Fusion Reactor Technology I
(459.760, 3 Credits)

Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

Introduction

- **Text Book**

- B. B. Kadomtsev, "Tokamak Plasma: A Complex Physical System", Institute of Physics Publishing, Bristol and Philadelphia (1992)
- L. C. Woods, "Theory of Tokamak Transport - New Aspects for Nuclear Fusion Reactor Design", WILEY-VCH (2006)
- A. A. Harms, K. F. Schoepf, G. H. Miley, D. R. Kingdon, "Principles of Fusion Energy", World Scientific Publishing Co. Pte. Ltd. (2000)
- R. O. Dendy, "Plasma Physics: An Introductory Course", Cambridge U niversity Press (February 24, 1995)

- **Reference**

- J. Wesson, "Tokamaks", Oxford University Press, 3rd Edition (2004)

Introduction

Evaluation

- Attendance: 10%
- Homework & Presentation: 30%
- Midterm exam: 30%
- Final exam: 30%

Contents

Week 1. Magnetic Confinement

Week 2. Fusion Reactor Energetics (Harms 2, 7.1-7.5)

Week 3. How to Build a Tokamak (Dendy 17 by T. N. Todd)

Week 4. Tokamak Operation (I): Startup

Week 5. Tokamak Operation (II):
Basic Tokamak Plasma Parameters (Wood 1.2, 1.3)

Week 7-8. Tokamak Operation (III): Tokamak Operation Mode

Week 9-10. Tokamak Operation Limits (I):
Plasma Instabilities (Kadomtsev 6, 7, Wood 6)

Week 11-12. Tokamak Operation Limits (II):
Plasma Transport (Kadomtsev 8, 9, Wood 3, 4)

Week 13. Heating and Current Drive (Kadomtsev 10)

Week 14. Divertor and Plasma-Wall Interaction

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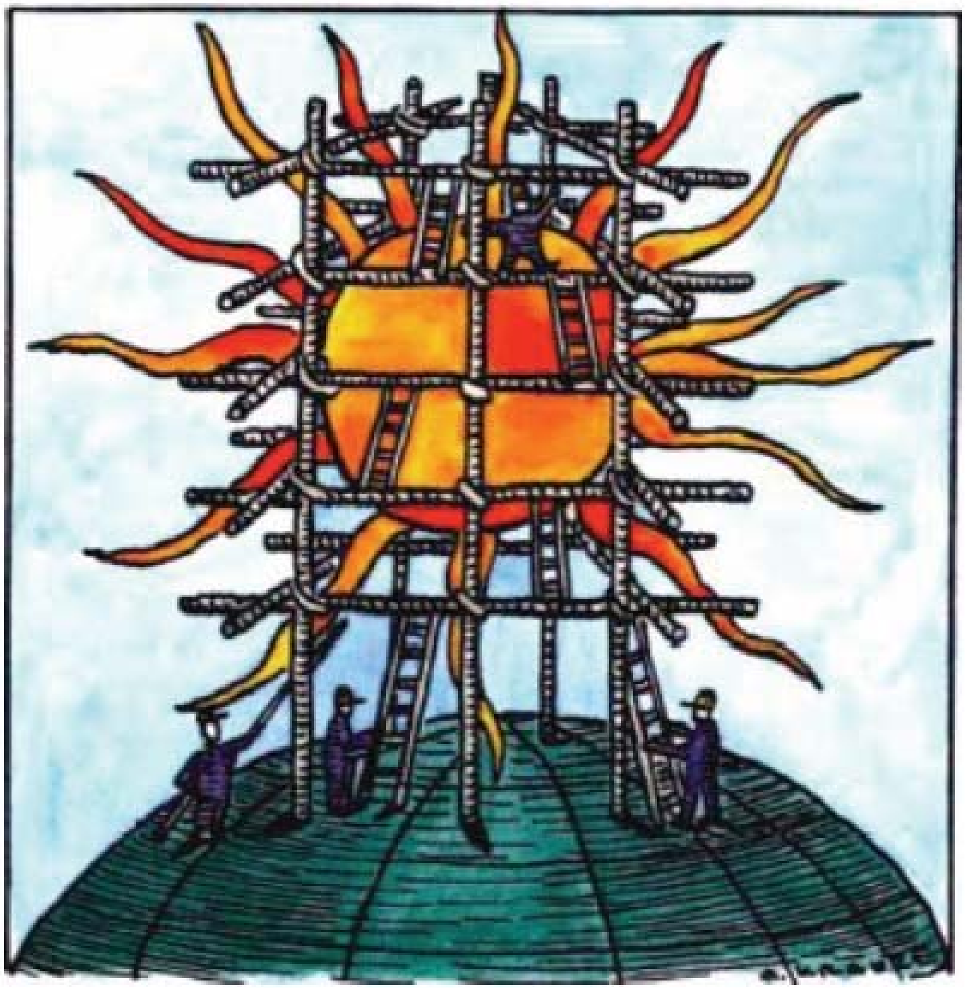
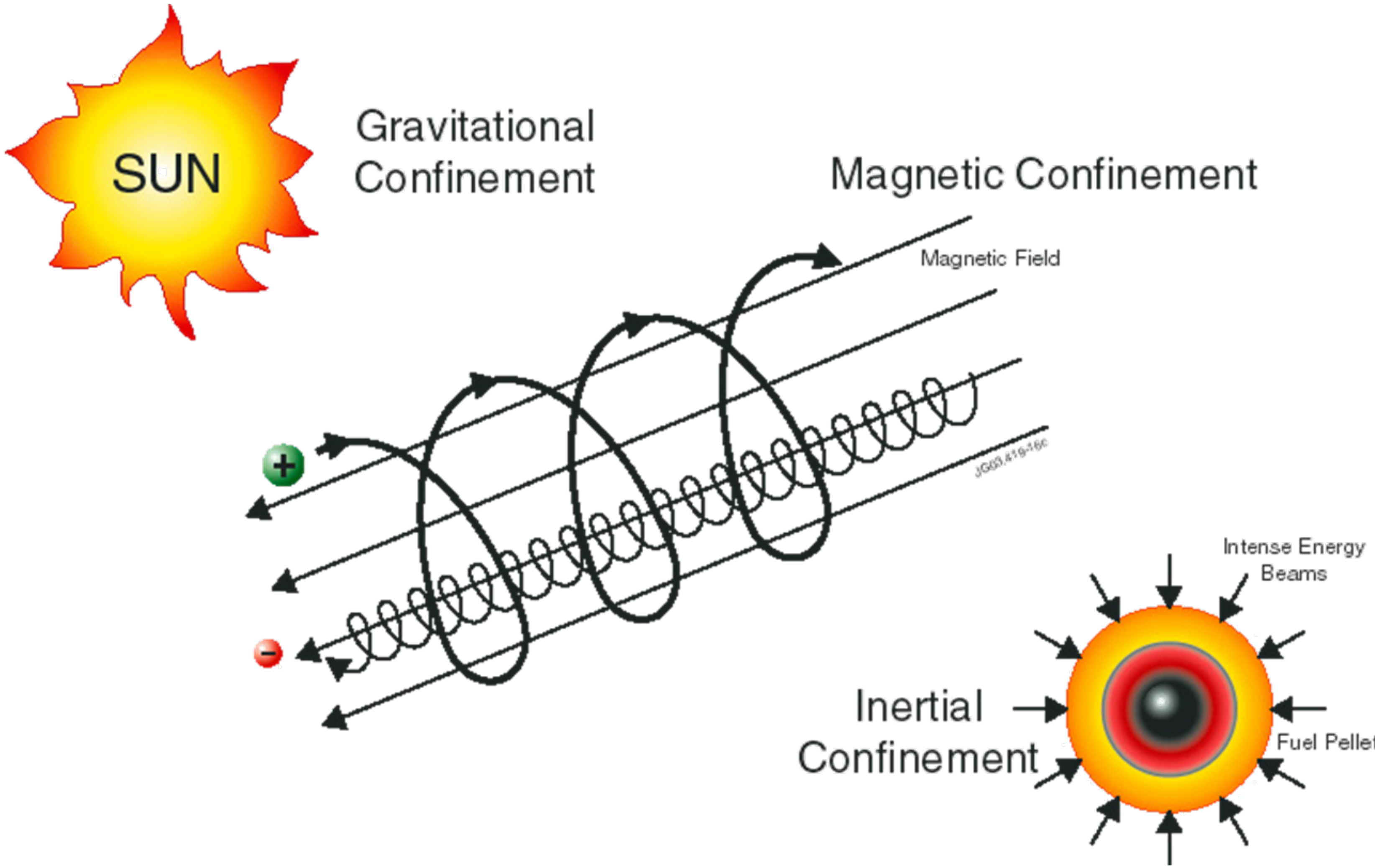
Week 13. Heating and Current Drive (Kadomtsev 10)

Week 14. Divertor and Plasma-Wall Interaction

To build a sun on earth

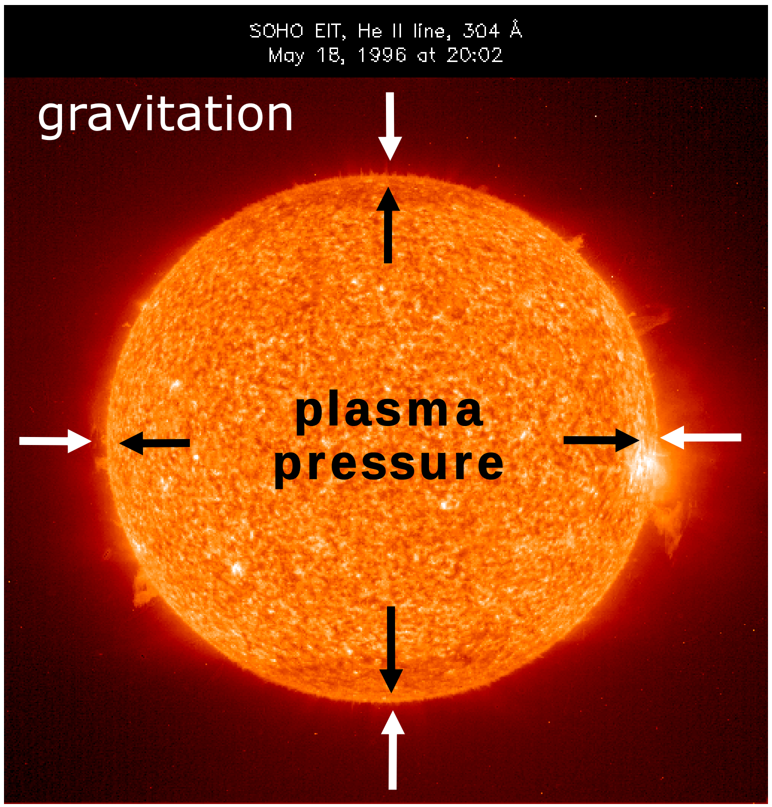


To build a sun on earth

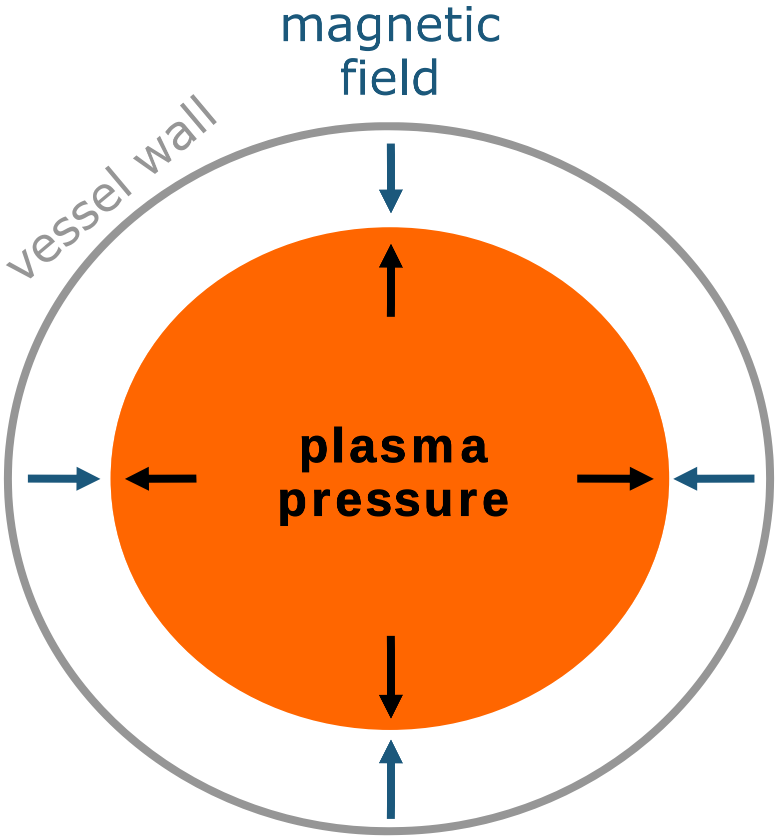


Magnetic confinement

- **Imitation of the Sun on Earth**

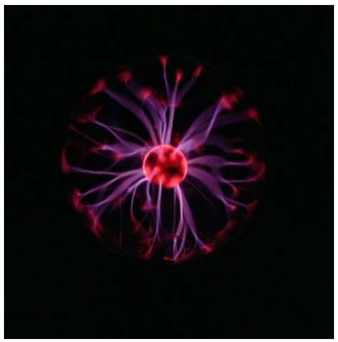


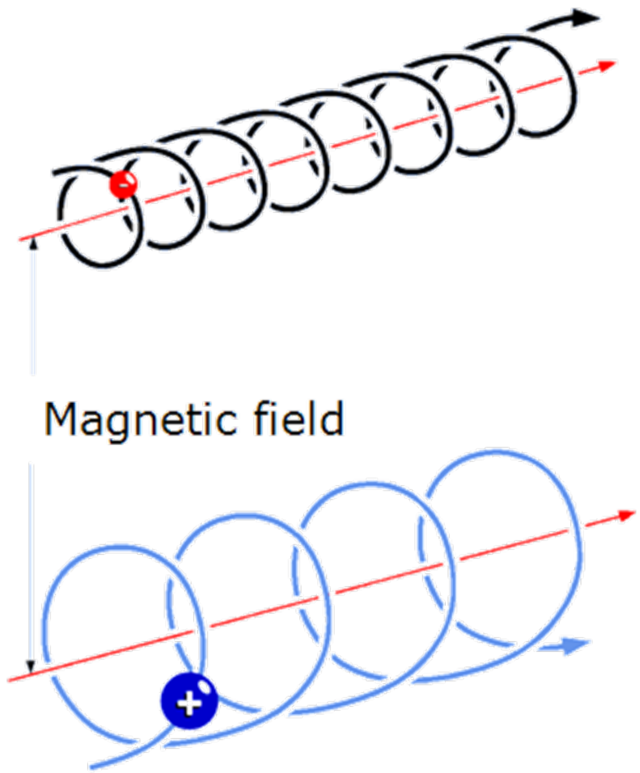
Equilibrium in the sun

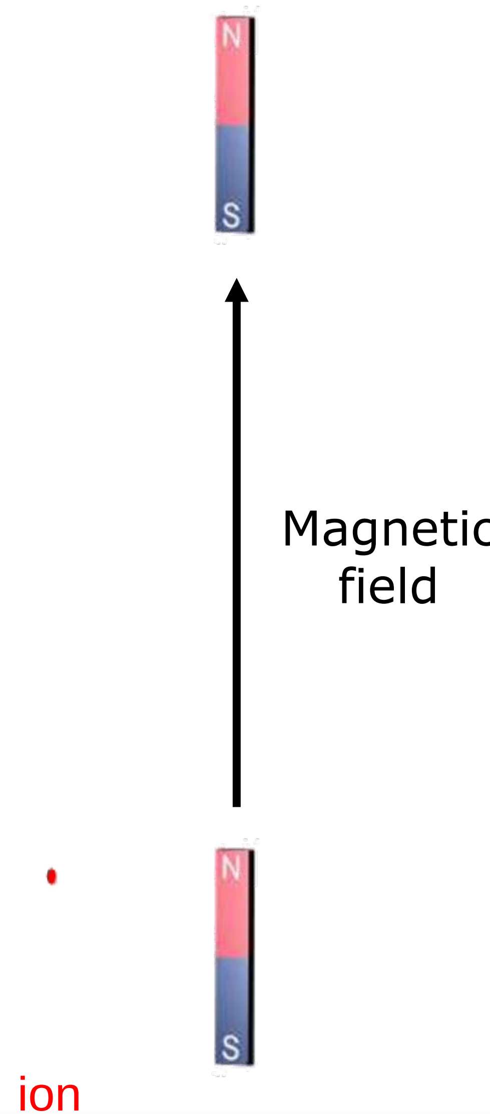


Plasma on earth
much, much smaller & tiny mass!

