c \times B}{R_c^2 B^2}$$

- Not present in FRCs
- Causes reactor damage in tokamaks
- Complex stellarator field coils

Chen, F. F. Introduction to plasma physics and controlled fusion, volume 3. Springer, (2015).

High plasma pressure

Fuel	Z	E_{fus} [MeV]	E_{ch} [MeV]	Neutronicity
D-T	1	17.6	3.5	0.80
D-D	1	12.5	4.2	0.66
D-^{3}He	2	18.3	18.3	~ 0.05
p-^{11}B	5	8.7	8.7	~ 0.001

FRC magnetic efficiency

- Low magnetic field strength, $\sim 1T$
- High beta

$$\beta = \frac{nk_BT}{B^2/2\mu_0} \sim 1$$

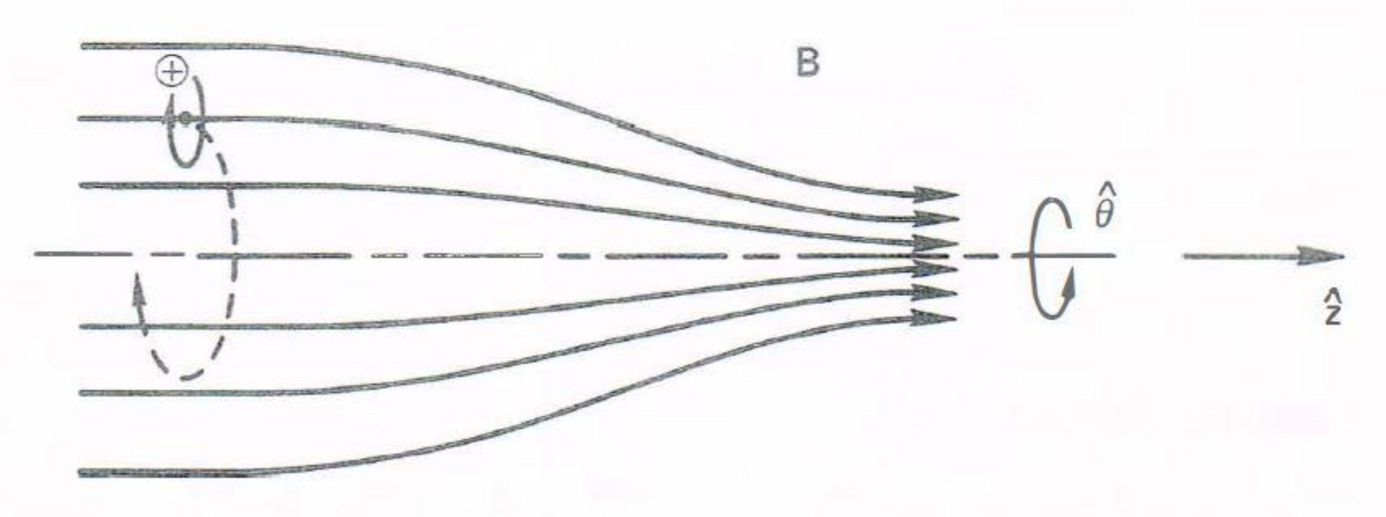
- Large temperatures per unit magnetic field
- Aneutronic fusion capable!

$$p + {}^{11}B \rightarrow 3\alpha$$

Chen, F. F. Introduction to plasma physics and controlled fusion, volume 3. Springer, (2015).

Natural Diverter

Particle extraction and direct energy conversion



Particle extraction and direct energy conversion

- Particles follow open magnetic field lines
- Electrodes at the diverters can collect charged fusion products
- Electricity can be generated directly from ionic flow in plasma

Chen, F. F. Introduction to plasma physics and controlled fusion, volume 3. Springer, (2015).

