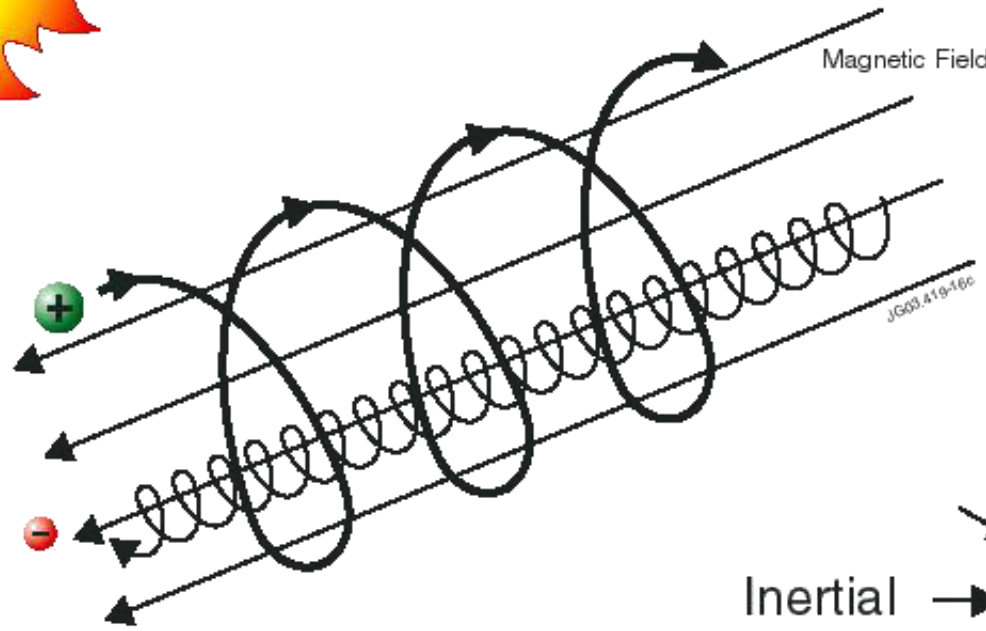
Introduction to Nuclear Fusion

Prof. Dr. Yong-Su Na

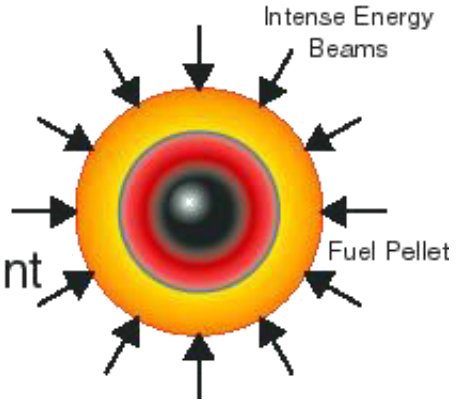
To build a sun on earth

Gravitational Confinement

Magnetic Confinement



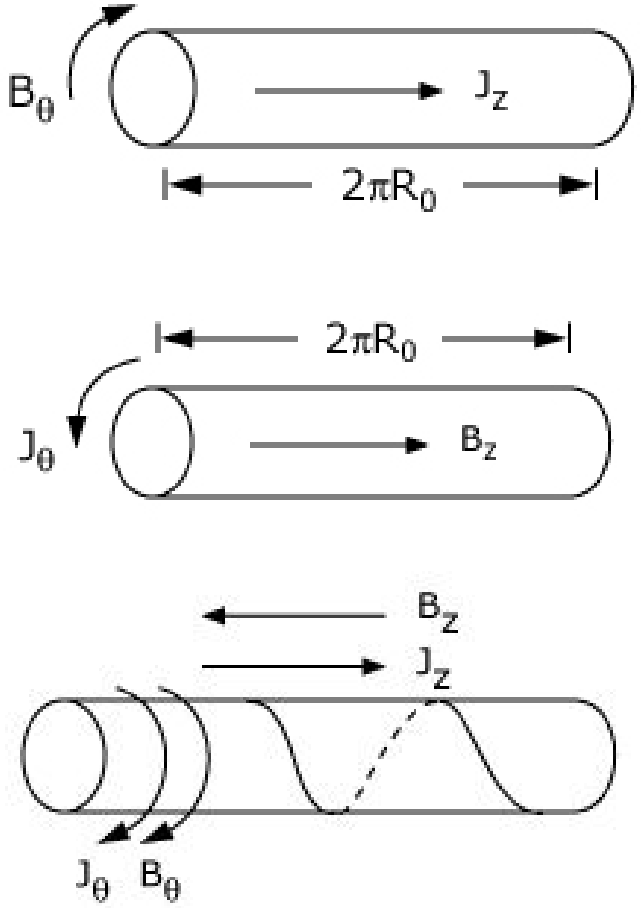
- Open magnetic confinement
- Closed magnetic confinement