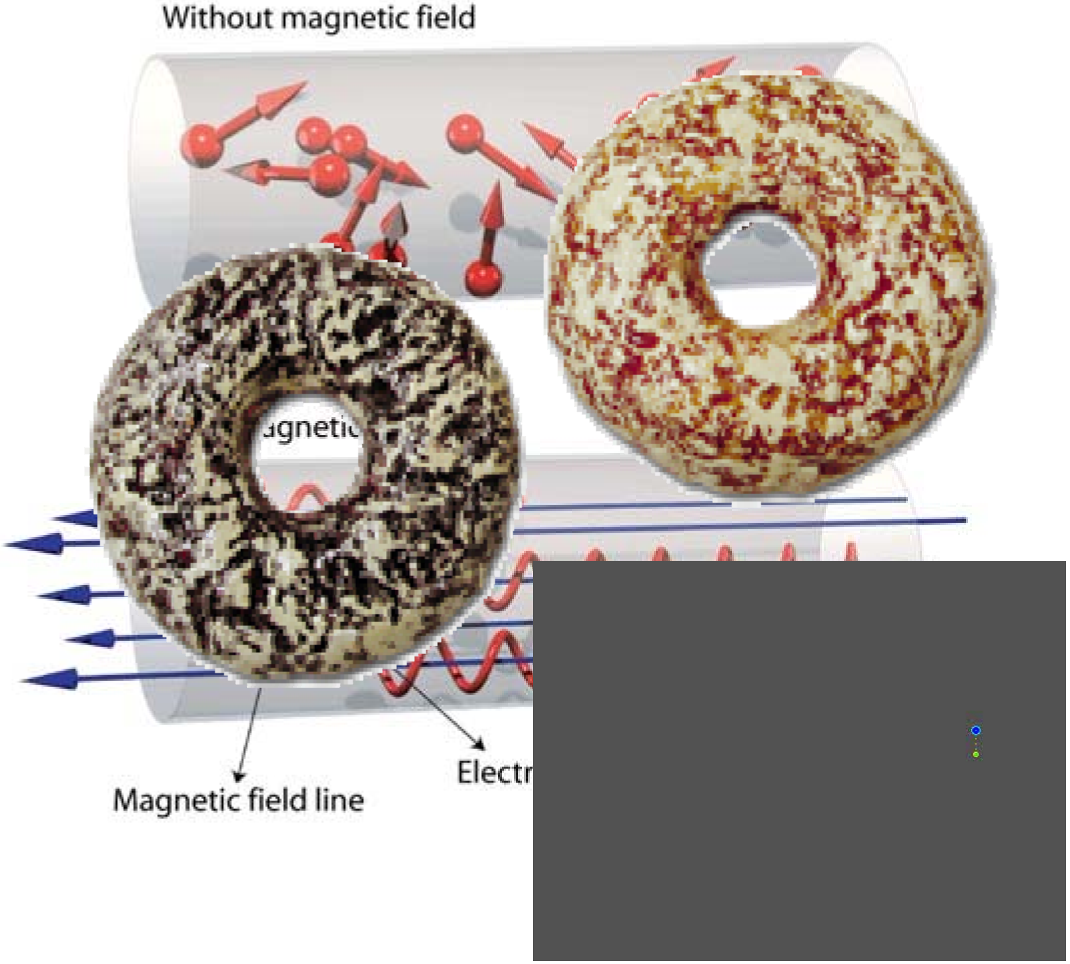
Magnetic confinement

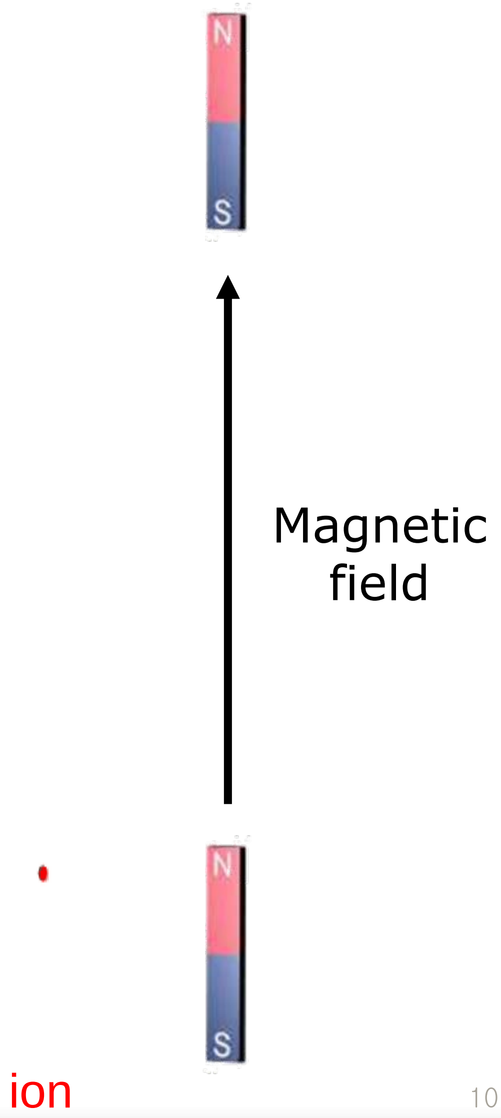




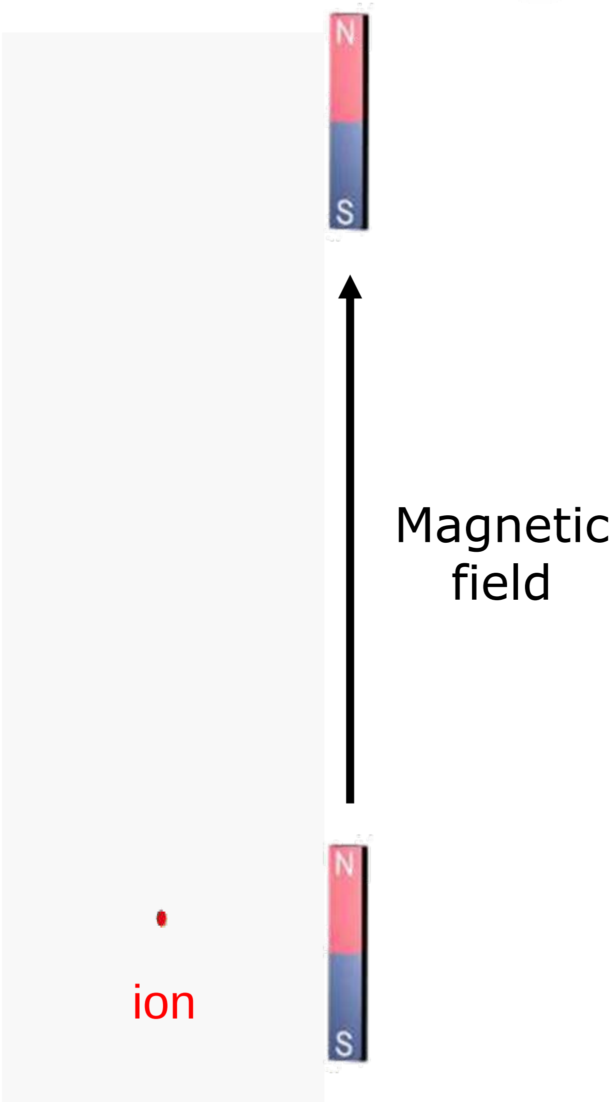


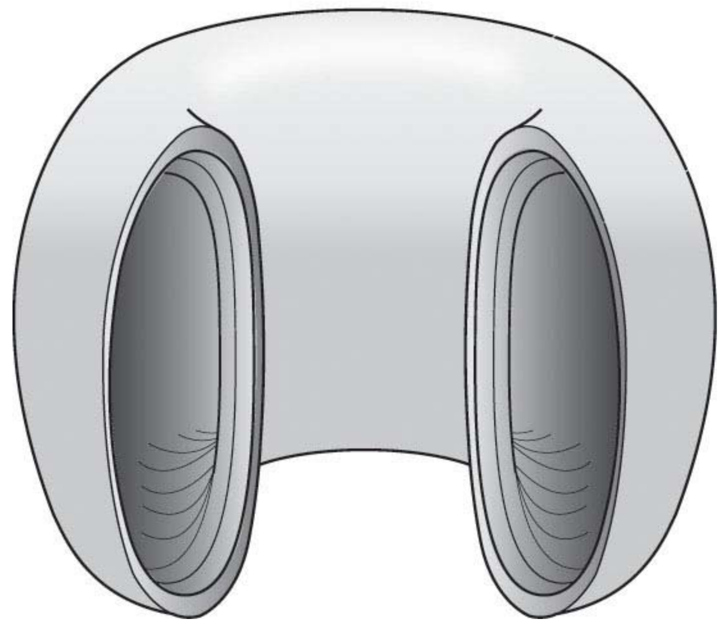
Open Magnetic Systems





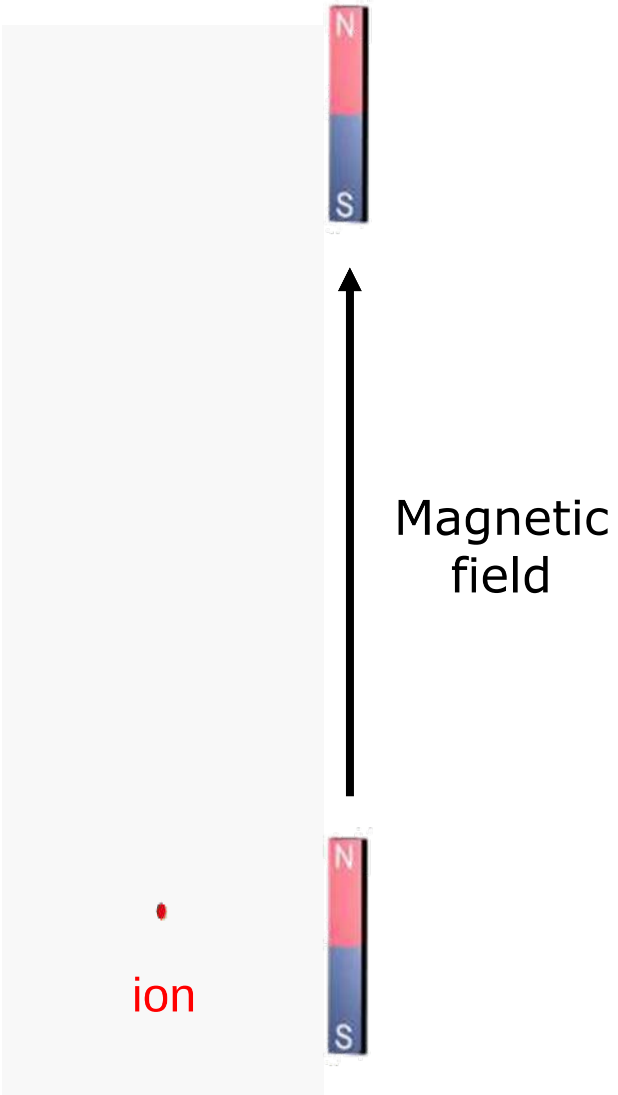
Closed Magnetic Systems

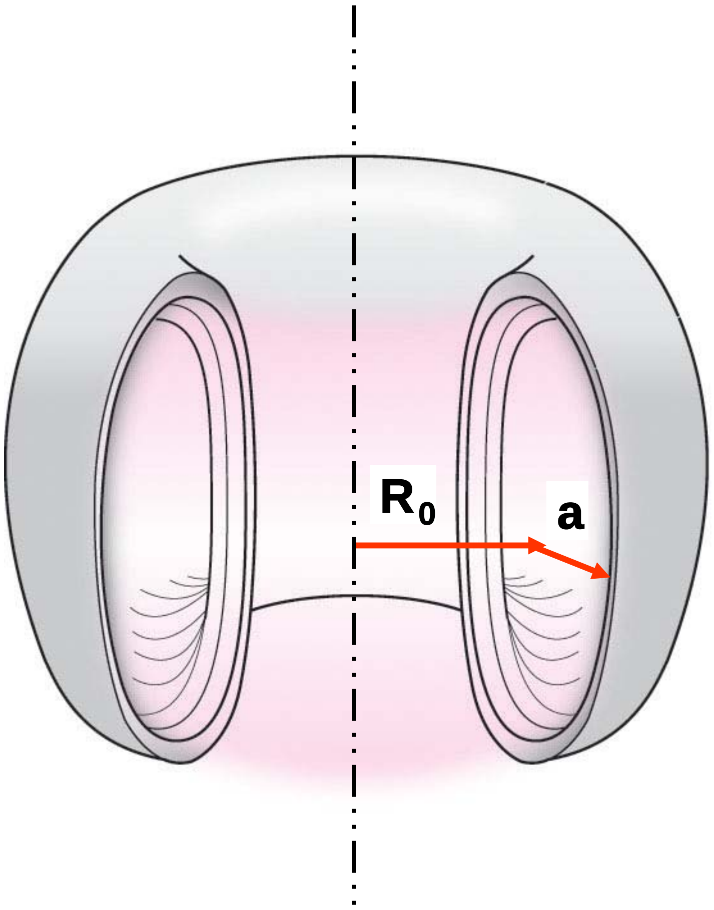




Donut-shaped vacuum vessel

Closed Magnetic Systems

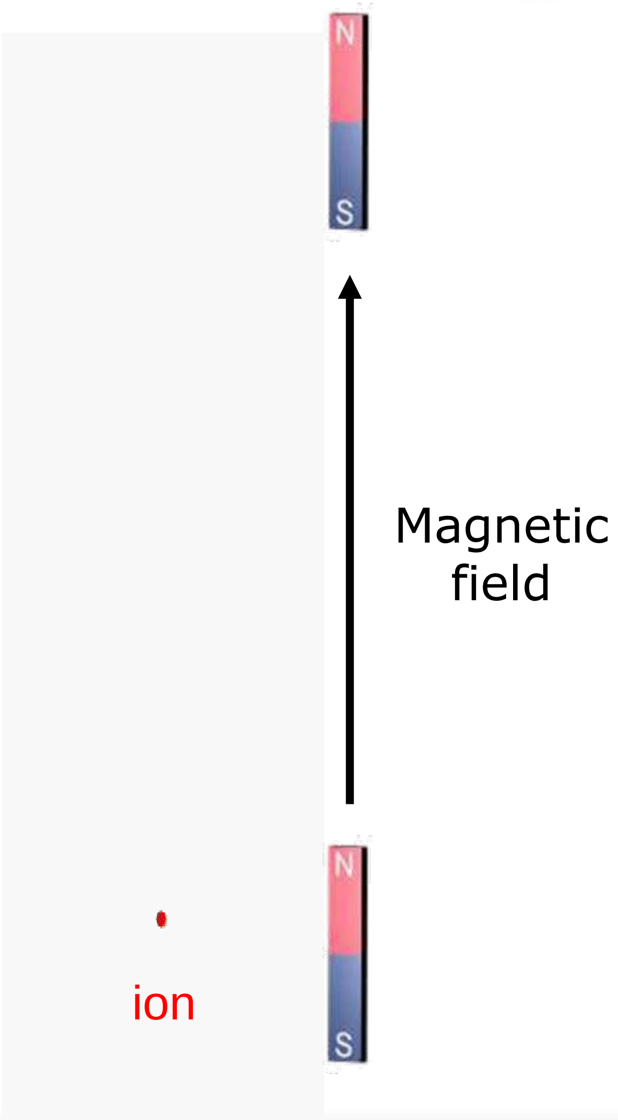


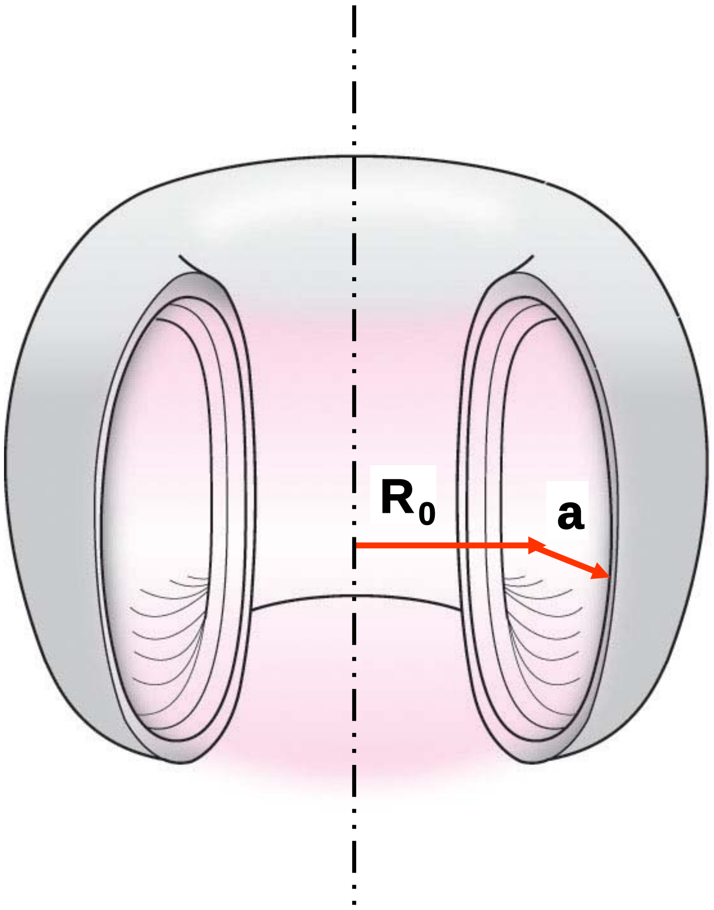


Plasma needs to be confined

R_0 = 1.8 m, a = 0.5 m in KSTAR

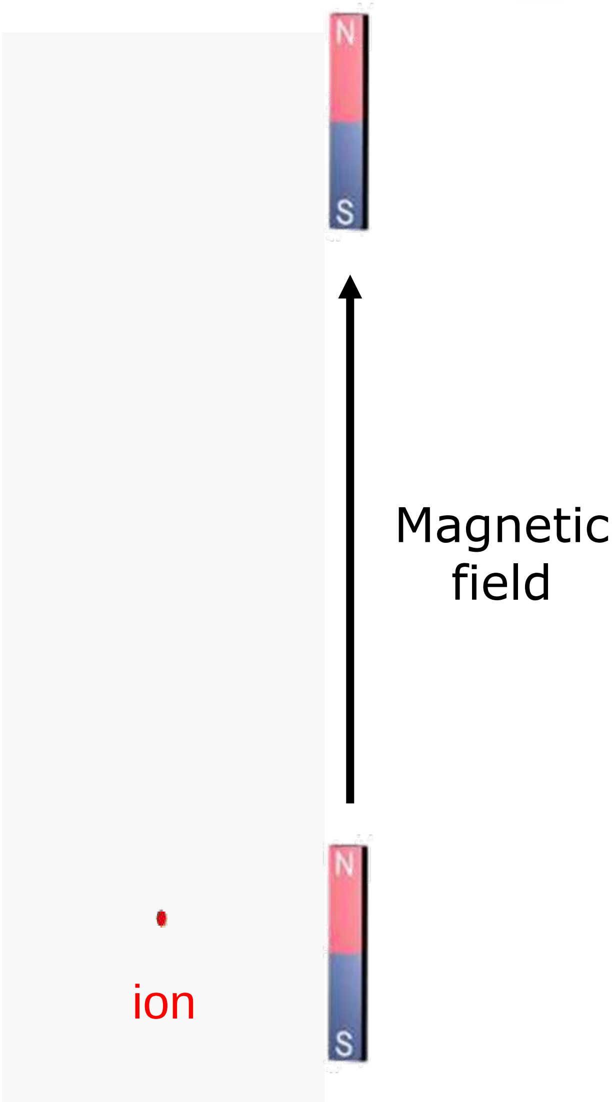
Closed Magnetic Systems

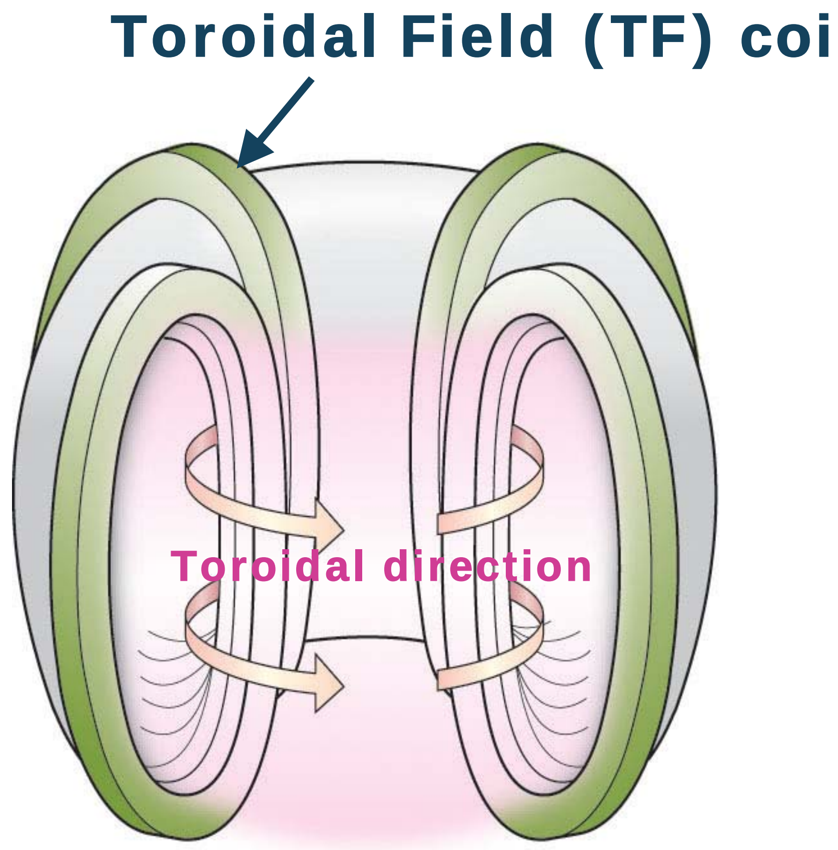




Plasma needs to be confined
R_0 = 6.2 m, a = 2.0 m in ITER

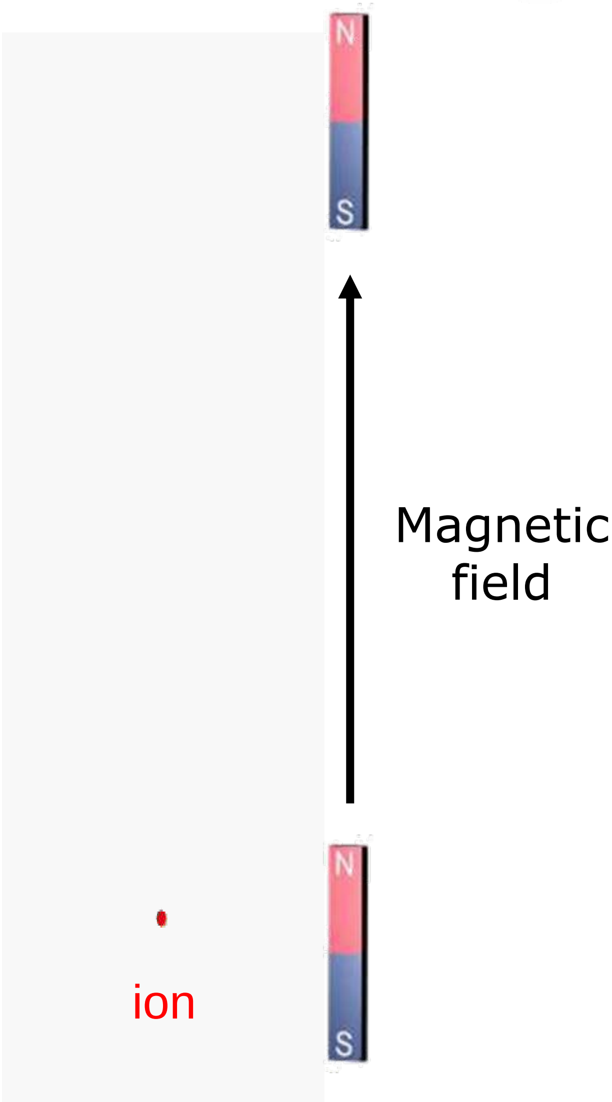
Closed Magnetic Systems

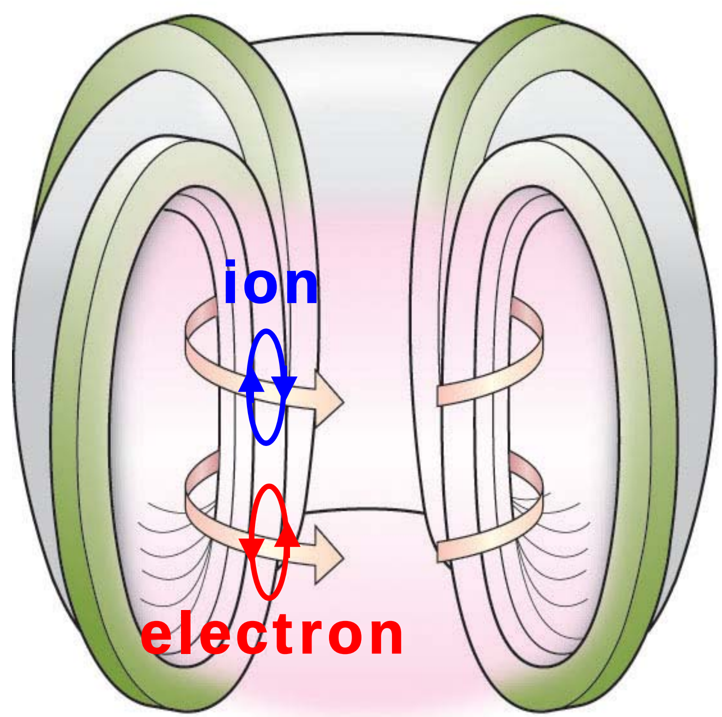




Applying toroidal magnetic field
3.5 T in KSTAR, 5.3 T in ITER

Closed Magnetic Systems





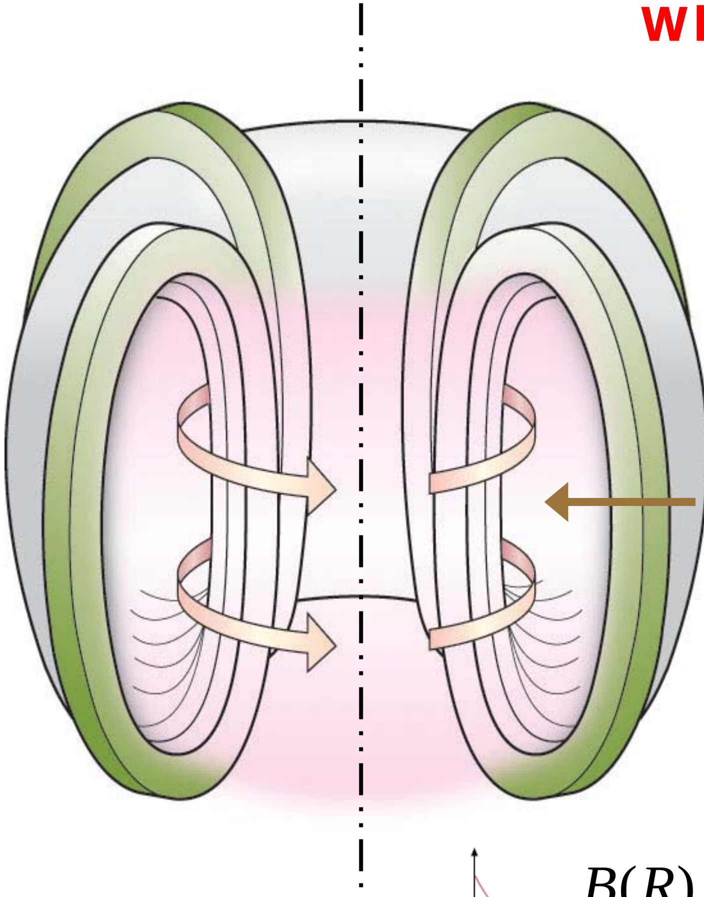
Magnetic field of earth?

0.5 Gauss = 0.00005 T

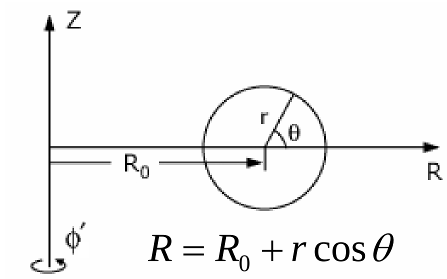
What kind of drift motions?