Translation

Gradient magnetic fields

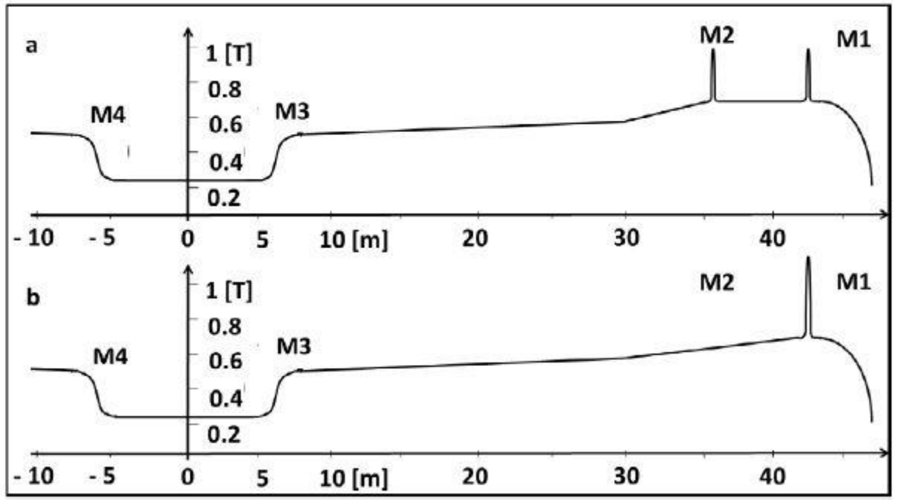


FIG: Magnetic field gradient and mirror coils

Translation trapping

- Translated by magnetic field gradients
- Confined by magnetic mirrors
- Kinetic to thermal energy conversion

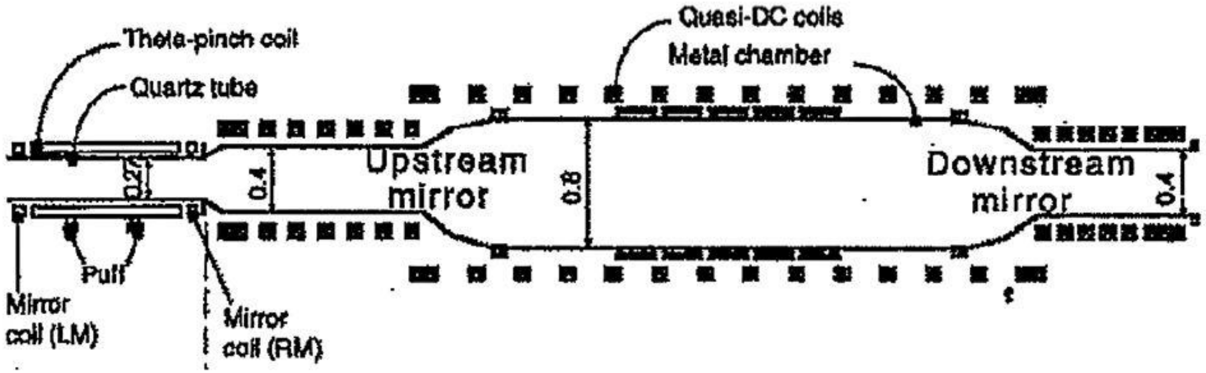
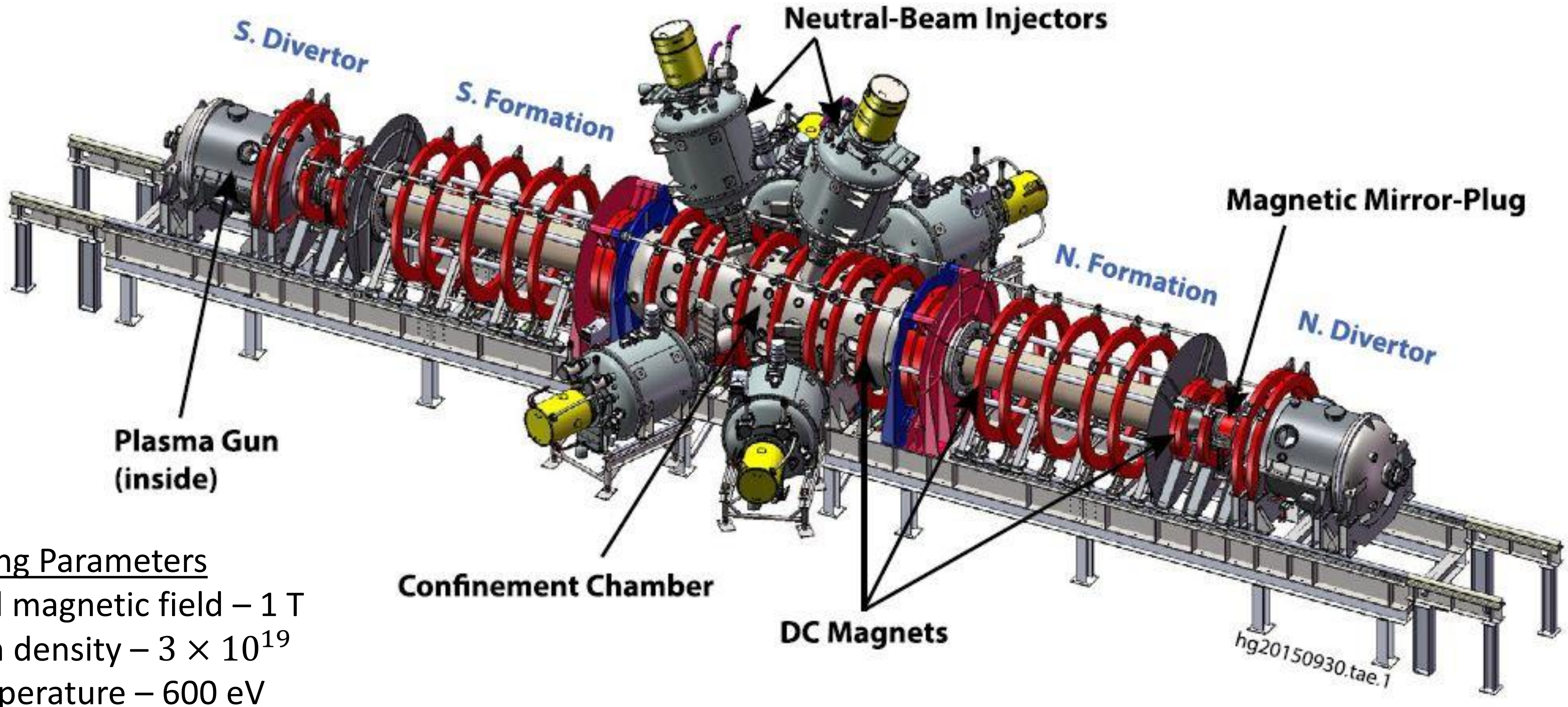