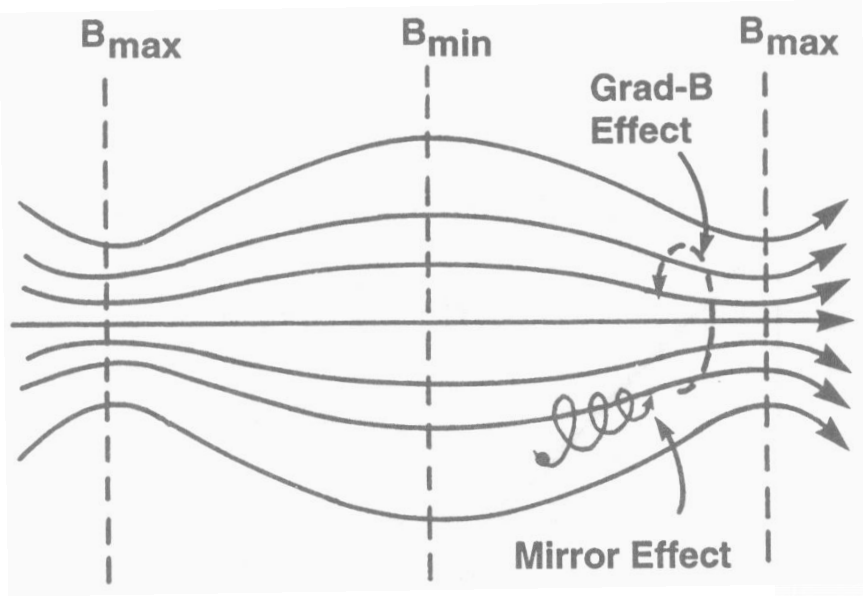
Inertial Confinement

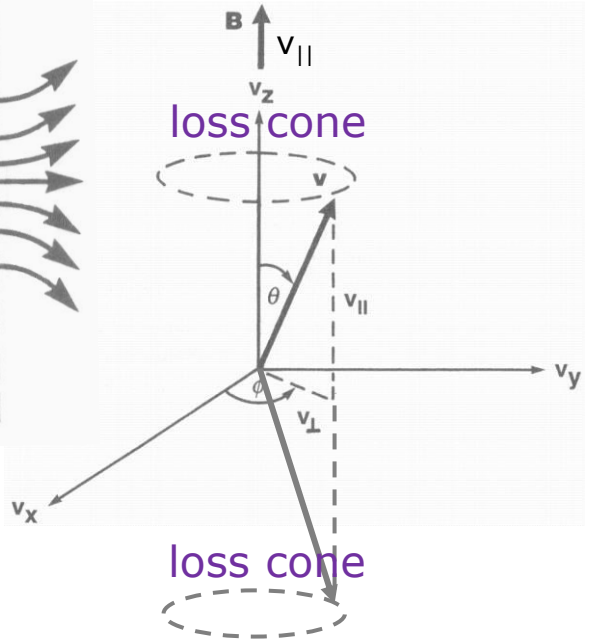
What is closed magnetic confinement?