Closed Magnetic Systems

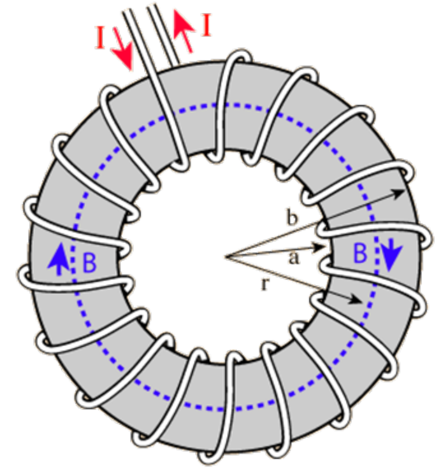
Where does the gradient come from?



∇B



$$R = R_0 + r\cos\theta$$
$$Z = r\sin\theta$$



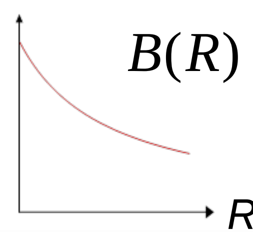
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

$$\oint \mathbf{B}_\phi \cdot d\mathbf{l} = \mu_0 N I_c$$

$$B_\phi(R) = \frac{\mu_0 N I_c}{2\pi R} = \left(\frac{R_0}{R}\right) B_\phi(R_0)$$

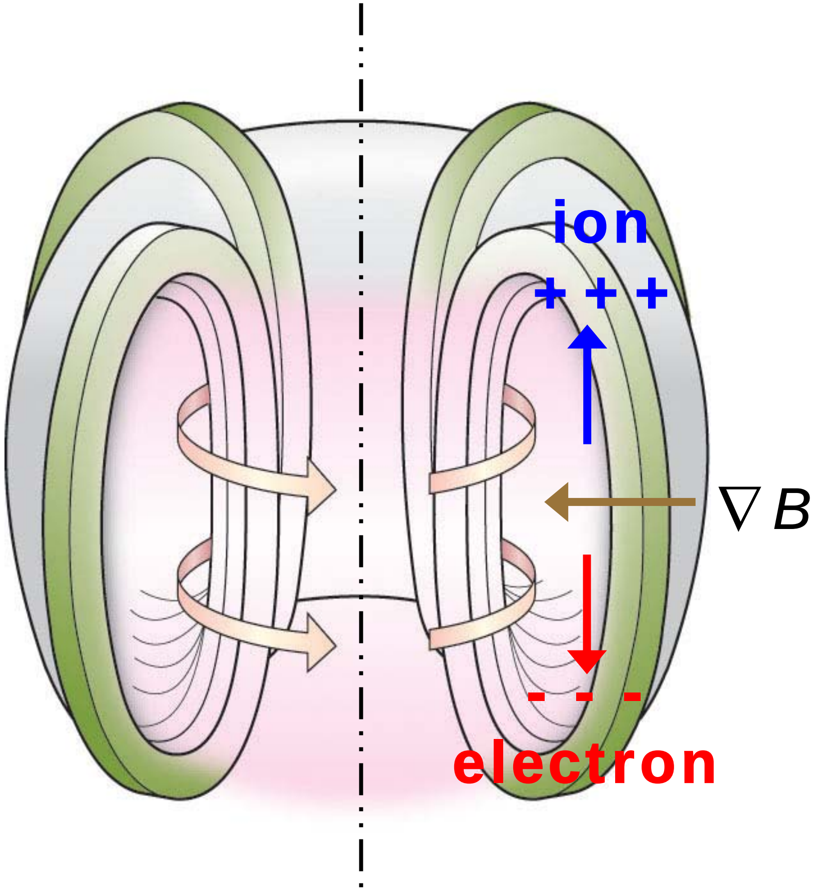
$$= \frac{B_\phi(R_0)}{1 + (r/R_0)\cos\theta} = \frac{B_\phi(R_0)}{1 + \varepsilon\cos\theta}$$

$$= B_\phi(r,\theta)$$



$$B(R) \propto \frac{1}{R}$$

Closed Magnetic Systems



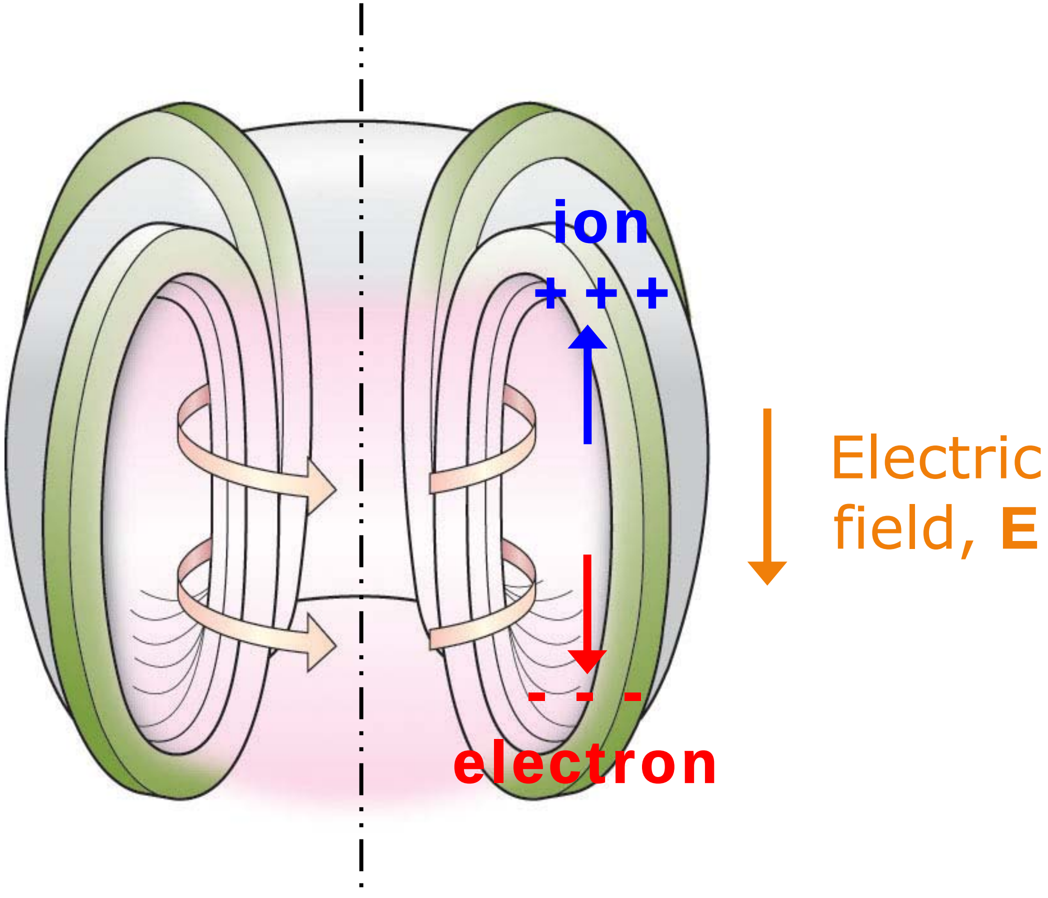
$$\mathbf{v}_{D,R} = \frac{mv_\parallel^2}{qB_0^2}\frac{\mathbf{R}_0 \times \mathbf{B}_0}{R^2}$$

$$\mathbf{v}_{D,\nabla B} = \pm\frac{1}{2}v_\perp r_L \frac{\mathbf{B}\times\nabla B}{B^2}$$

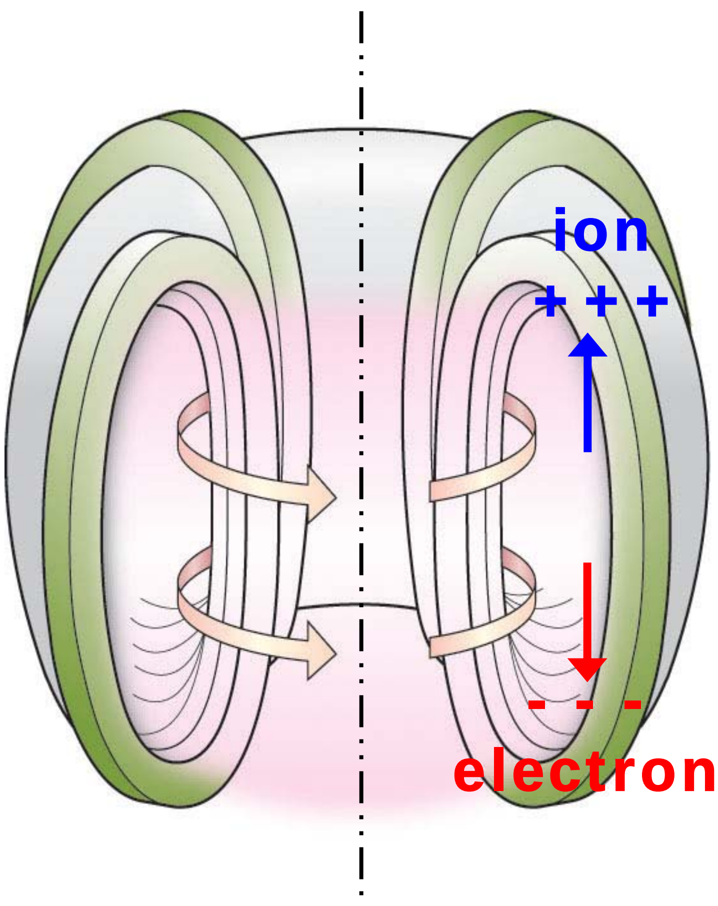
$$= \frac{mv_\perp^2}{2qB}\frac{\mathbf{B}\times\nabla B}{B^2}$$

$$\mathbf{v}_D = \frac{m}{q}\frac{1}{R_0 B_\phi(R_0)}\left[v_\parallel^2 + \frac{v_\perp^2}{2}\right]\mathbf{e}_Z$$

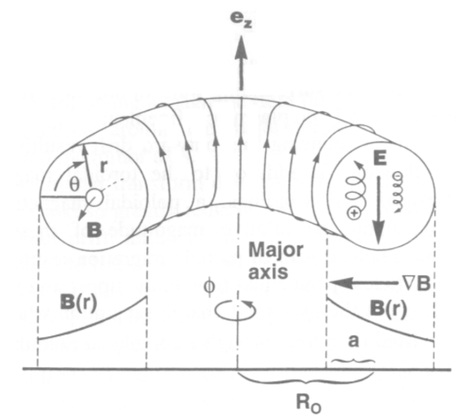
Closed Magnetic Systems



Closed Magnetic Systems



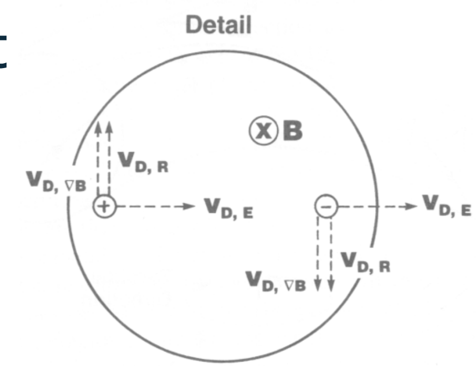
Ex**B** drift



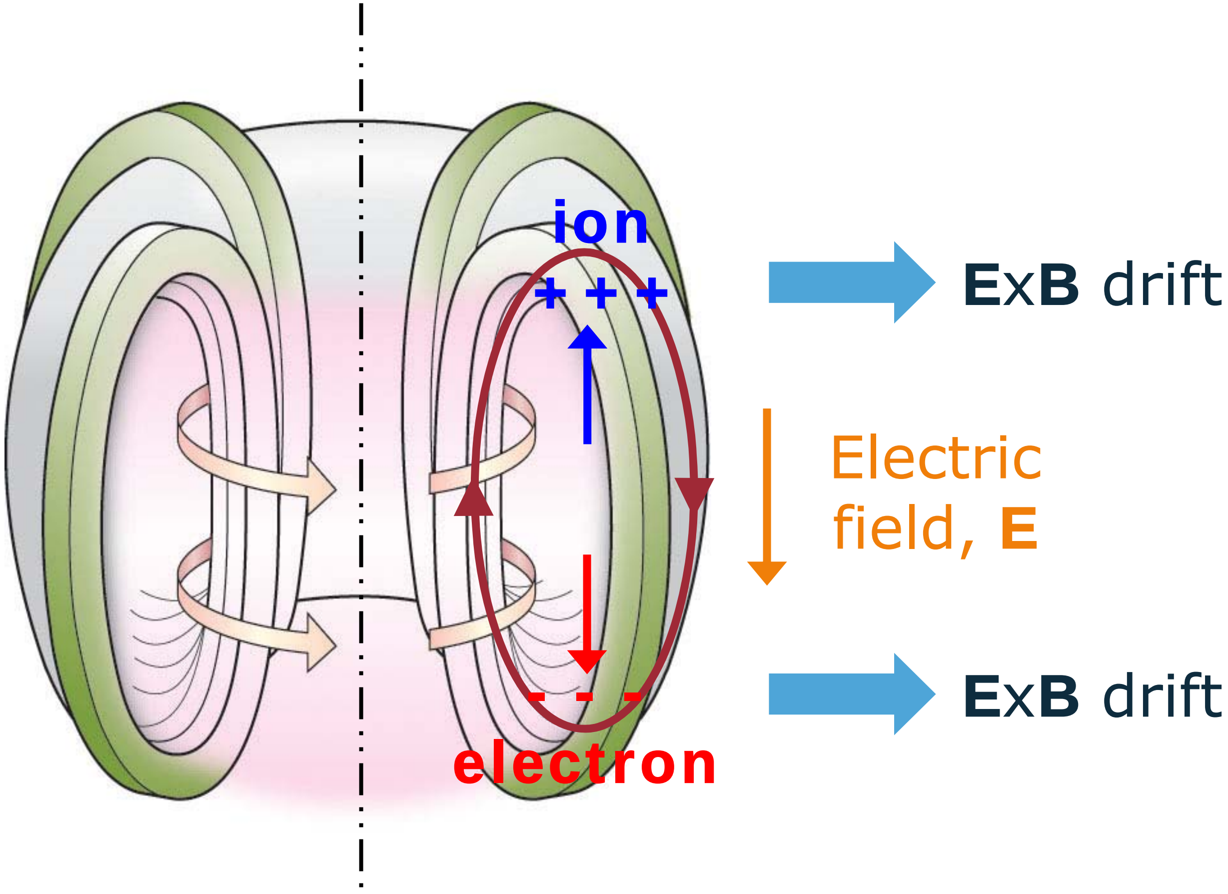
Electric field, **E**

$$\mathbf{v}_{D,E} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = \frac{E}{B_\phi(R_0)}\cdot\frac{\mathbf{R}}{R_0}$$

Ex**B** drift



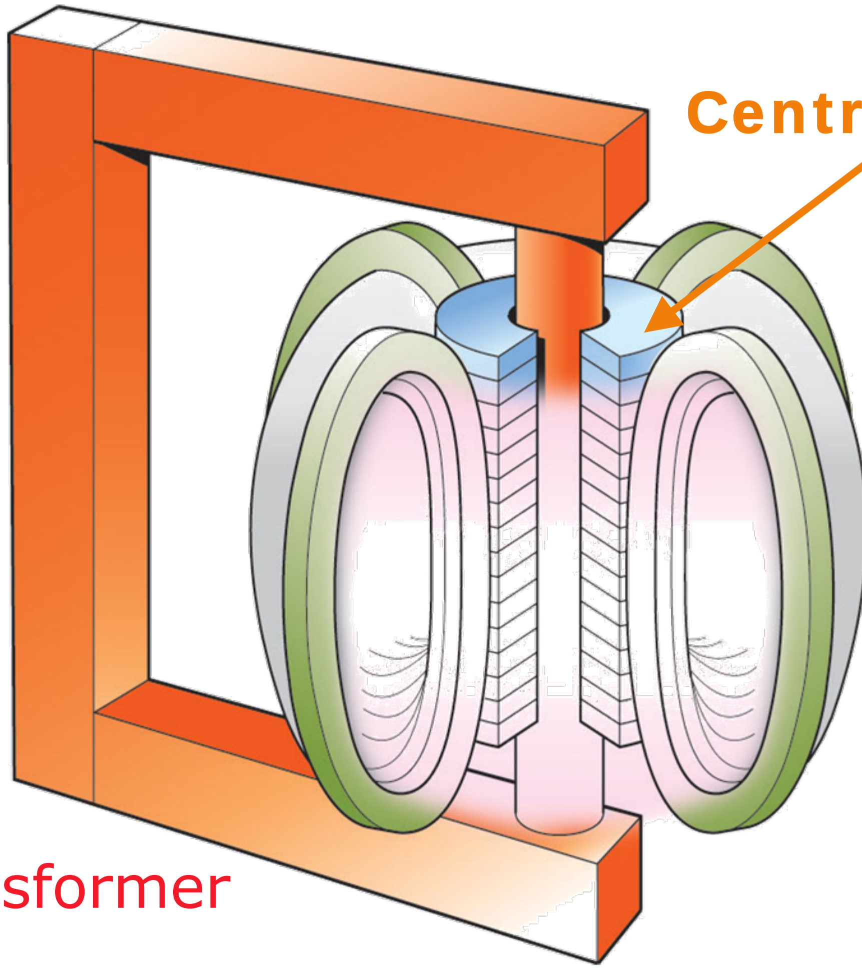
Closed Magnetic Systems

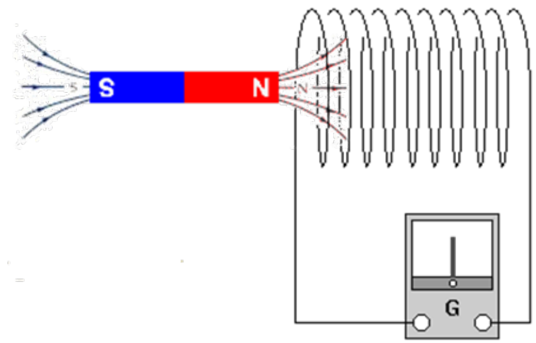


Poloidal magnetic field required

Plasma current → Tokamak

Tokamak



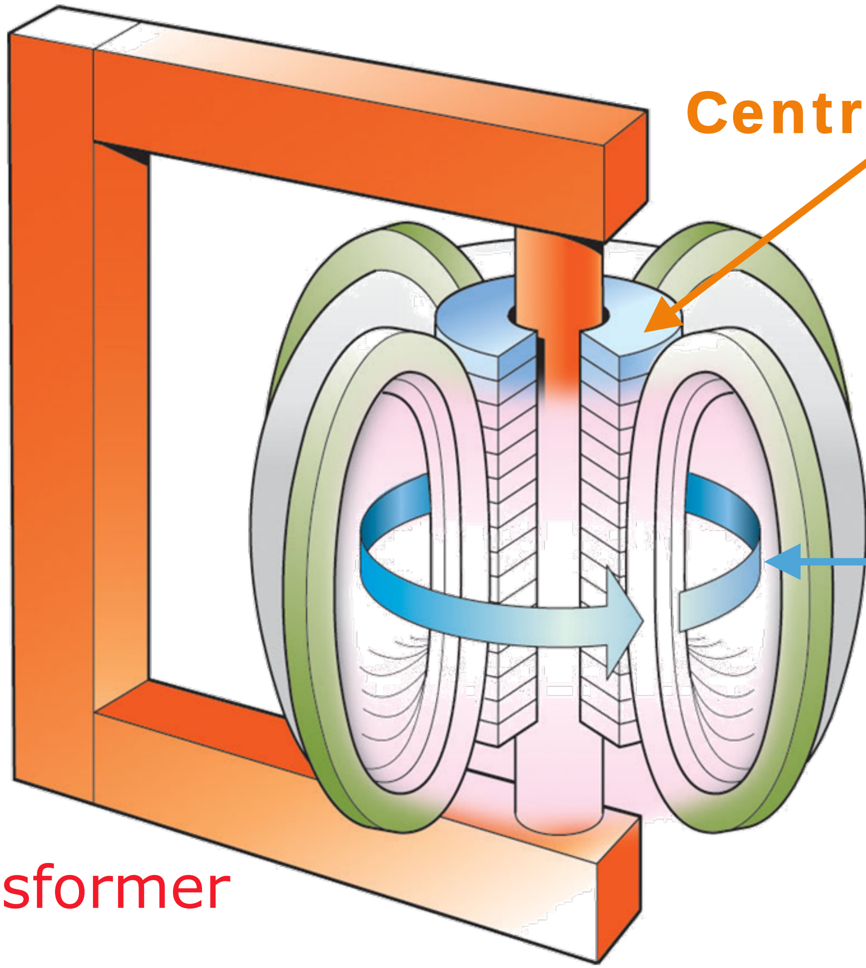


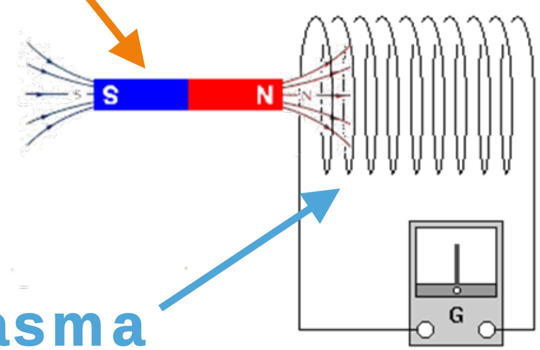
Faraday's law

$$v = -\frac{d}{dt}\int_S B \cdot ds$$

Tokamak

Central Solenoid (CS)