FIG: Early translation trapping experiment

Results from TAE

Tri Alpha Energy

C-2U confinement chamber



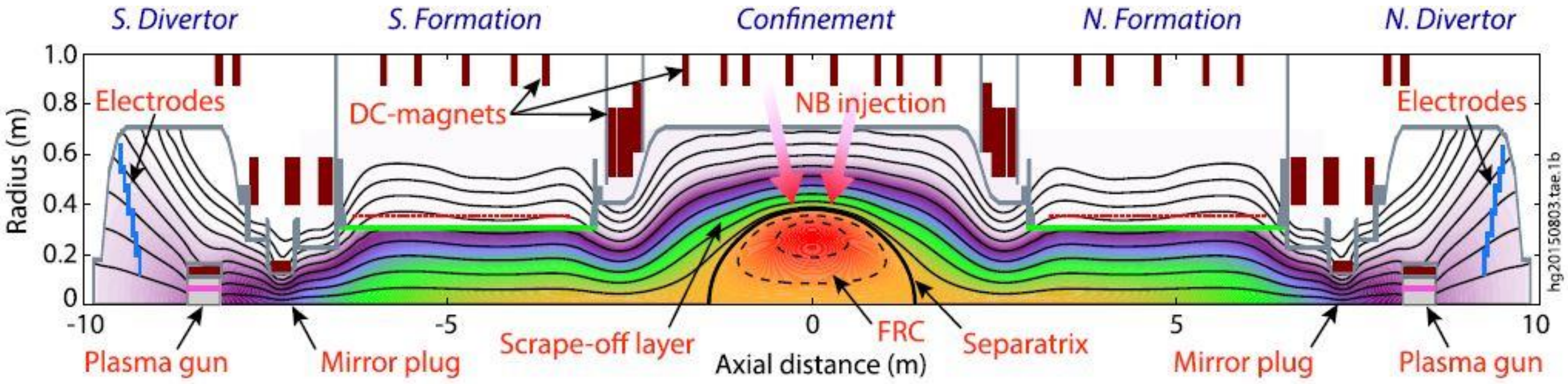
<u>Operating Parameters</u>
External magnetic field – 1 T
Electron density – 3×10^{19}
Ion temperature – 600 eV
Electron temperature – 150 eV

75 ft x 35 ft x 25 ft

Binderbauer, et al. Physics of Plasmas 22(5), 056110 (2015).

Tri Alpha Energy (cont'd.)

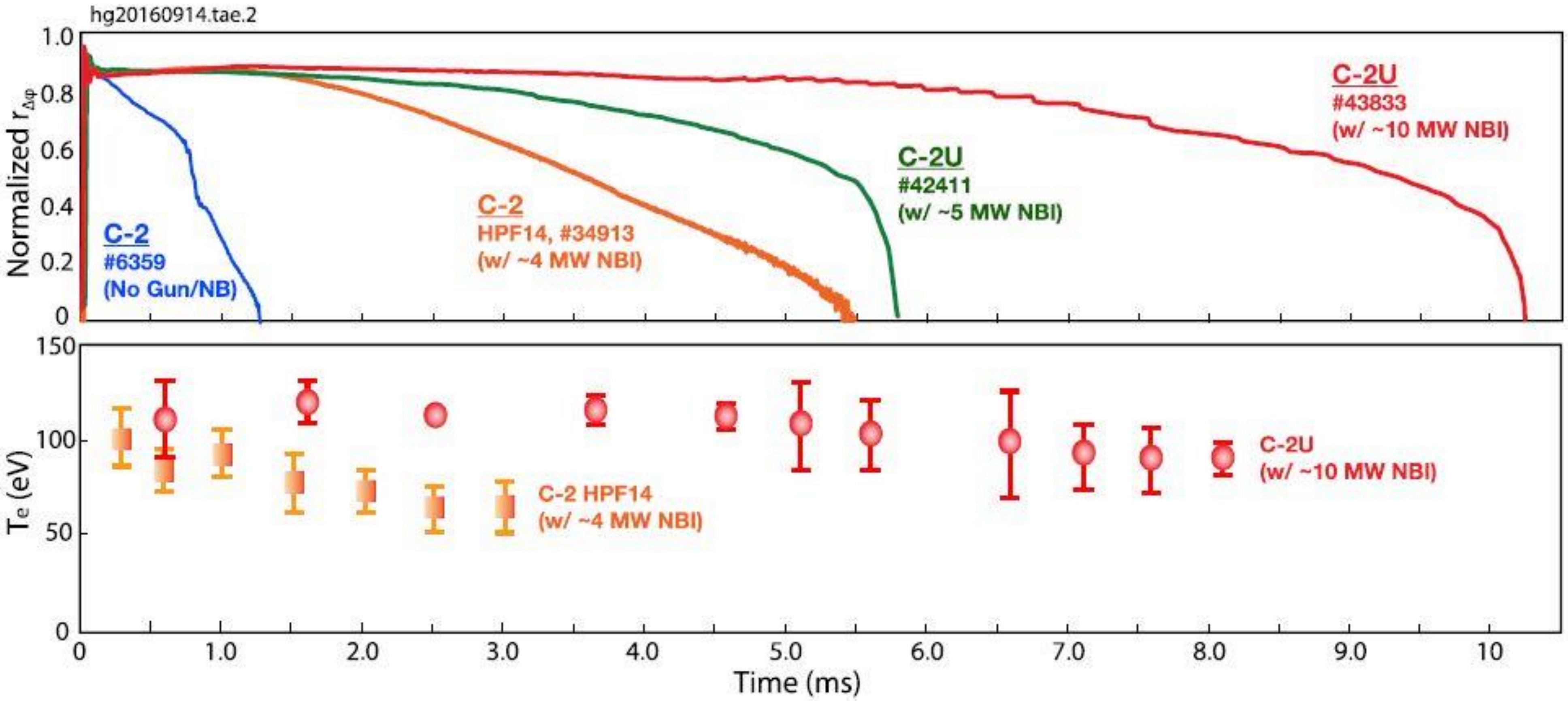
FRC formation by collisional merging



Binderbauer, et al. Physics of Plasmas 22(5), 056110 (2015).