Plasma

Transformer

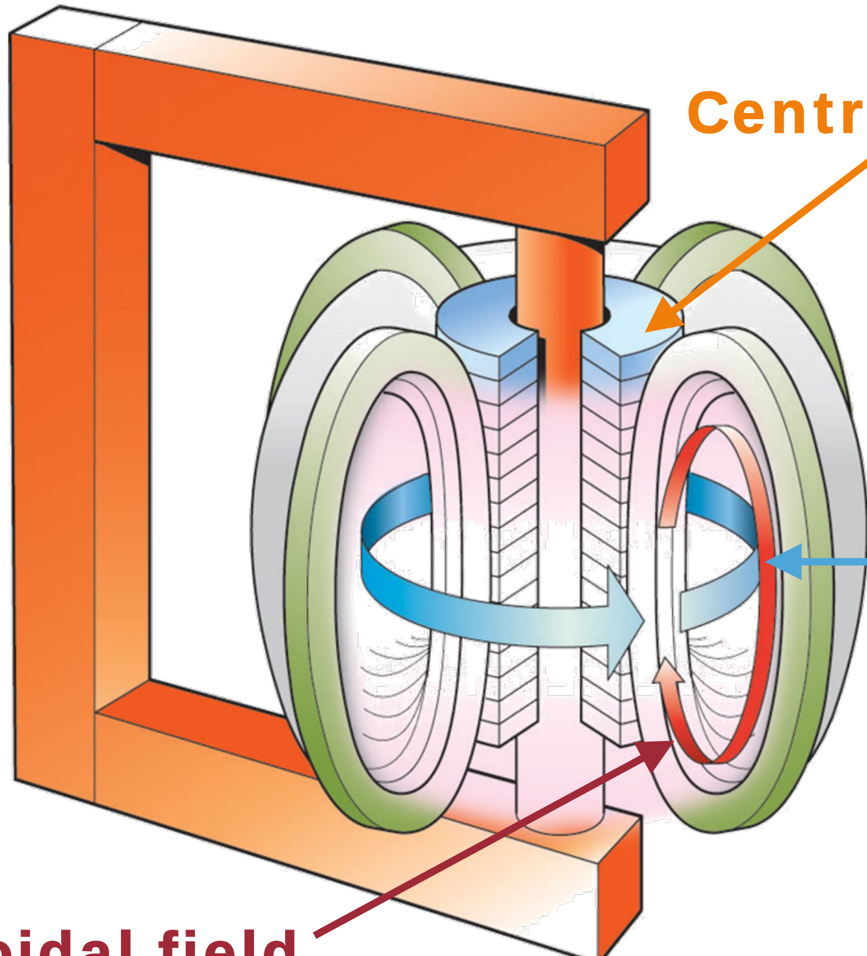
$$-\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}$$

$$\Rightarrow \quad -\frac{d\psi_{trans}}{dt} = \oint \mathbf{E}\cdot d\mathbf{l}$$

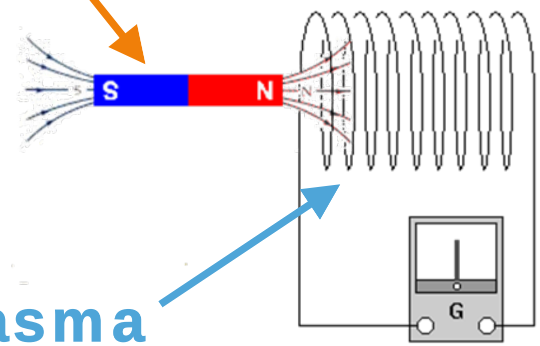
$$\Rightarrow \quad E_{\phi} = -\frac{1}{2\pi R}\frac{d\psi_{trans}}{dt}$$

$$\Rightarrow \quad J_{\phi} = \sigma E_{\phi}$$

Tokamak



Central Solenoid (CS)



Plasma

Poloidal field

$$-\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}$$

$$\Rightarrow \quad -\frac{d\psi_{trans}}{dt} = \oint \mathbf{E}\cdot d\mathbf{l}$$

$$\Rightarrow \quad E_\phi = -\frac{1}{2\pi R}\frac{d\psi_{trans}}{dt}$$

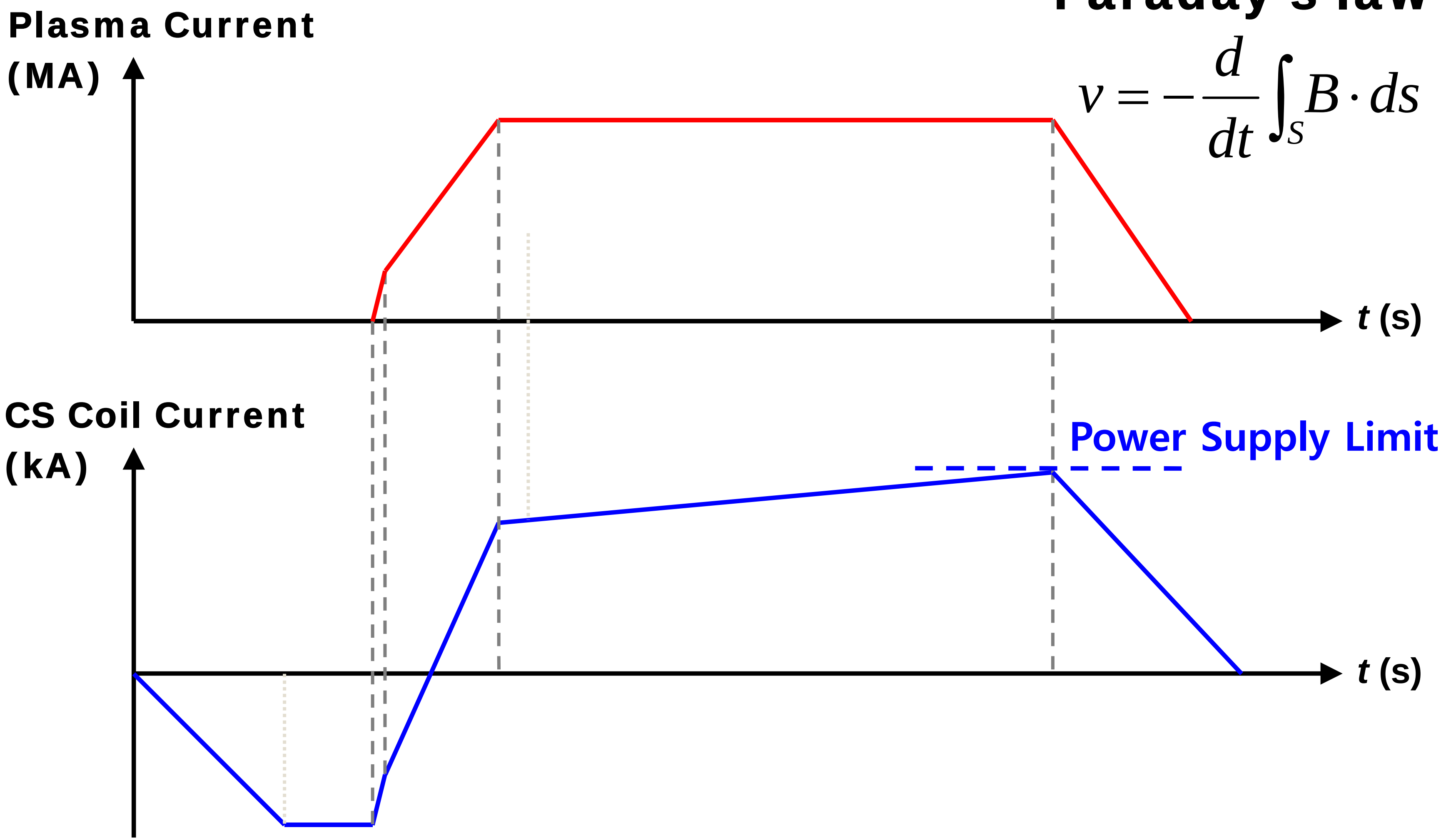
$$\Rightarrow \quad J_\phi = \sigma E_\phi$$

Pulsed Operation!

Pulsed Operation

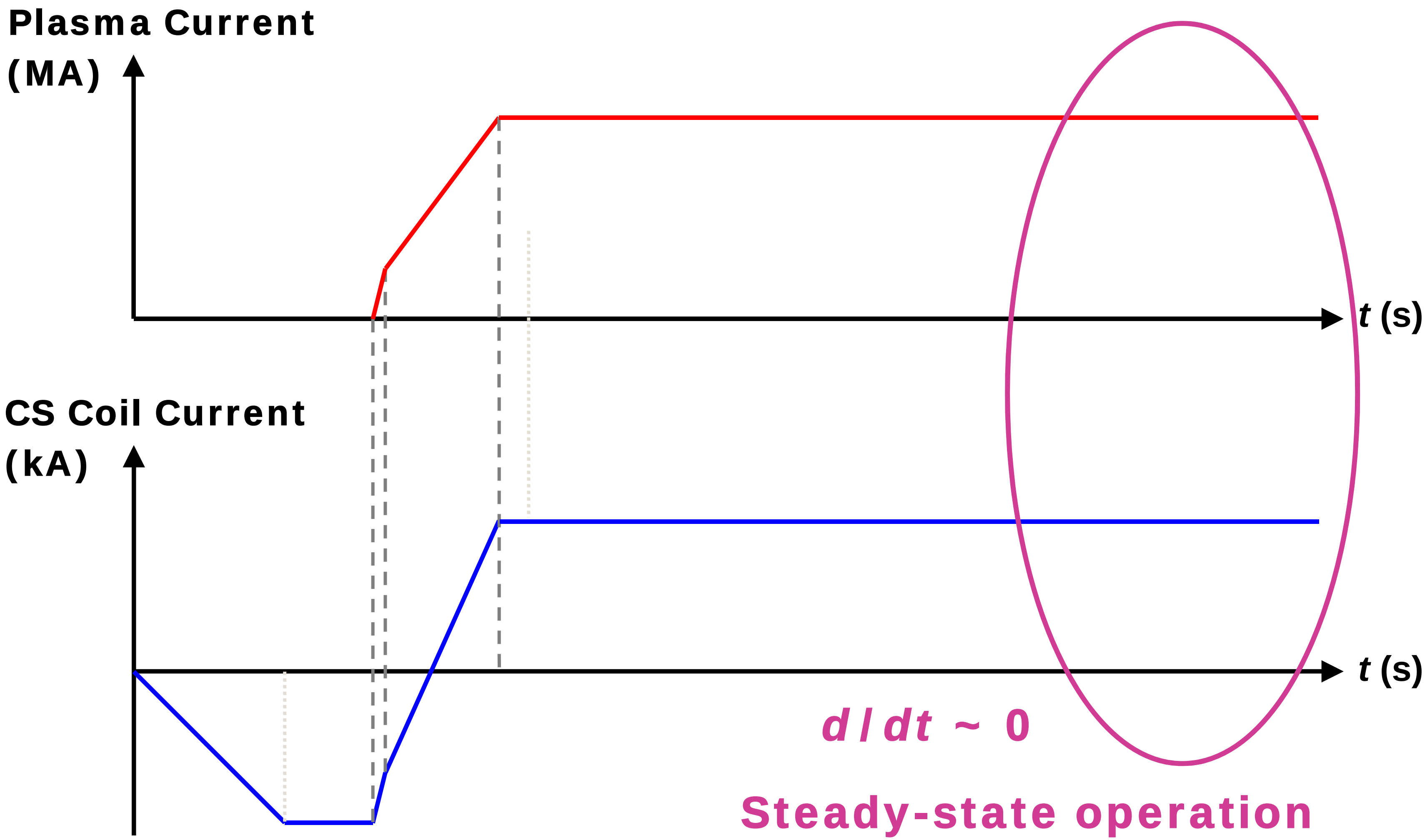
Faraday's law

$$v = -\frac{d}{dt}\int_S B \cdot ds$$



Inherent drawback of Tokamak!

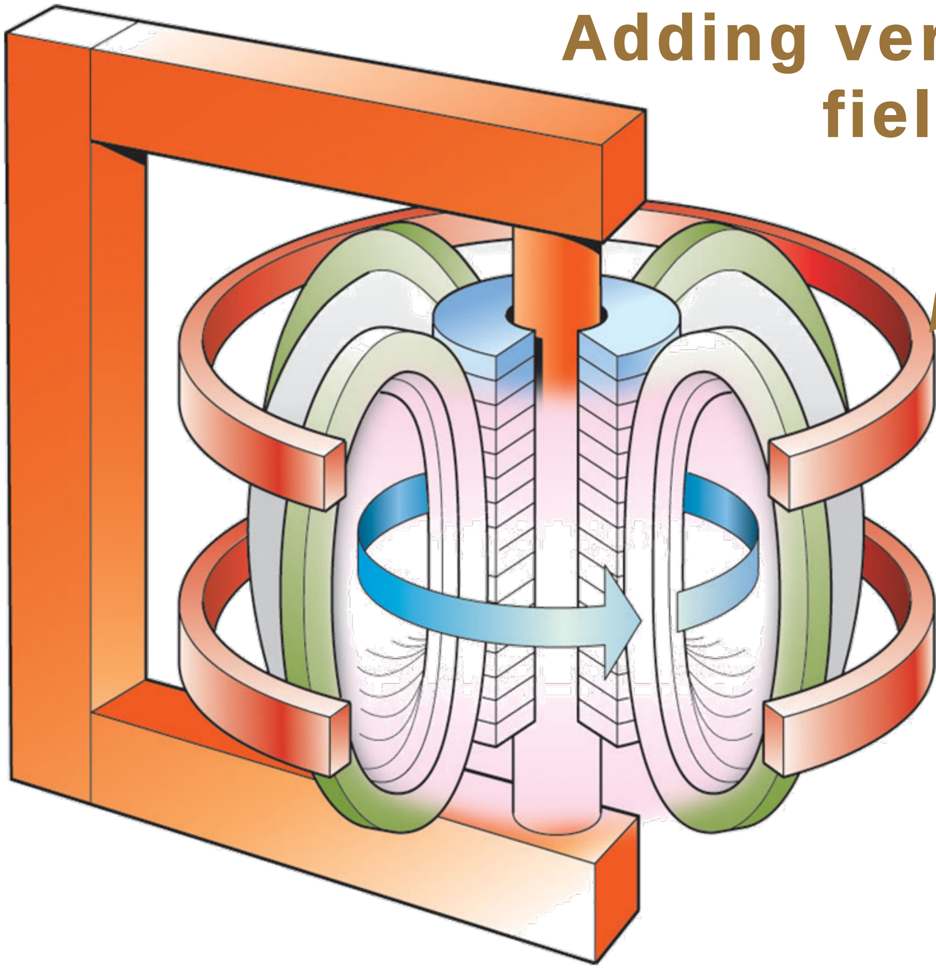
Steady-State Operation

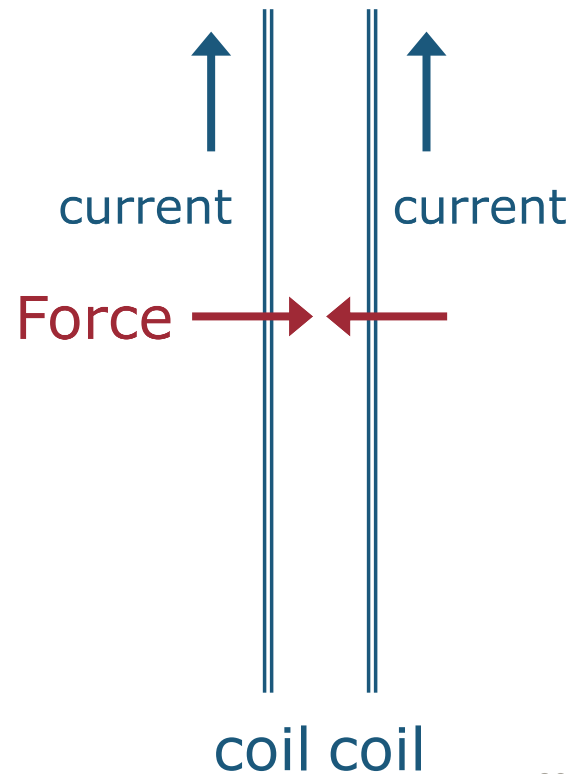


Steady-state operation
by external current drive

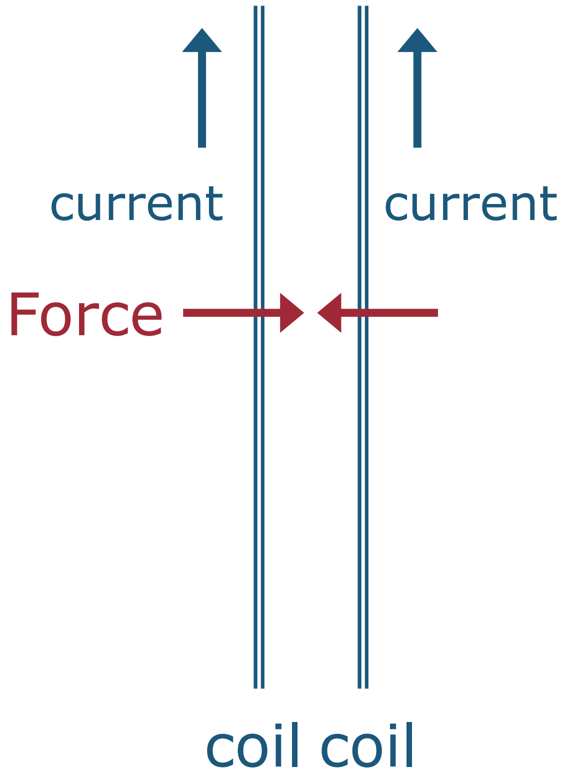
Tokamak

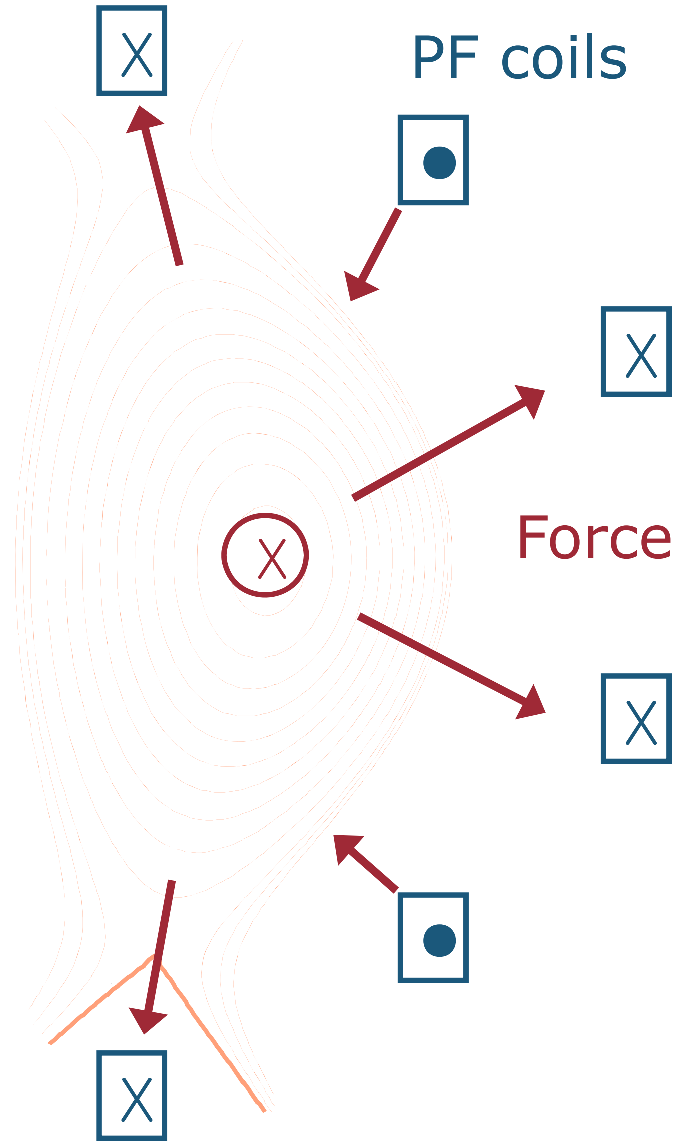
Adding vertical (equilibrium) field coils (PF)