High performance FRC

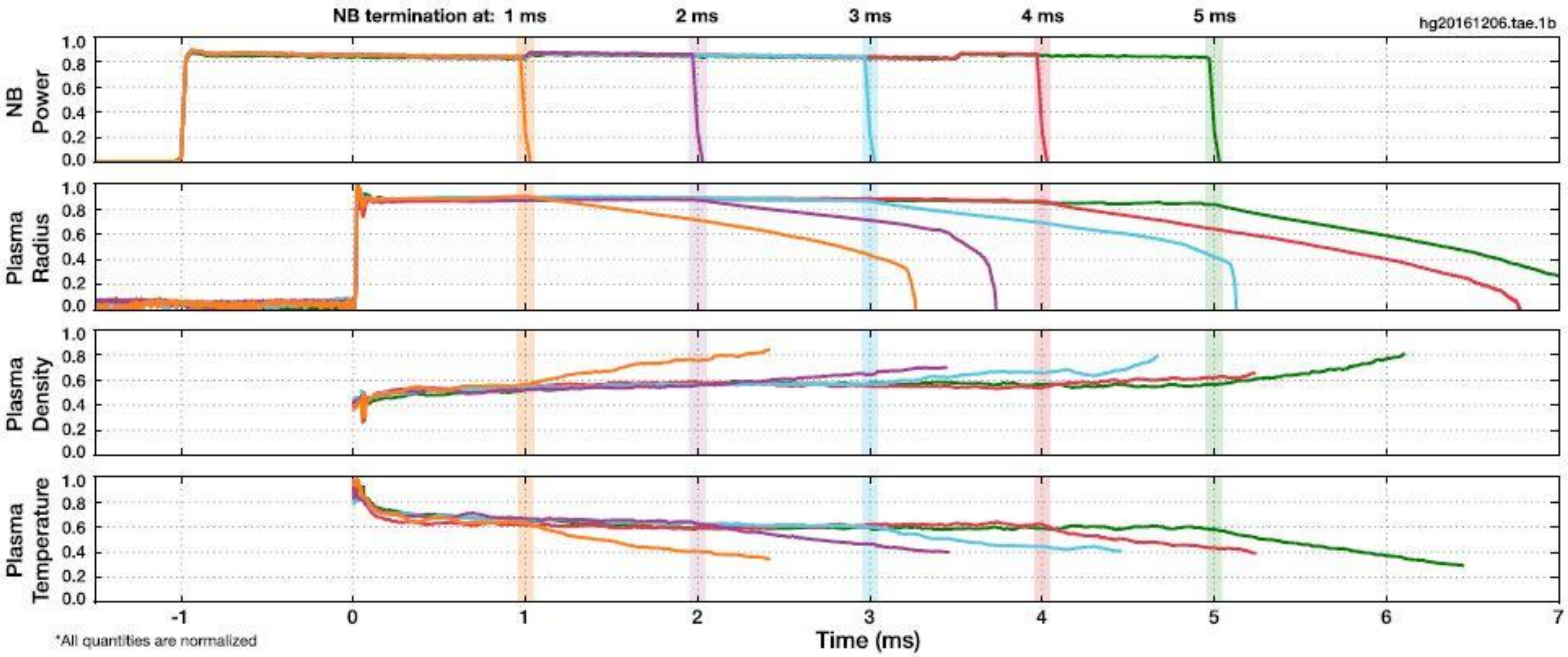
Record FRC confinement



Binderbauer, et al. Physics of Plasmas 22(5), 056110 (2015).