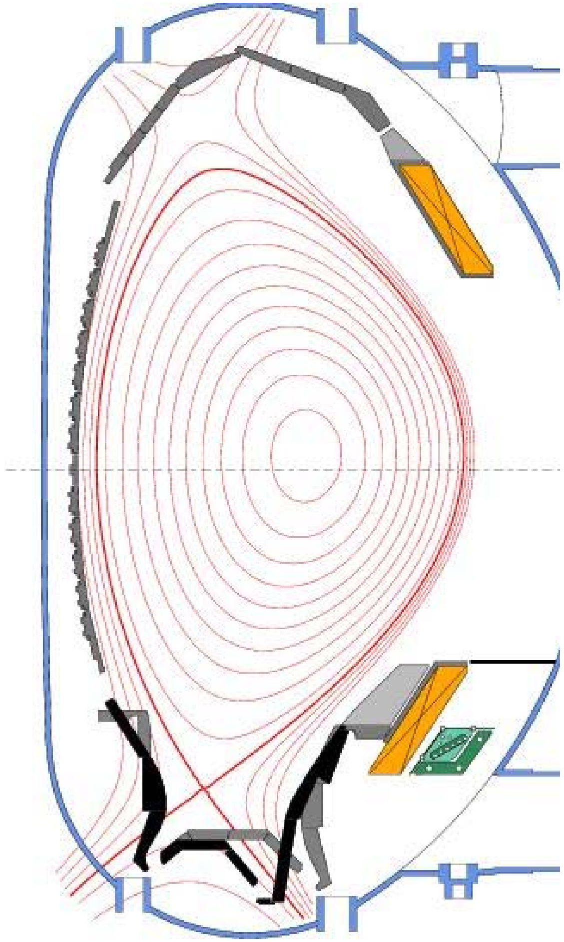
Tokamak

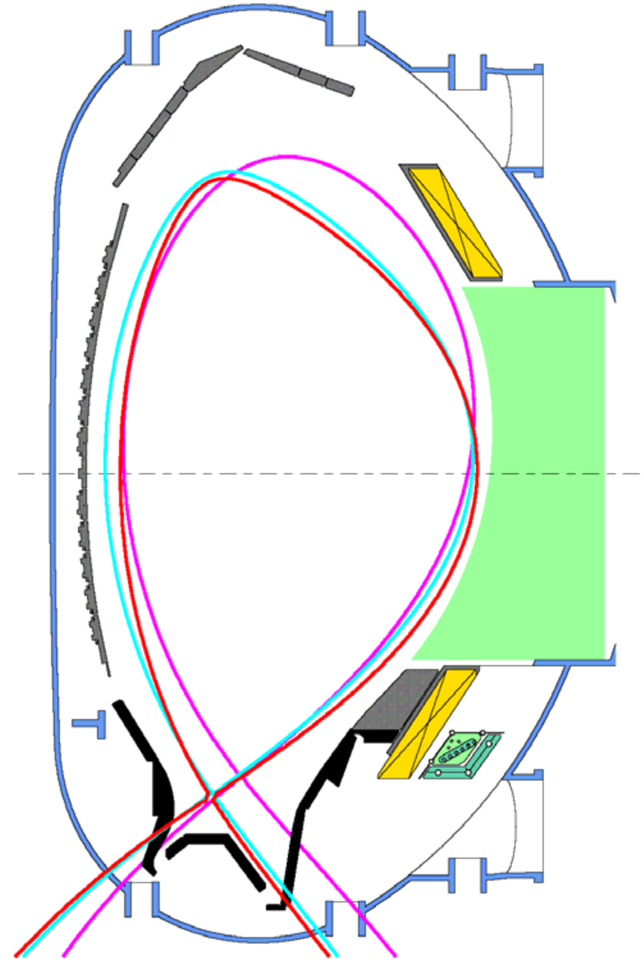




Plasma shaping by PF coils

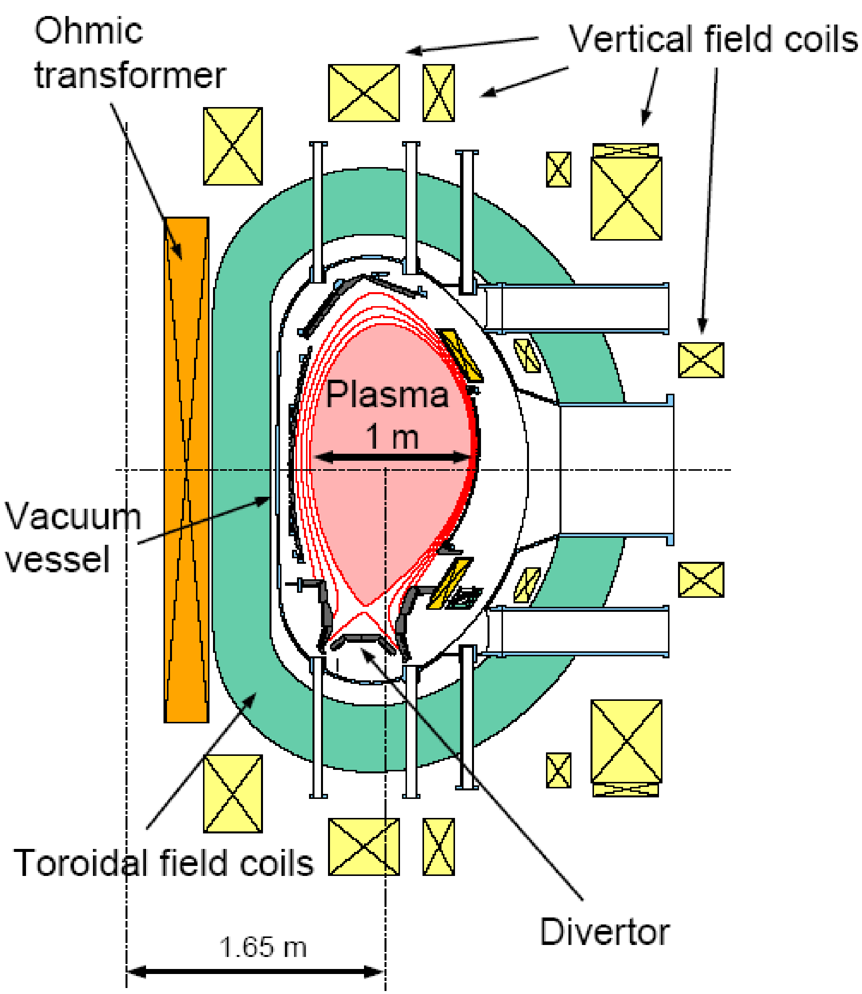
Tokamak



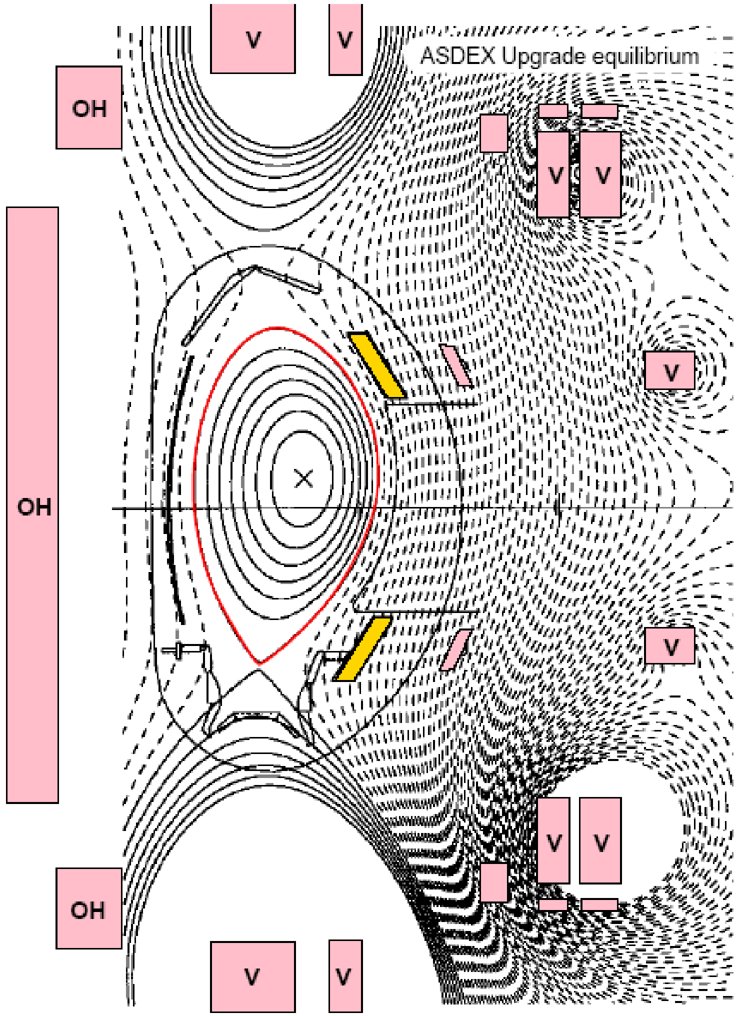


- The plasma shape can be modified by PF coil currents.

Tokamak

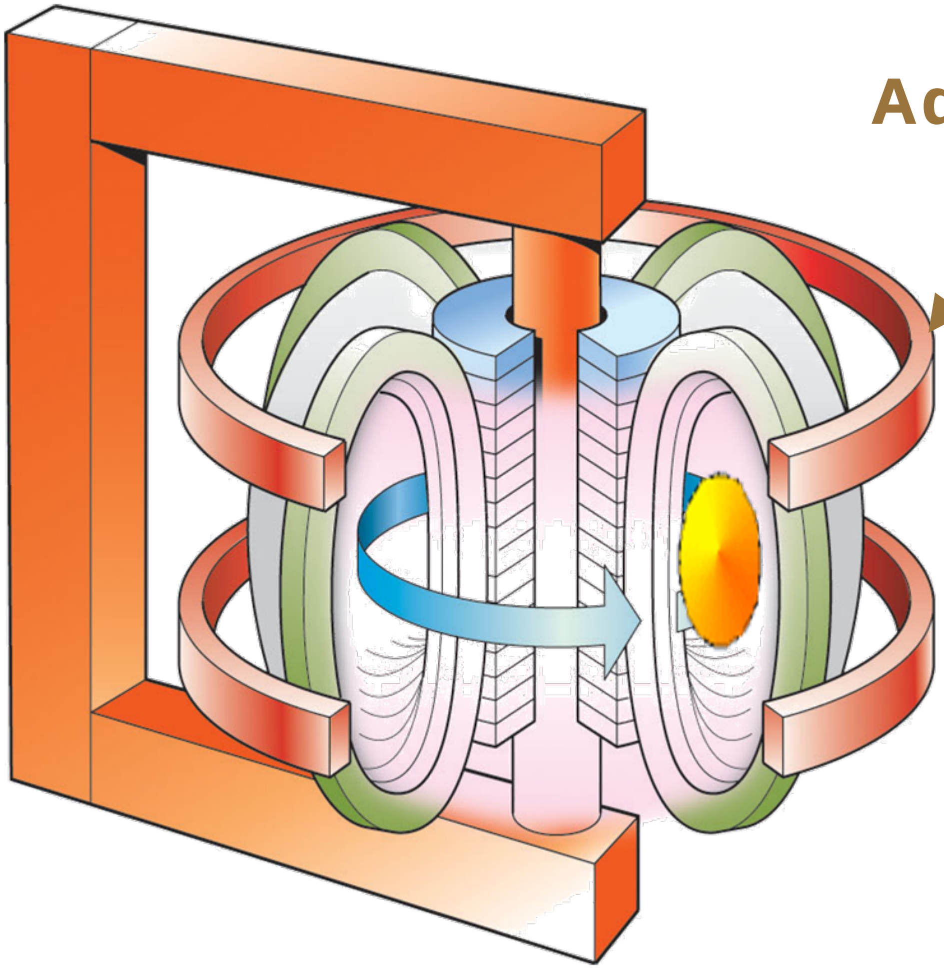


Ohmic transformer
Vertical field coils
Plasma
1 m
Vacuum vessel
Toroidal field coils
1.65 m
Divertor



ASDEX Upgrade equilibrium
OH
V

Tokamak

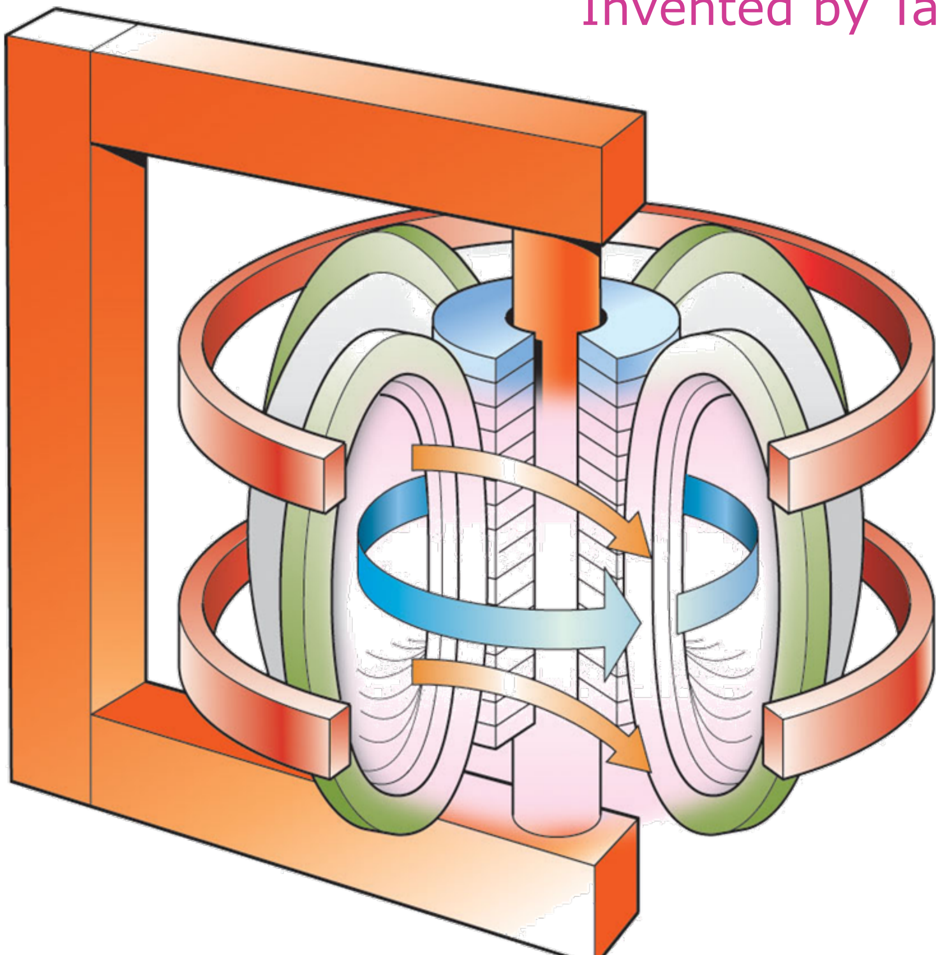


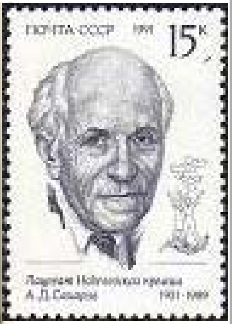
Adding vertical field coils (PF)

Plasma shaping by PF coils

Tokamak

Invented by Tamm and Sakharov in 1952

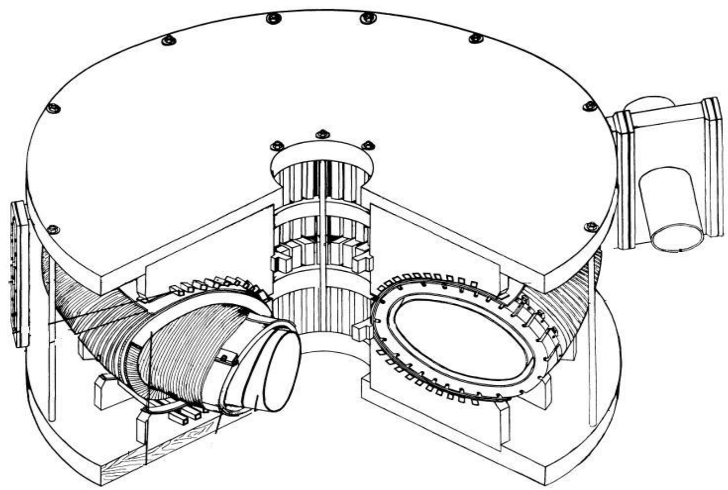




Toroidalnaja **ka**mera **ma**gnitnaja **k**atushka
(Toroidal chamber magnetic coil)

Tokamak

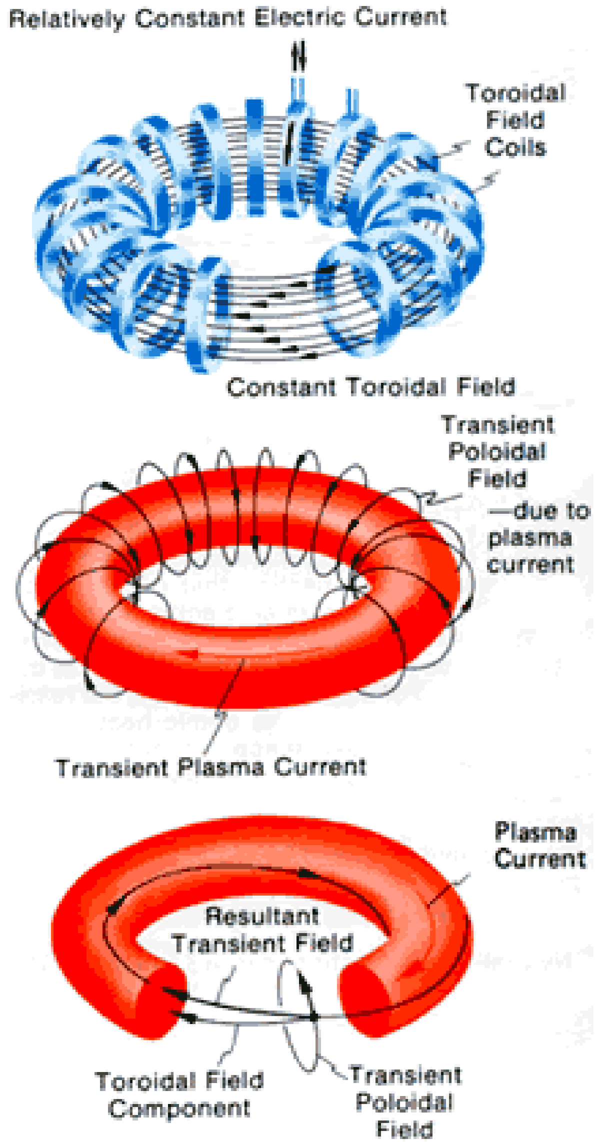
Invented by Tamm and Sakharov in 1952



Cutaway of the Toroidal Chamber in Artsimovitch's Paper *Research on Controlled Nuclear Fusion in the USSR*

Toroidalnaja **ka**mera **ma**gnitnaja **k**atushka
(Toroidal chamber magnetic coil)

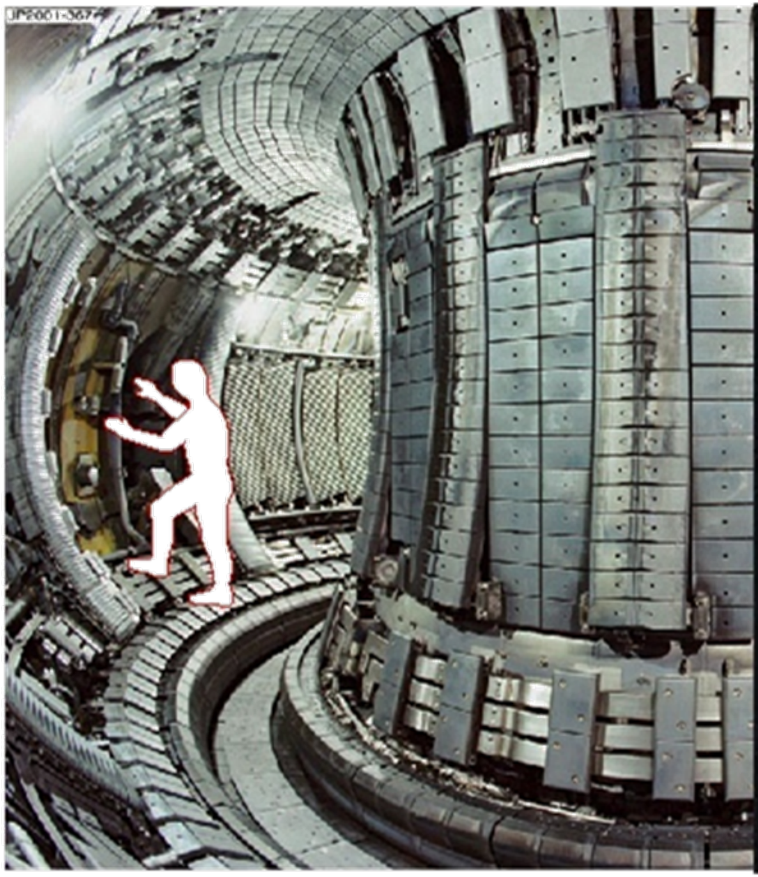
Tokamak



http://www.splung.com/content/sid/5/page/fusion

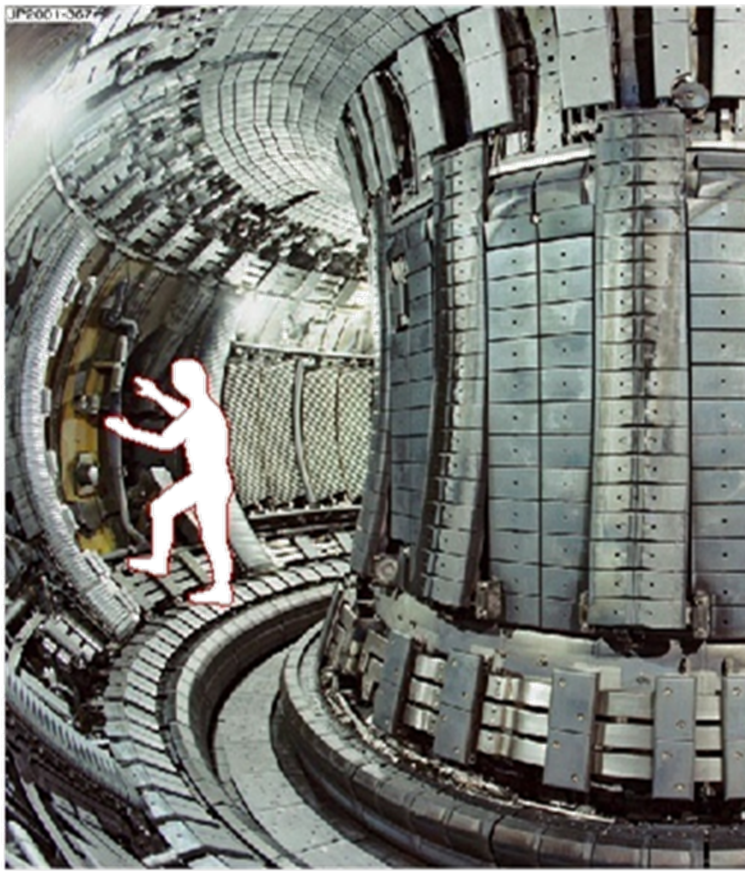
Tokamak

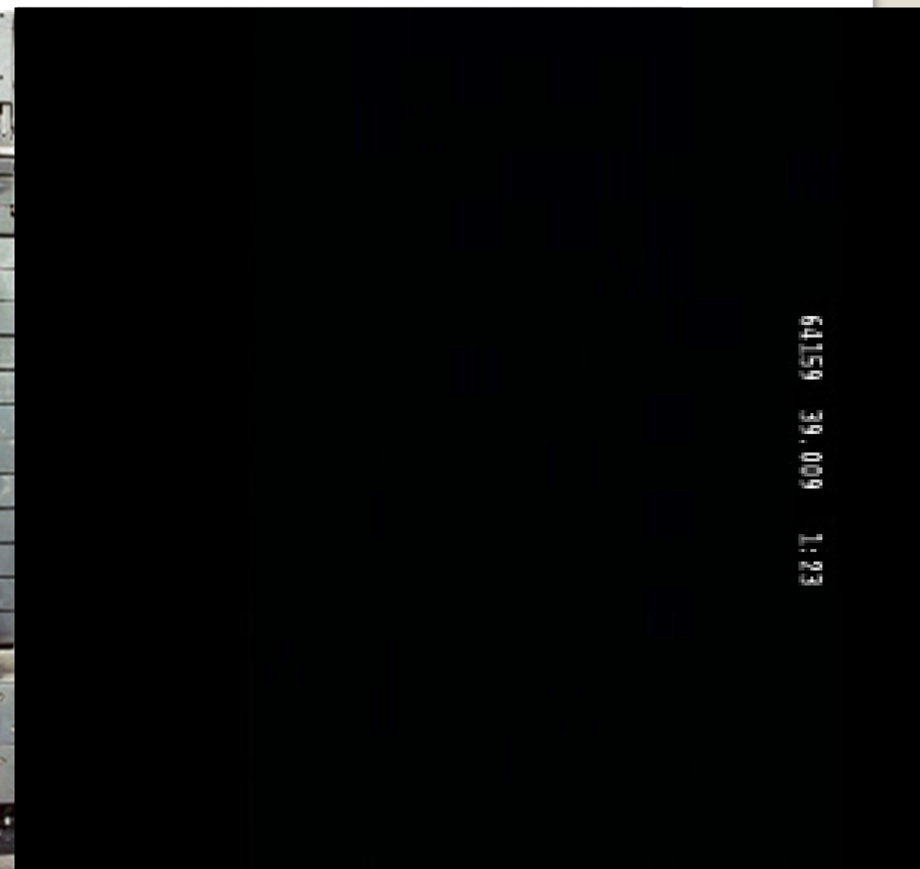
JET (Joint European Torus): R_0 = 3 m, a = 0.9 m, 1983-today



Tokamak

JET (Joint European Torus): R_0 = 3 m, a = 0.9 m, 1983-today



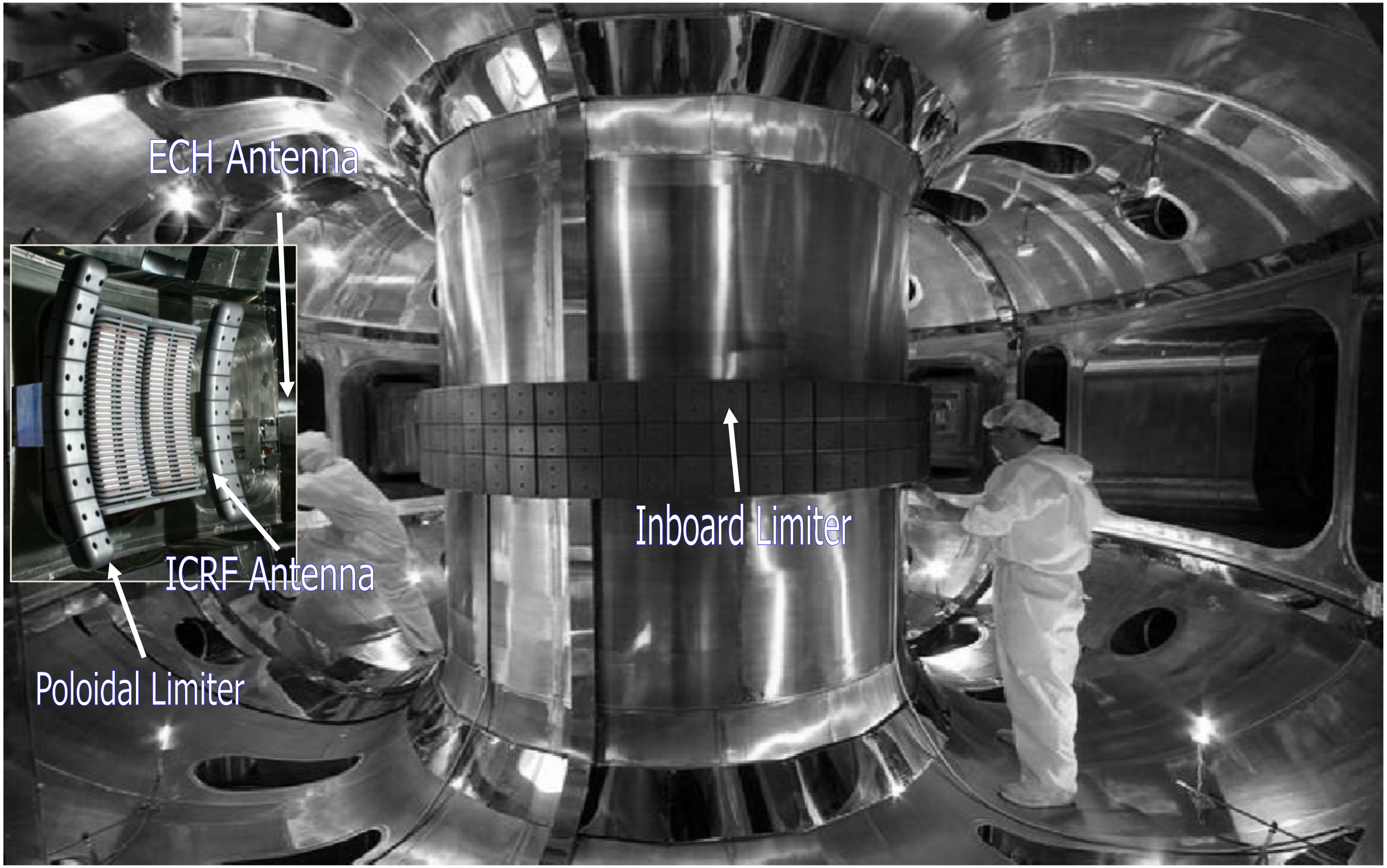


Impurity radiation typically peaks at temperature less than 100 eV, so that clean, hot plasmas radiates mostly from the peripheral regions.

Tokamak

Tokamak

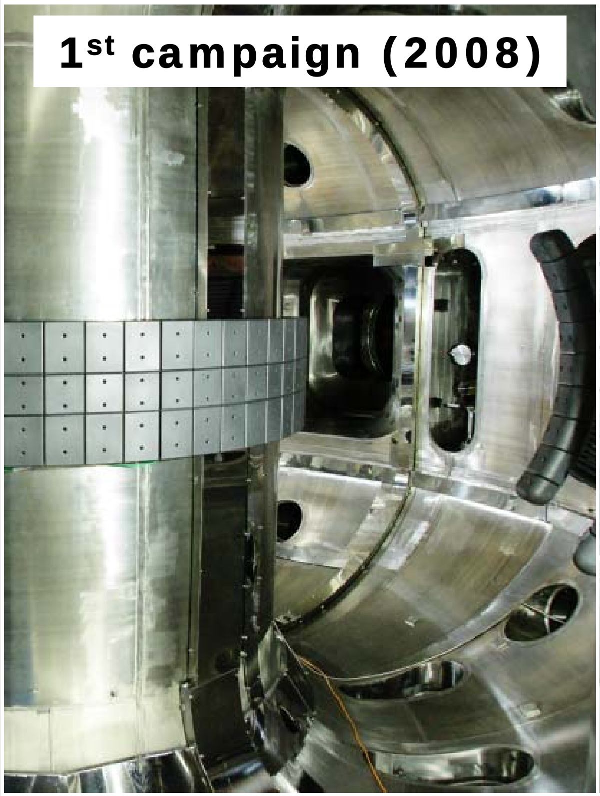
KSTAR (Korea Superconducting Tokamak Advanced Research):
R_0 = 1.8 m, a = 0.5 m, 2008-today



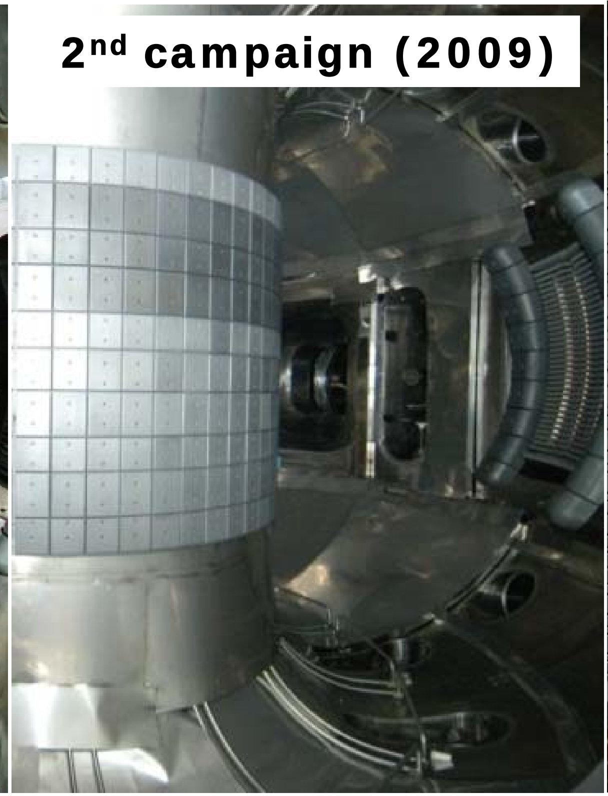
Tokamak

KSTAR (Korea Superconducting Tokamak Advanced Research):

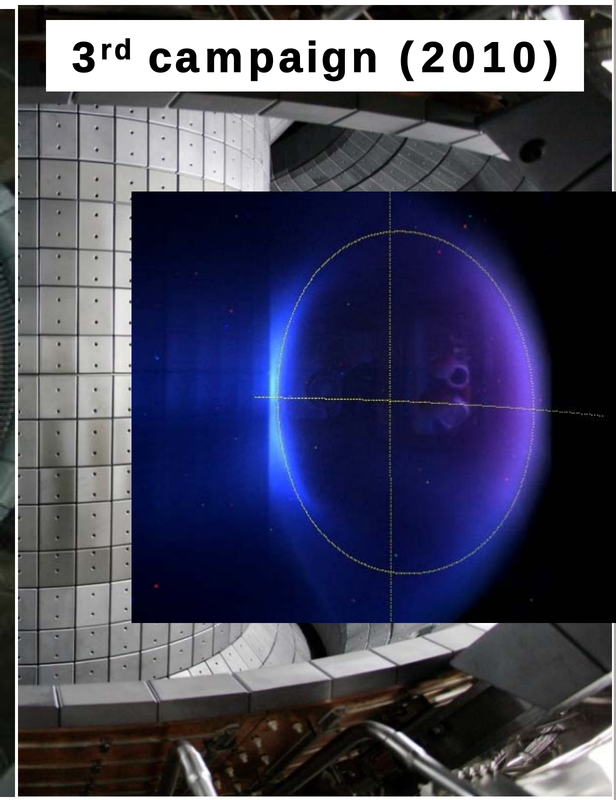
R_0 = 1.8 m, a = 0.5 m, 2008-today



1st campaign (2008)



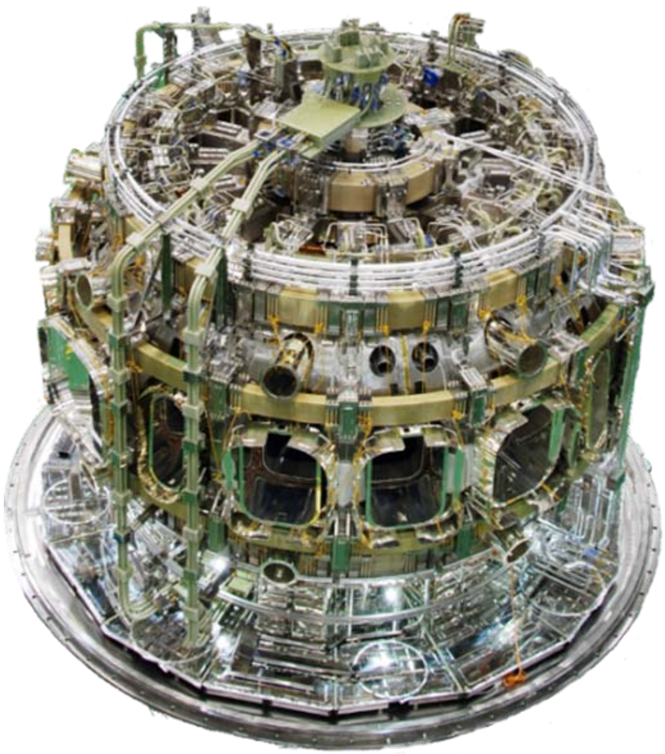
2nd campaign (2009)

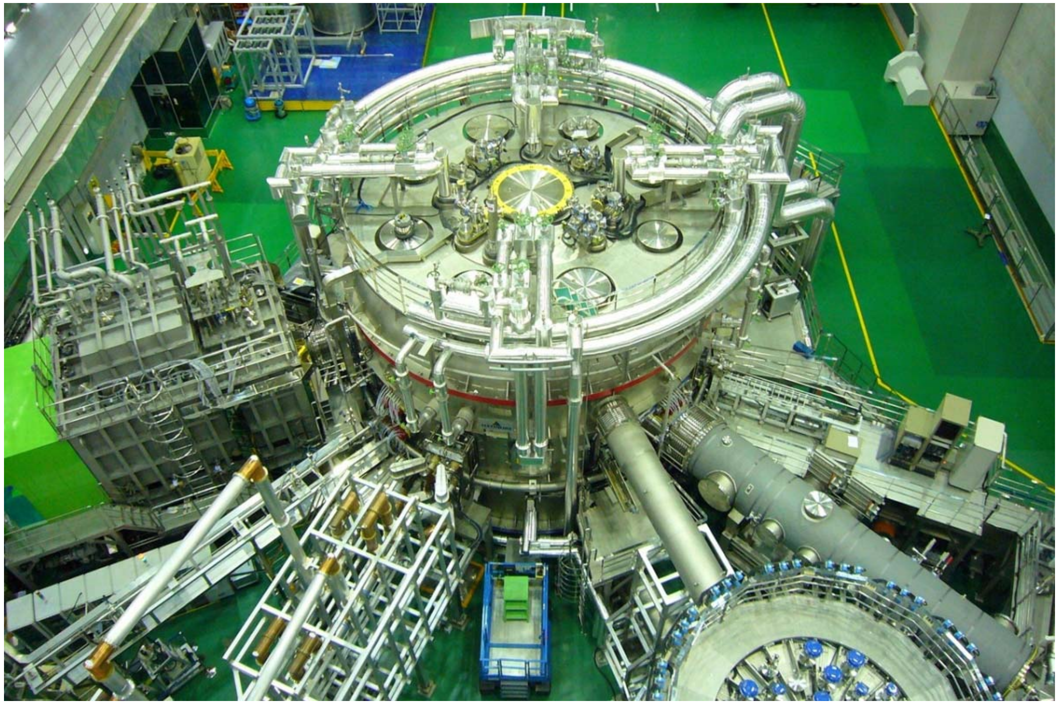


3rd campaign (2010)

Tokamak

KSTAR (Korea Superconducting Tokamak Advanced Research):
R_0 = 1.8 m, a = 0.5 m, 2008-today

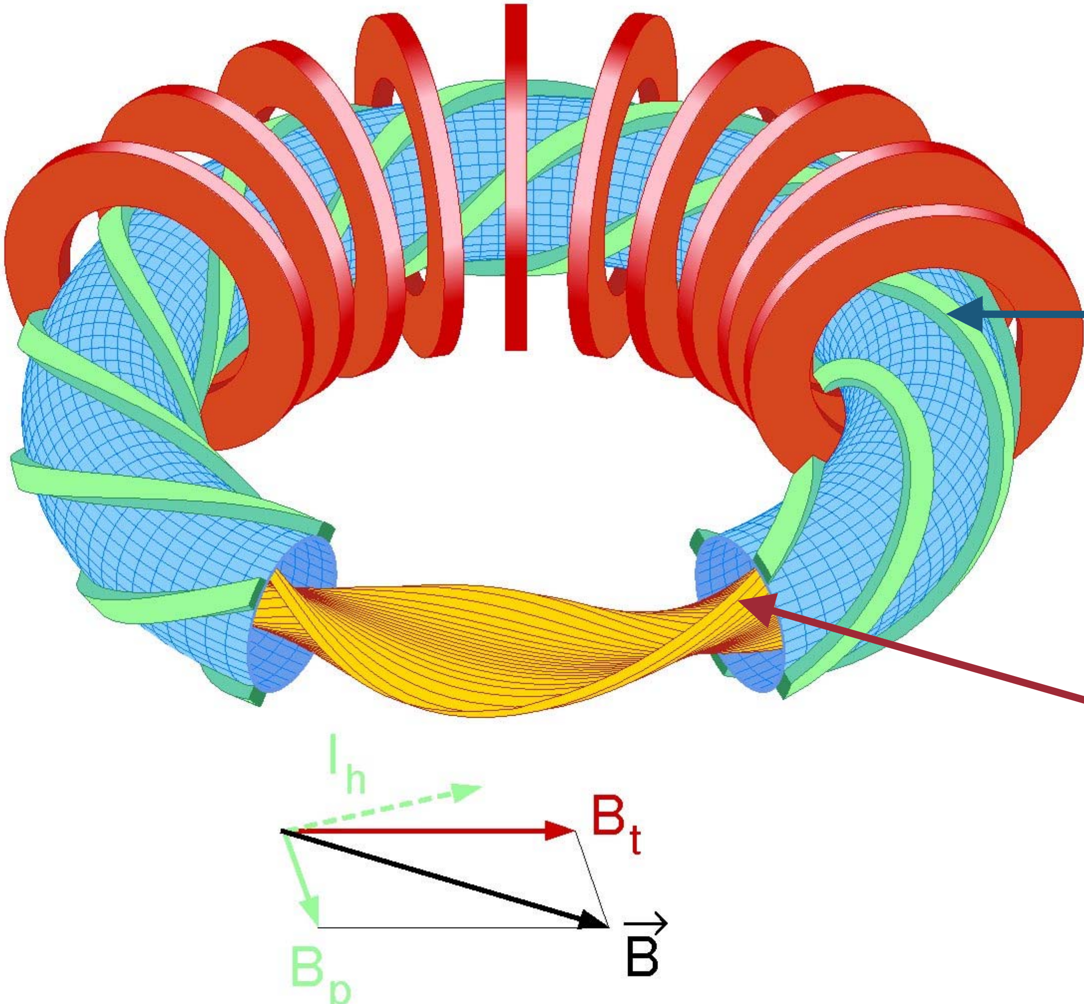




Tokamak

KSTAR (Korea Superconducting Tokamak Advanced Research):
R_0 = 1.8 m, a = 0.5 m, 2008-today

Stellarator



External coils

Poloidal field
induced by
the external coils

Stellarator

THE PHYSICS OF FLUIDS

VOLUME 1, NUMBER 4 JULY-AUGUST, 1958

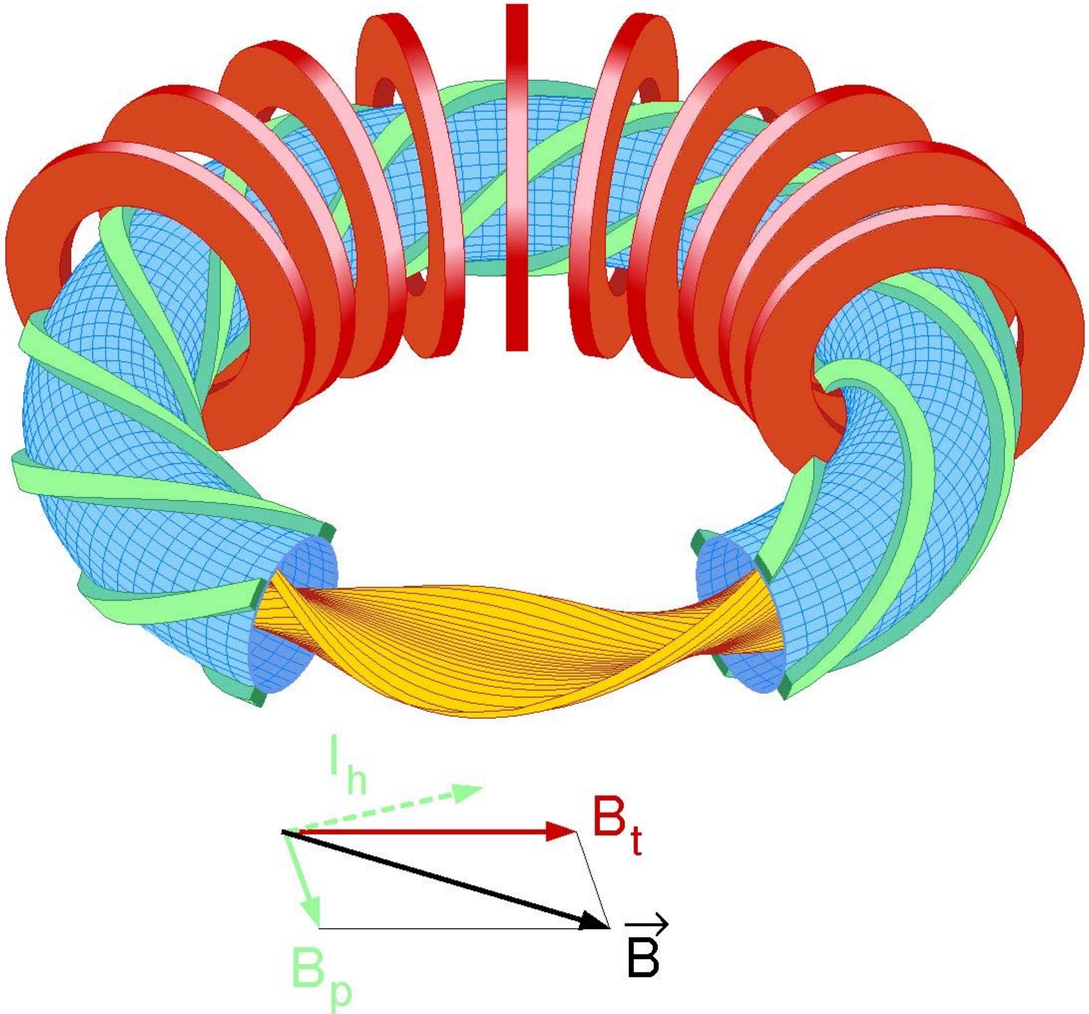
The Stellarator Concept*

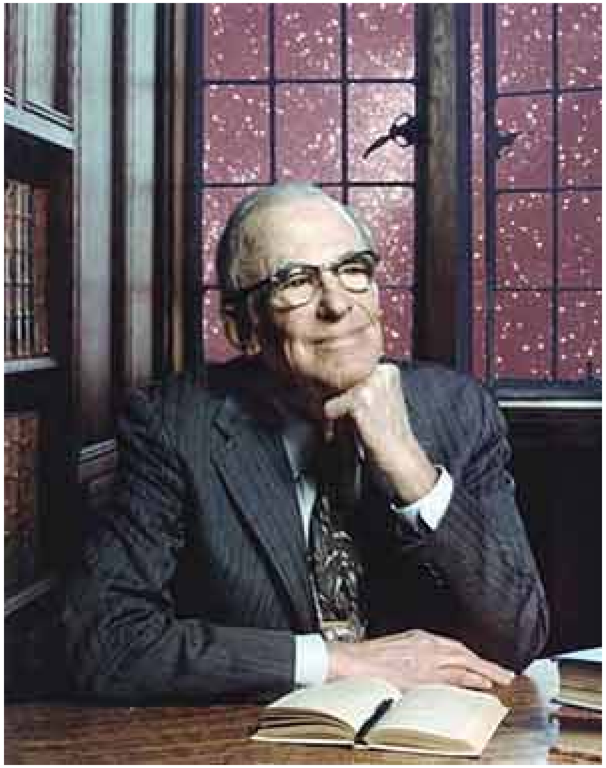
LYMAN SPITZER, JR.
Project Matterhorn, Princeton University, Princeton, New Jersey
(Received May 27, 1958)

The basic concepts of the controlled thermonuclear program at Project Matterhorn, Princeton University are discussed. In particular, the theory of confinement of a fully ionized gas in the magnetic configuration of the stellarator is given, the theories of heating are outlined, and the bearing of observational results on these theories is described.