High performance FRC

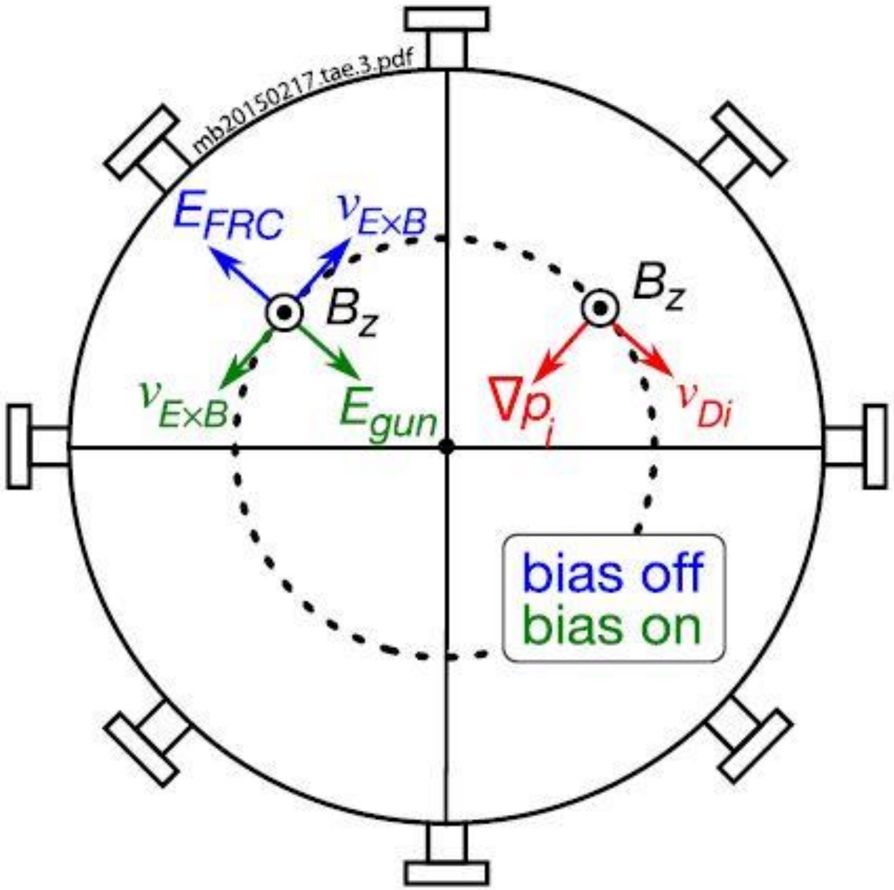
Correlation with neutral beam power



Binderbauer, et al. Physics of Plasmas 22(5), 056110 (2015).

Role of edge-biasing

Fluid drifts



Binderbauer, et al. Physics of Plasmas 22(5), 056110 (2015).