Stellarator

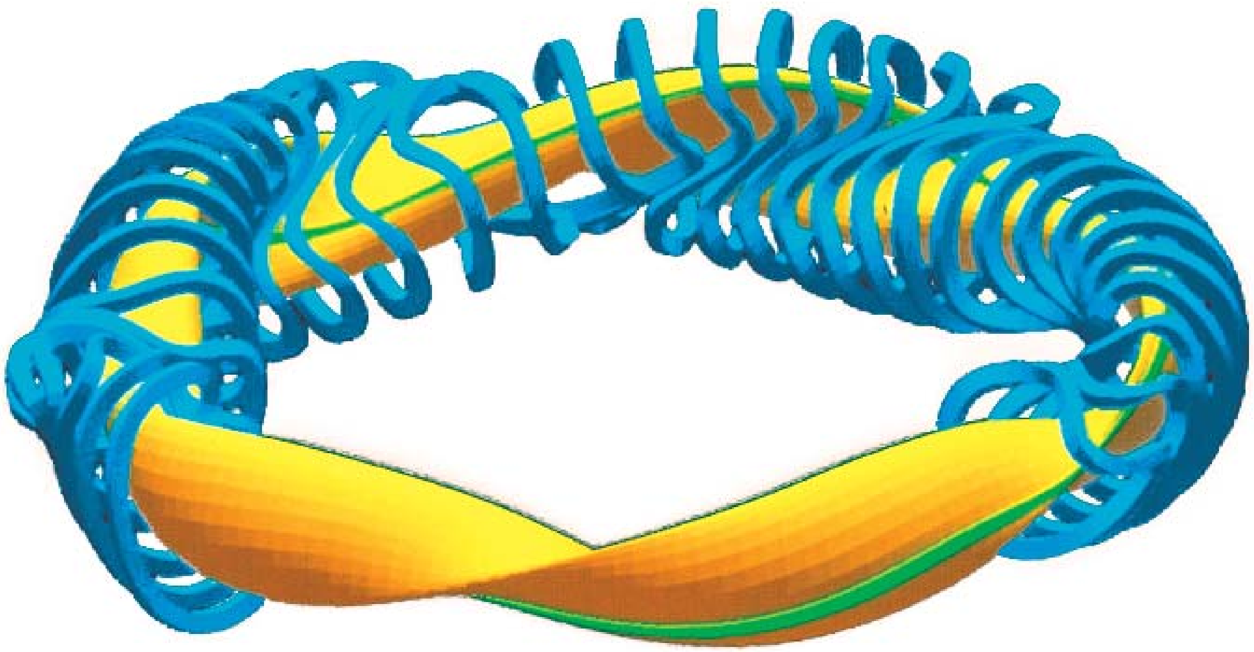
Invented by Lyman Spitzer, Jr. in Princeton in 1951





Stellarator

Wendelstein 7-X, Germany



3D configuration!

Stellarator

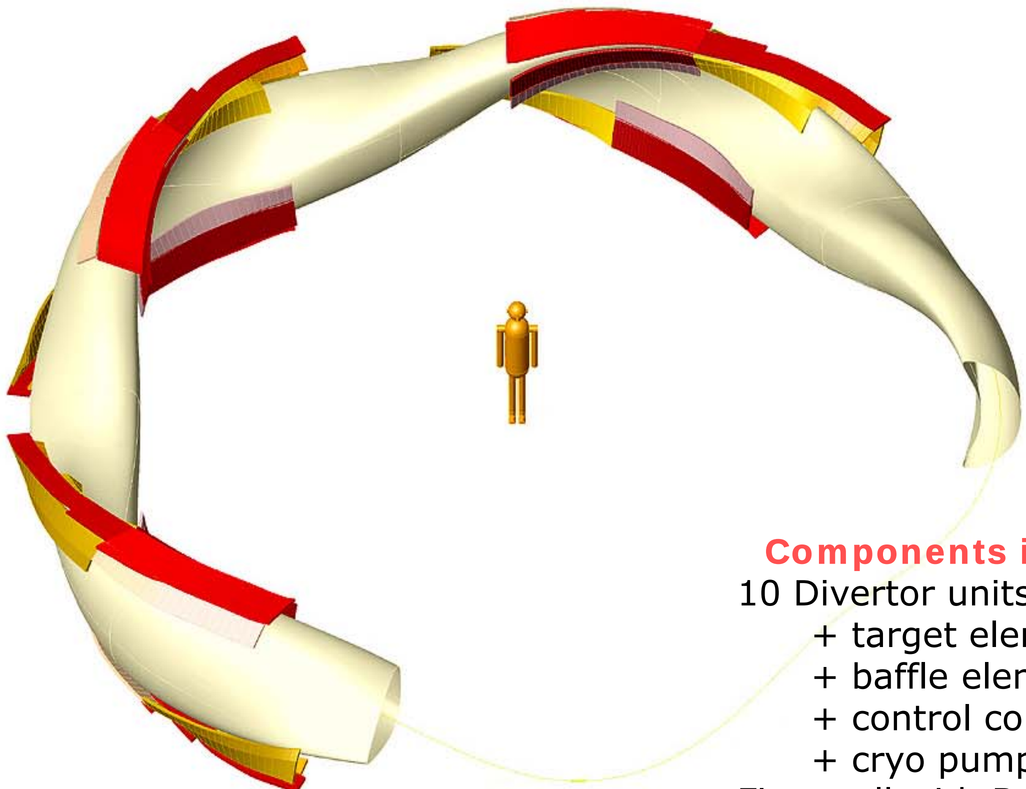
Plasma

Plasma Parameter

R: 5.5 m
$<a>$: 0.53 m
iota: 5/6 - 5/4
$n_e(0)_{max}$: $3*10^{20}$ m^{-3}
$T_e(0)_{max}$: 5 keV
$<\beta>$: < 5 %

Stellarator

Divertor



Components inside plasma vessel

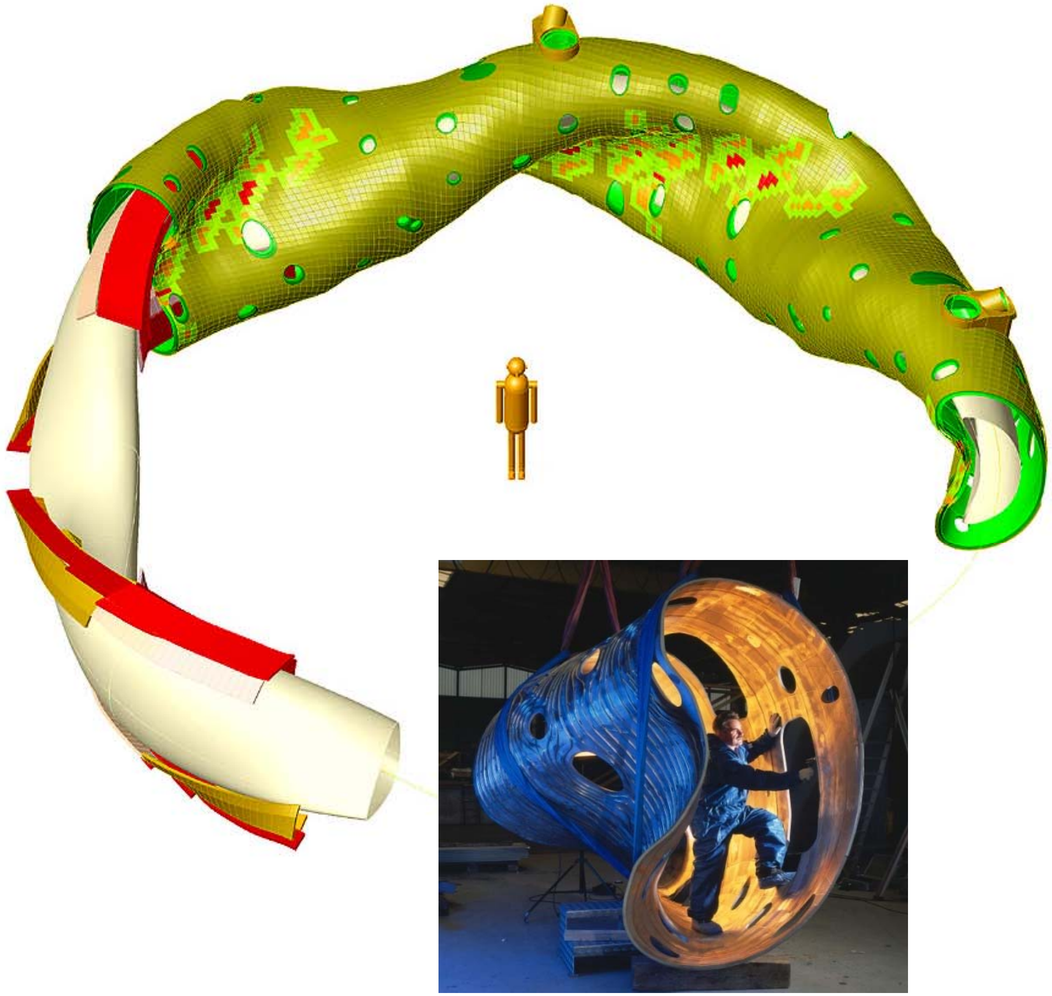
10 Divertor units
- + target elements (10 MW/m^2)
- + baffle elements (0.5 MW/m^2)
- + control coils
- + cryo pumps

First wall with B_4C coating (0.2 MW/m^2)
Diagnostics

- Design for steady state operation -

Stellarator

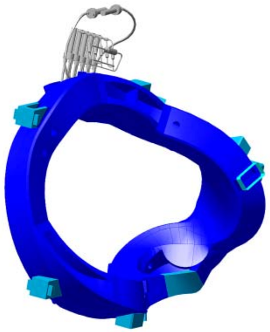
Plasma Vessel

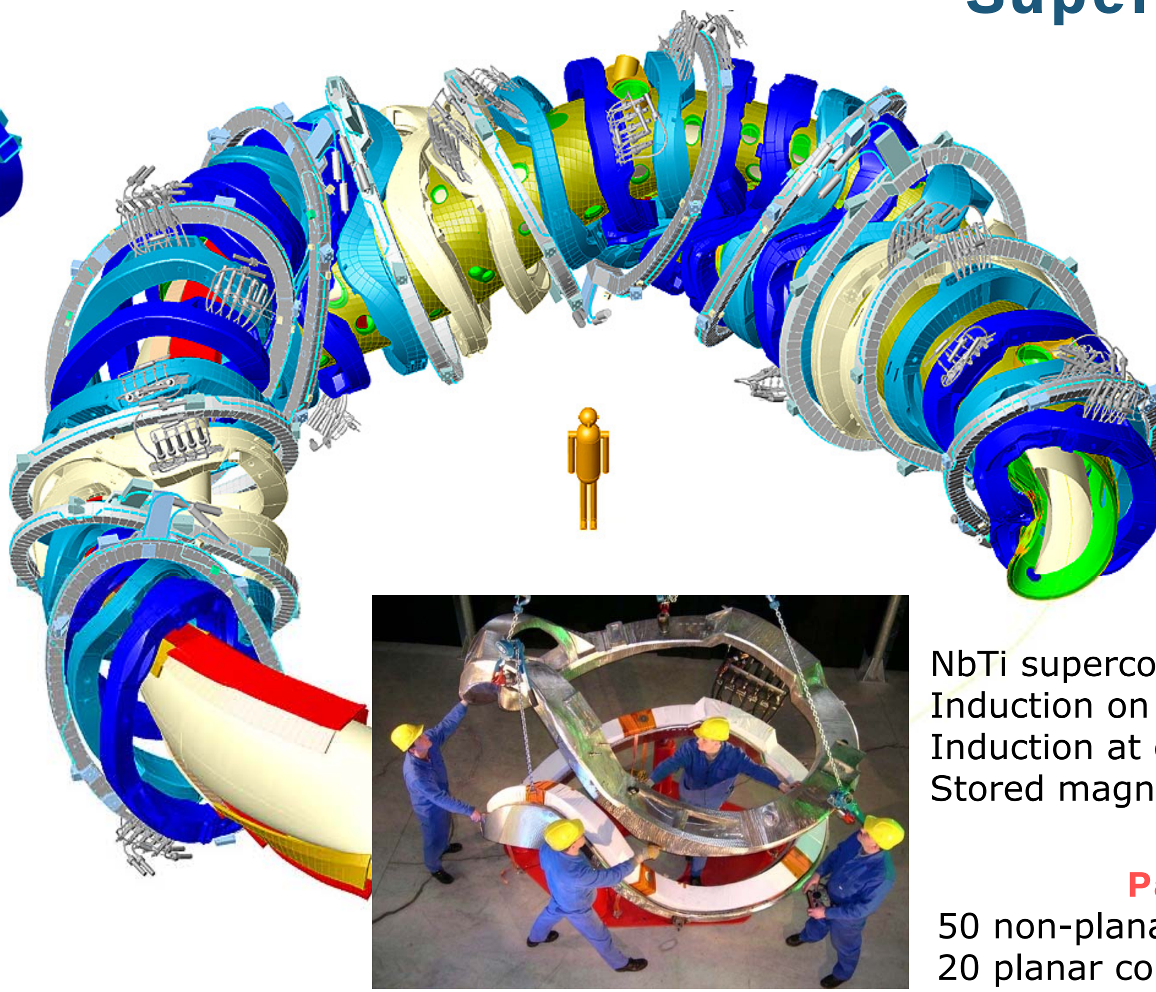


Parameter
Volume: 110 m^3
Surface: 200 m^2
Vacuum: < 10^{-8} mbar
Mass: 35 t
Tolerances < 2 mm

Stellarator

Superconducting Coils





Coils

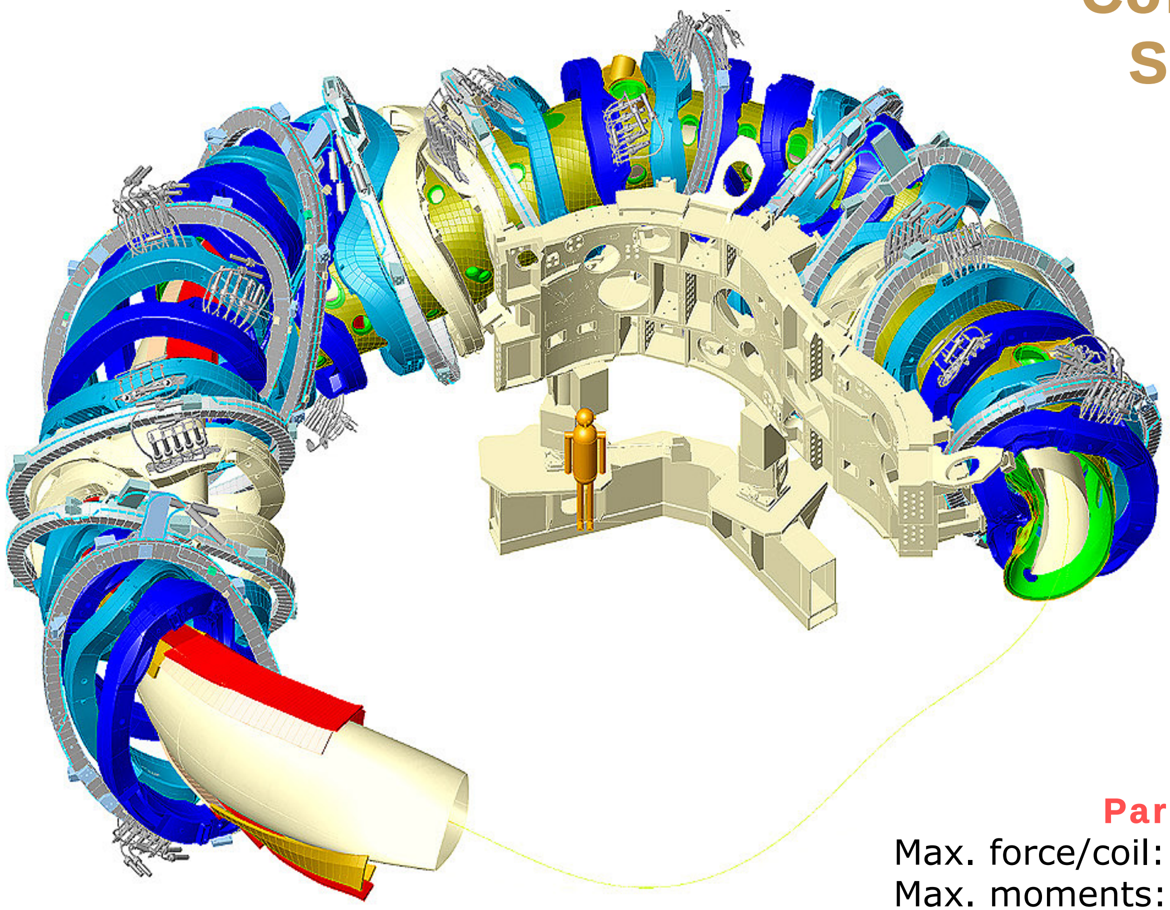
NbTi superconductor (> 3.4 K)
Induction on axis: 2.5 T (< 3T)
Induction at coil: 6.8 T at 17.8 kA
Stored magnetic energy: 600 MJ

Parameter

50 non-planar coils, 5 types
20 planar coils, 2 types, variation
5 modules, 2 sym. halfmodules

Stellarator

Coil Support Structure

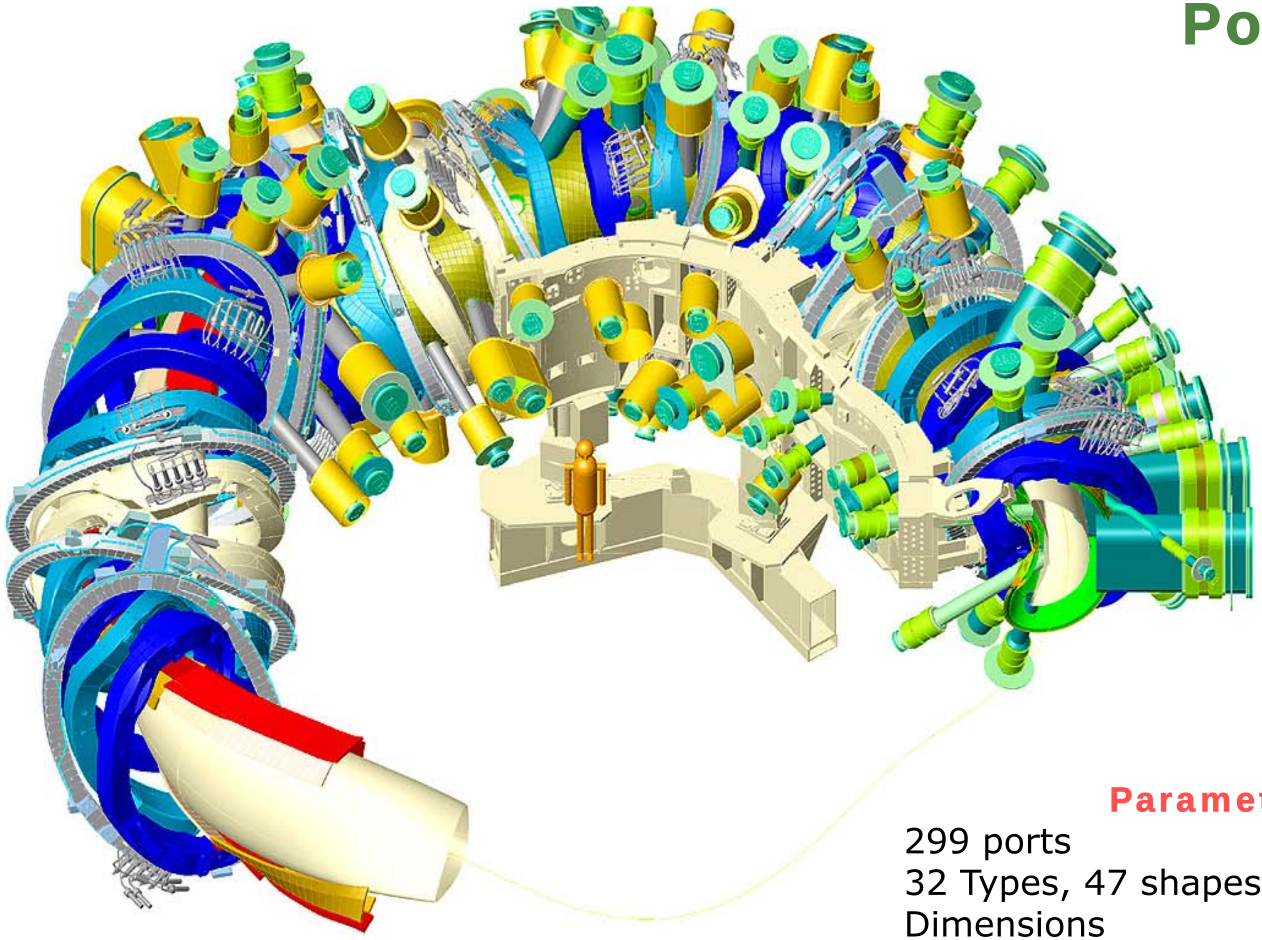


Parameter

Max. force/coil: 3.6 MN
Max. moments: 0.8 MNm
2 supports/coil
Welded connections between coils

Stellarator

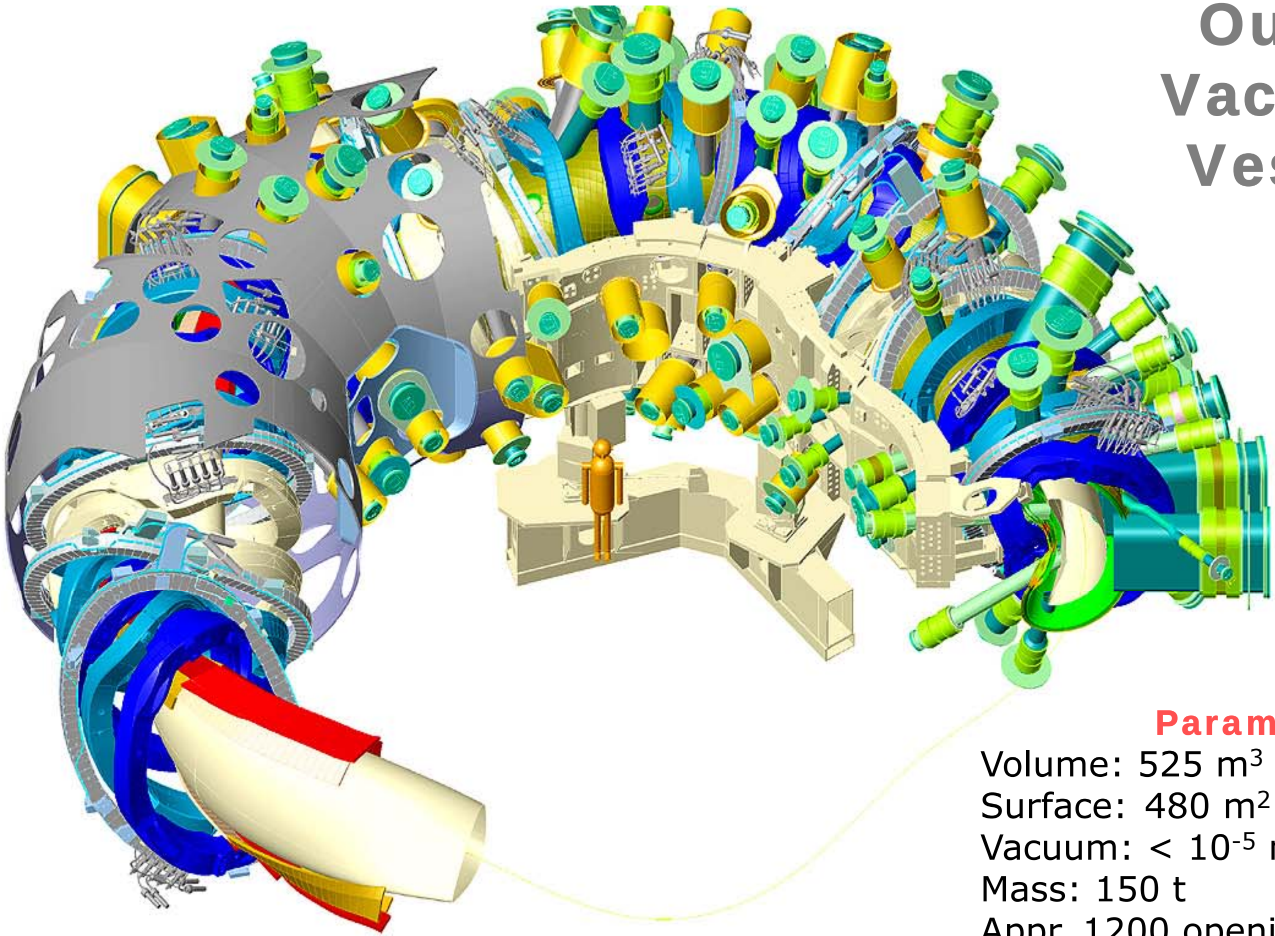
Ports



Parameter

299 ports
32 Types, 47 shapes
Dimensions
+ 100 -> 400 mm
+ 150x400 -> 400x1000 mm^2

Stellarator



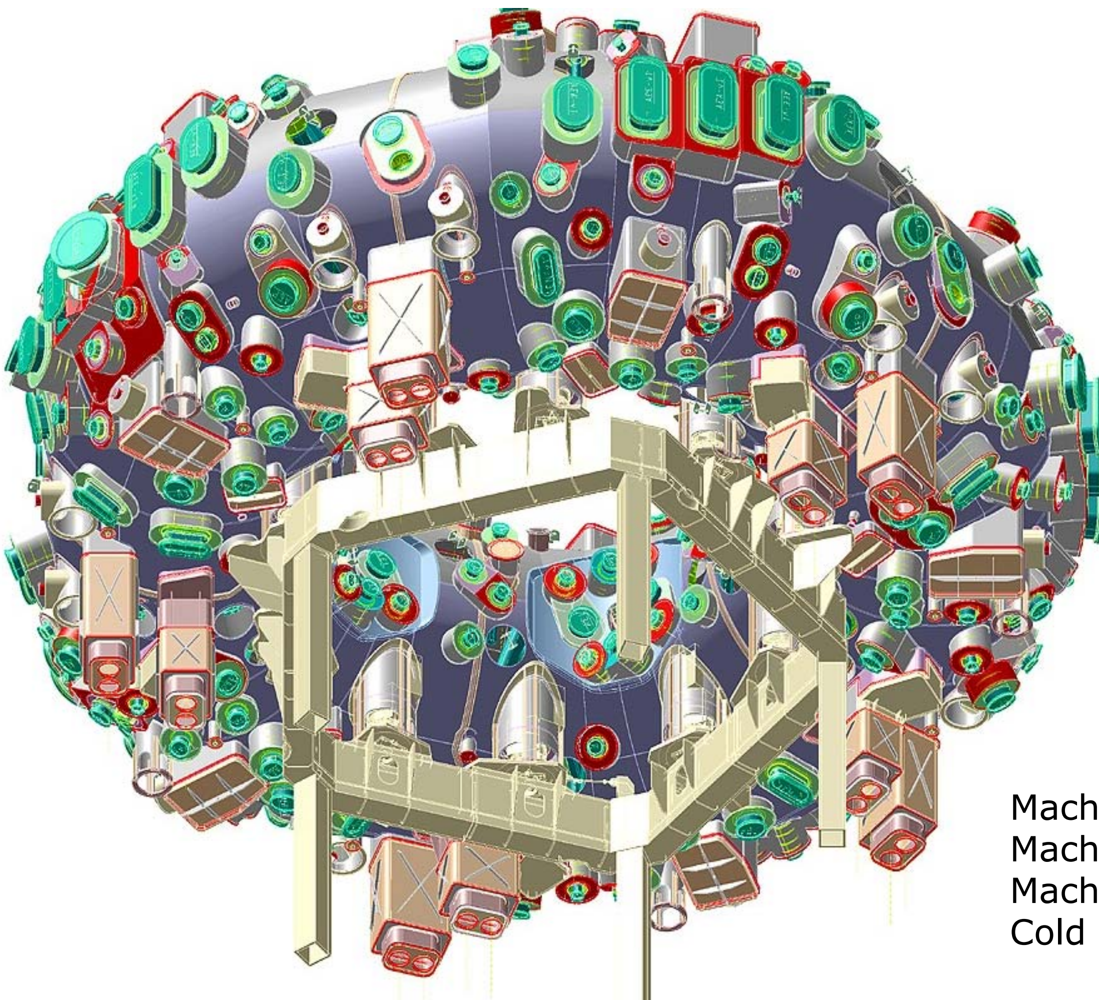
Outer
Vacuum
Vessel

Parameter

Volume: 525 m^3
Surface: 480 m^2
Vacuum: < 10^{-5} mbar
Mass: 150 t
Appr. 1200 openings

Thermal insulation on all warm surfaces of the cryostat

Stellarator



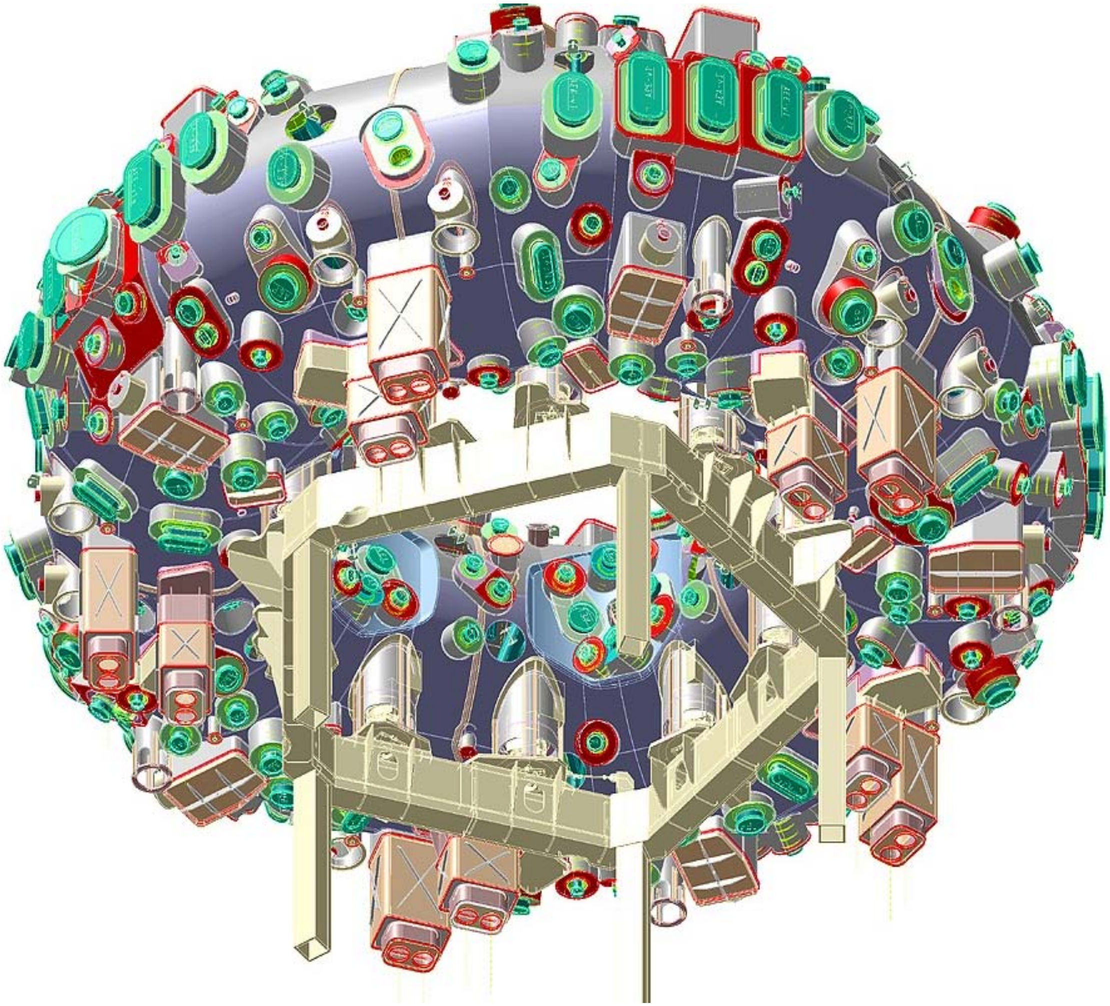
Schematic View

Parameter

Machine height: 4.5 m
Machine diameter: 16 m
Machine mass: 725 t
Cold mass: 425 t

Heating power: 15 - 30 MW
Nominal pulse length: 30 min

Stellarator

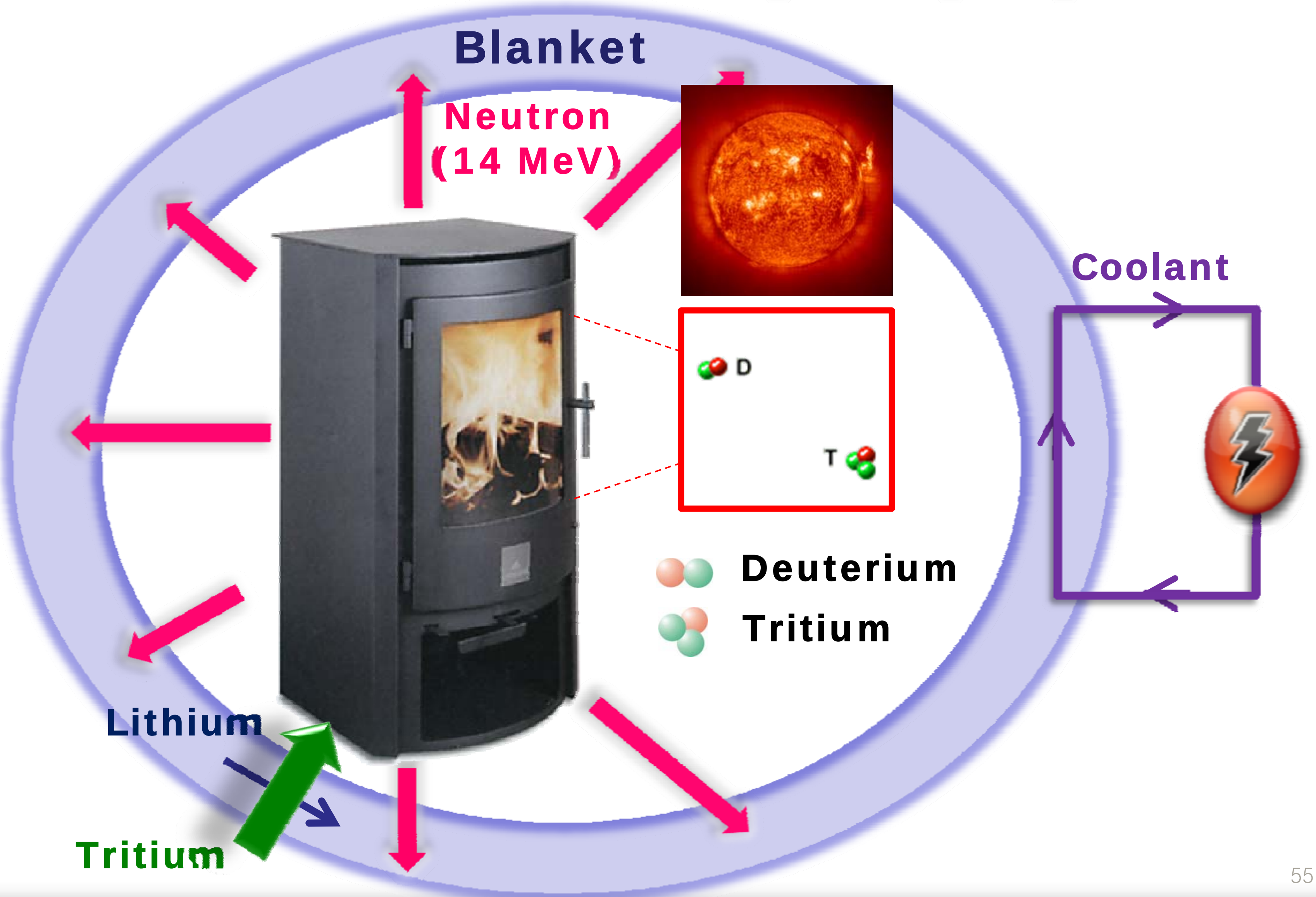


What a complex system it is!

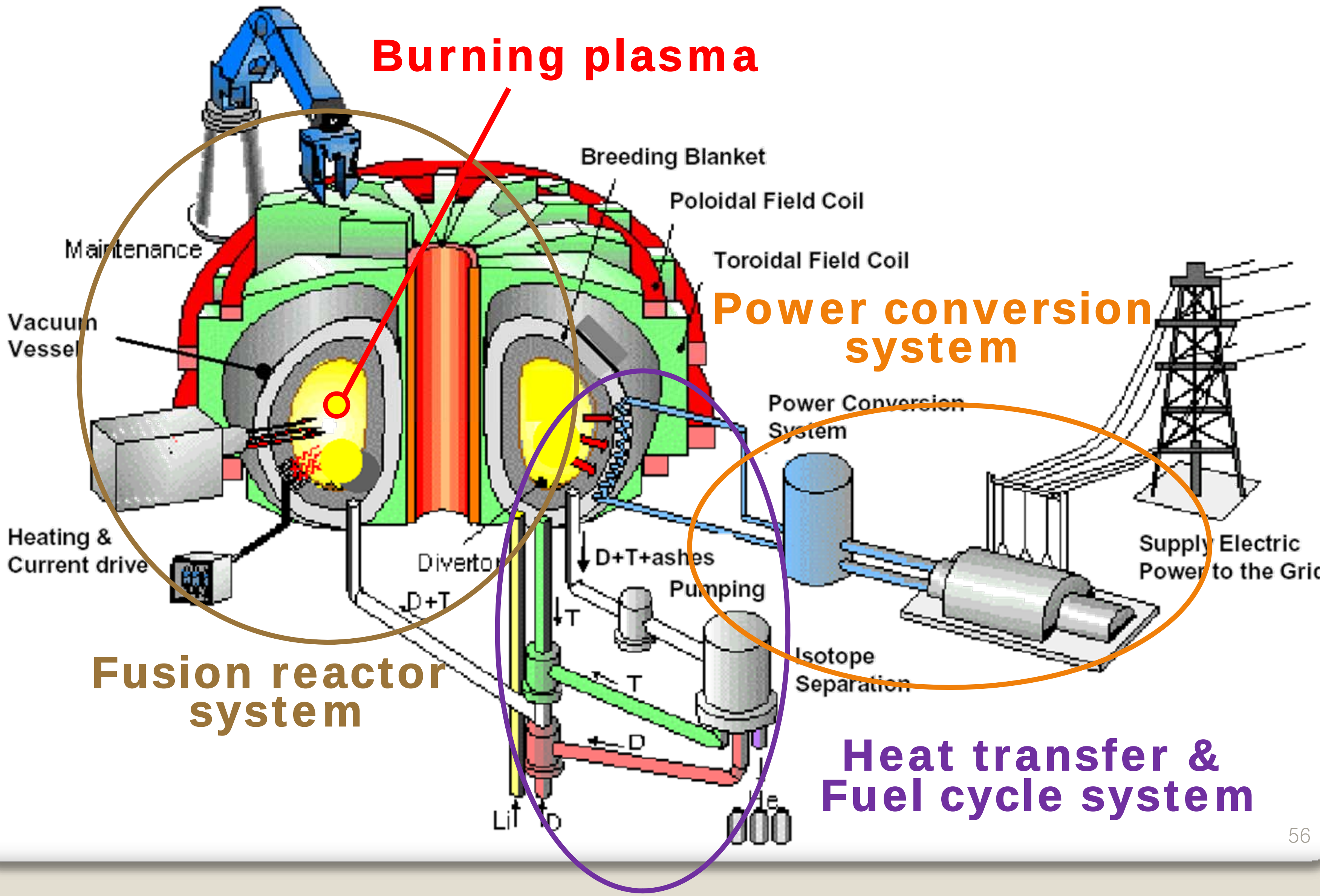
Tokamak .VS. Stellarator

	Advantage	Disadvantage
Tokamak	- Simple 2D structure, so relatively easy to analyze and fabricate the device - The most studied and successful up to now (mainstream in the roadmap to a feasible fusion reactor)	- Need an external current drive (inductive or non-inductive) for plasma current generation & steady-state operation - Subject to plasma current-driven instabilities and disruptions
Stellerator	- No external current drive necessary, so inherently steady-state operation possible - Relatively free from plasma current-driven instabilities and disruptions	- Complicated 3D structure, so difficult to analyse and fabricate the device - Large system size required with a high aspect ratio - Subject to large neoclassical transport at low collisionality - existence of boostrap current

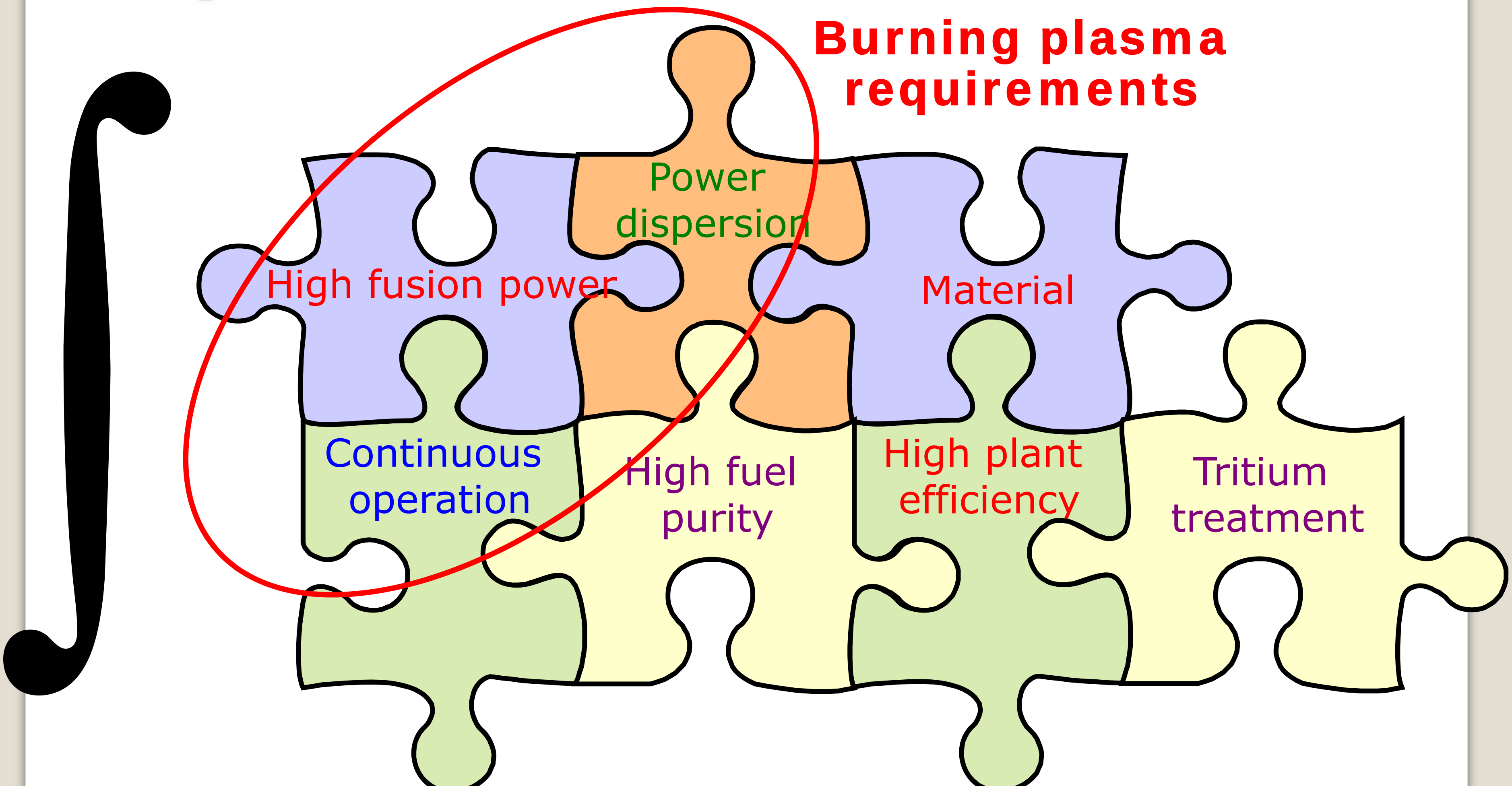
Fusion Power Plant (FPP) System



Fusion Power Plant (FPP) System



Requirements for FPP



Burning Plasma Requirements