Role of edge-biasing

Mitigation of rotational instability

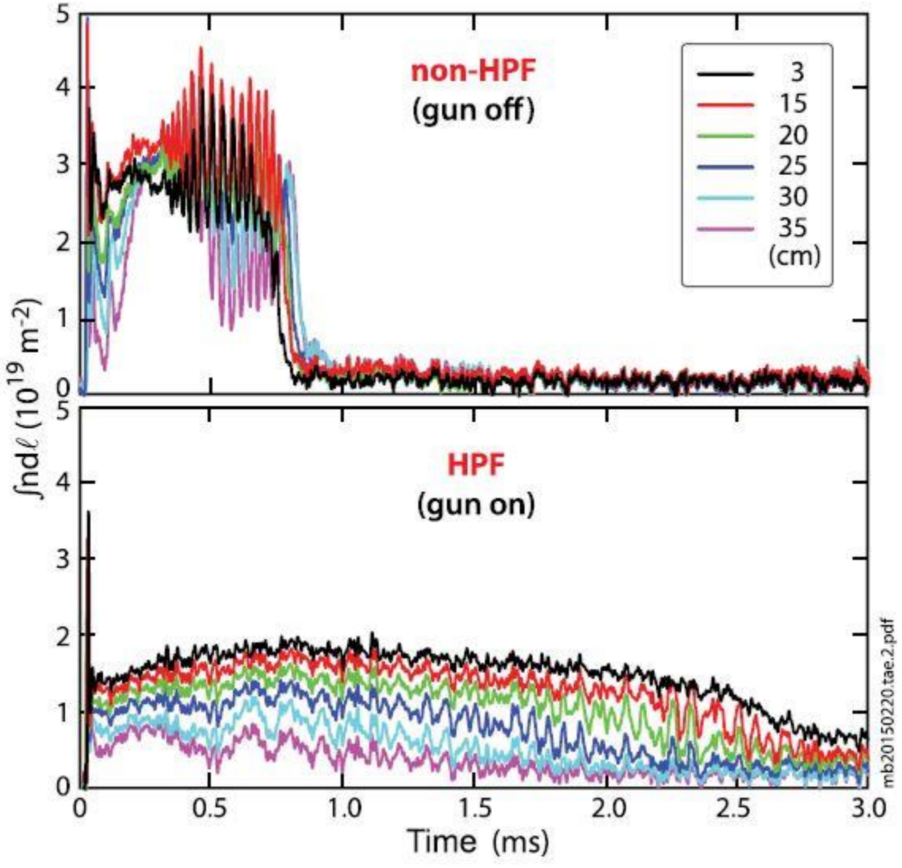


FIG: Measurement of line-integrated density

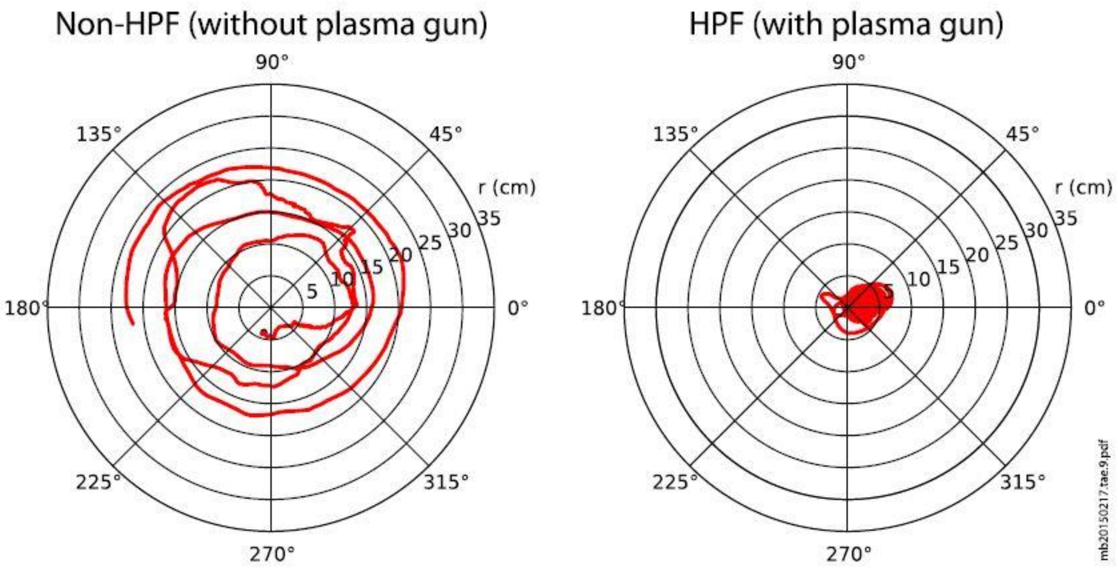


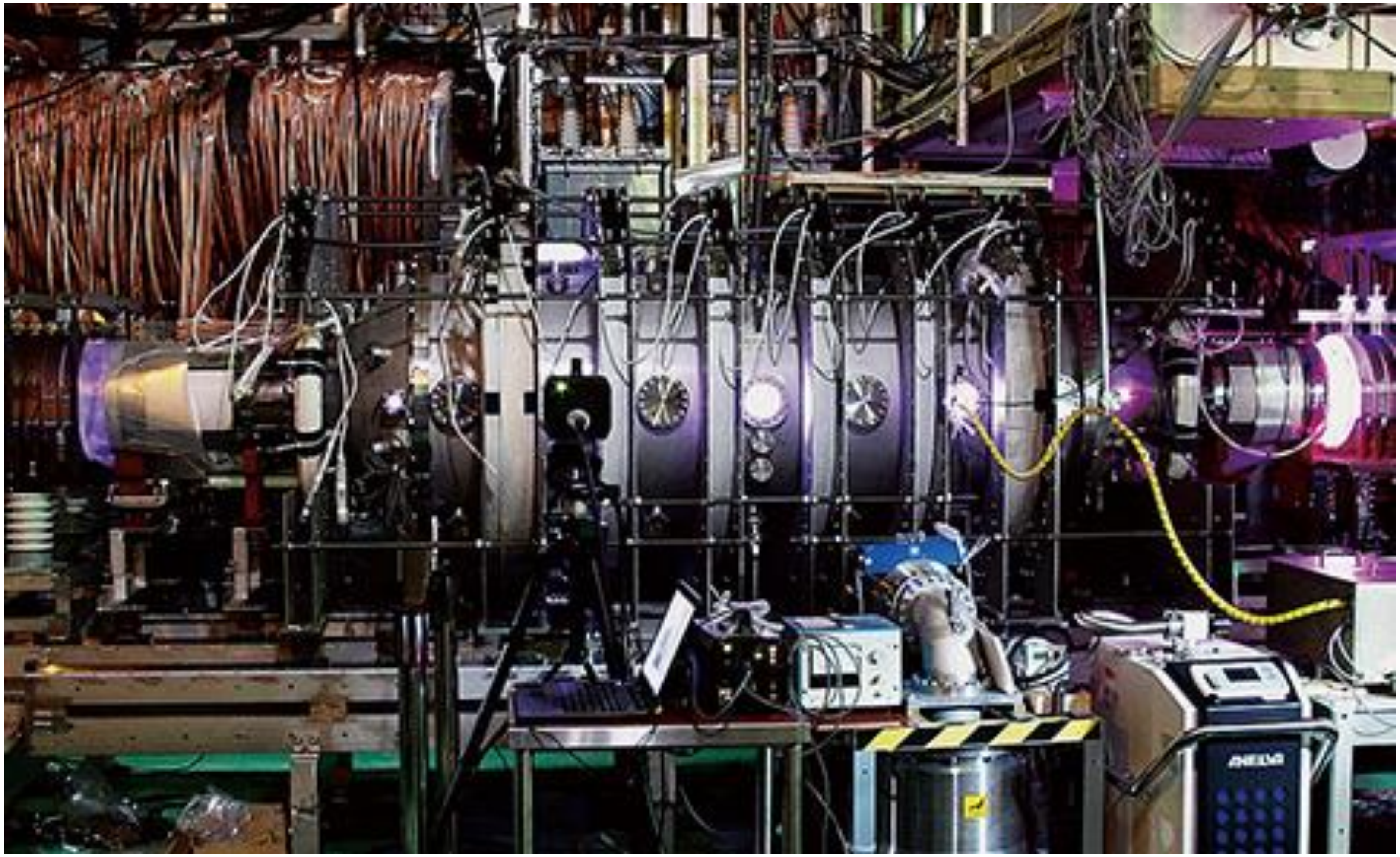
FIG: Particle trajectory in FRC

Binderbauer, et al. Physics of Plasmas 22(5), 056110 (2015).

Edge-biasing experiment

Summer research project at Nihon University

FAT-CM experiment



https://www.cst.nihon-u.ac.jp/research/facilities/lebra_a.html

Summer research project at Nihon University (cont'd.)

Edge-biasing of an FRC plasma

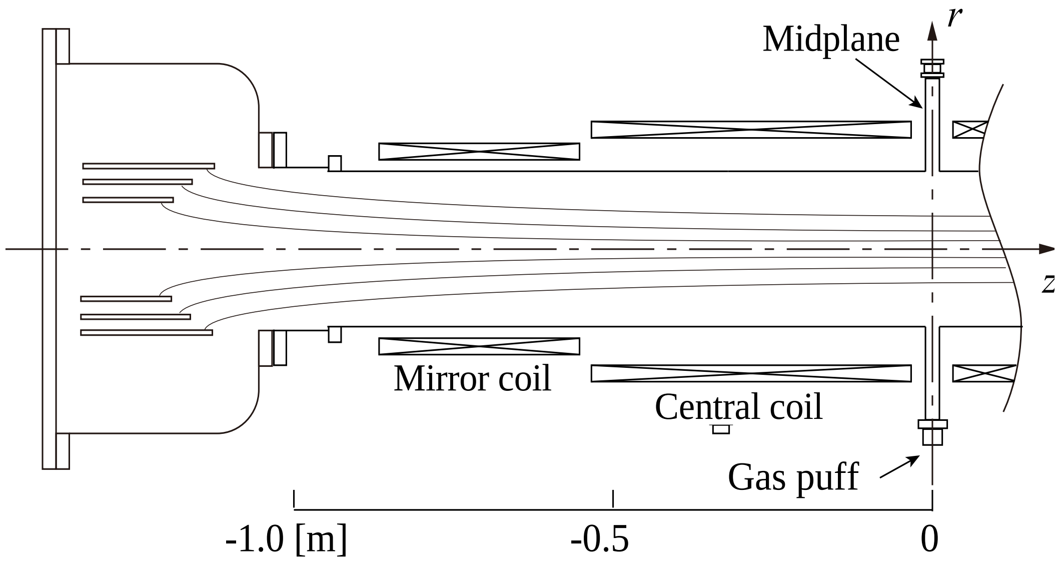


FIG: Conceptual drawing of coaxial layered biasing electrodes

Objectives

- Experimentally and theoretically verify the possibility of global and microscopic stability
- Radial electric field applied by biasing from the end regions of formation chamber
- Stabilization by driven toroidal flow shear and reduced spin-up

*Learn more about this at the poster session

Summary and conclusion

- The FRC is a practical means of harnessing fusion power
  - Simple geometry
  - Simple magnetic topology
  - High-beta
  - Natural divertor
  - Translatable
- Recent advancements have enabled high performance FRCs
  - Collisional merging
  - Neutral beam injection
  - Edge-biasing

Acknowledgements

Queen’s University supported this work through generous scholarships

Future work will be funded in part by Mitacs and JSPS

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