Open Magnetic System



$$\sin^2\theta \geq \frac{B_{\min}}{B_{\max}}$$



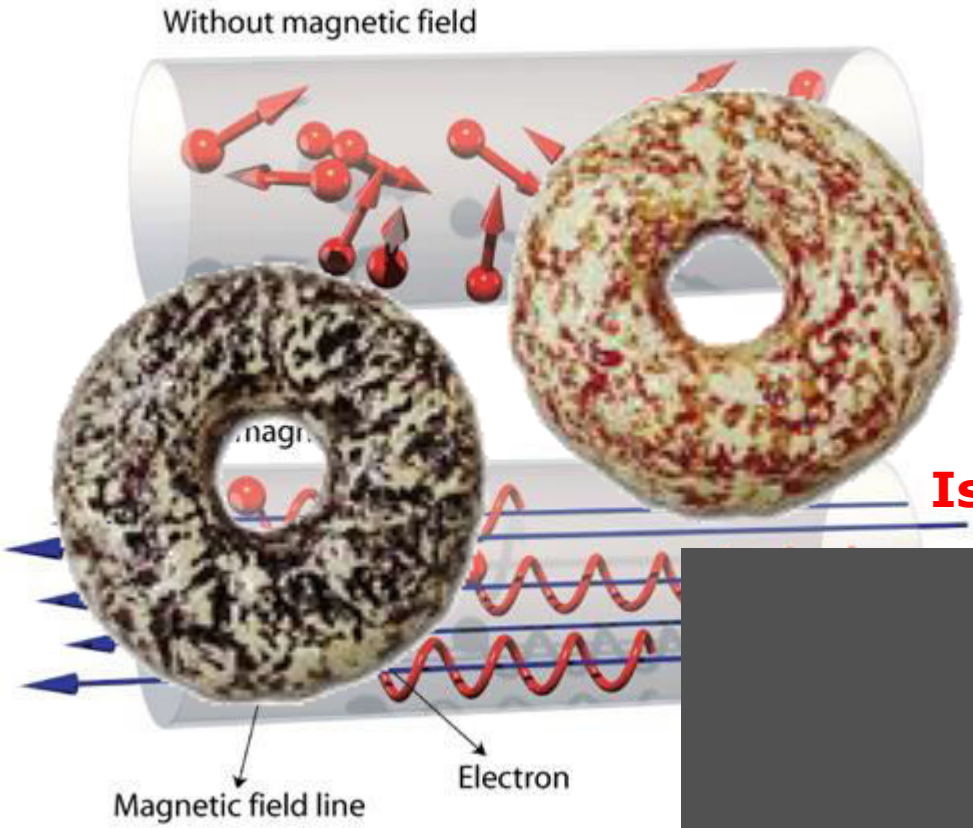


- Suffering from end losses

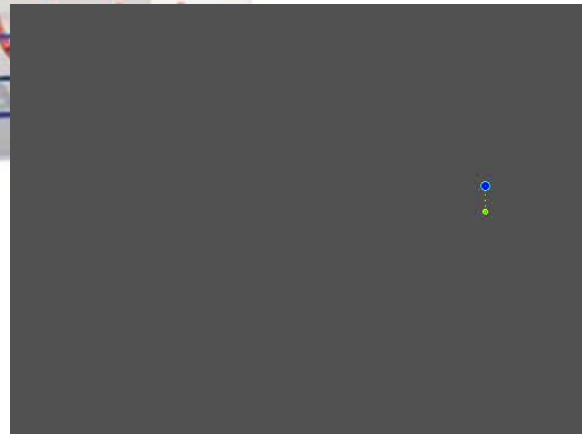
J.P. Freidberg, "Ideal Magneto-Hydro-Dynamics", lecture note

A. A. Harms et al, "Principles of Fusion Energy", World Scientific (2000)

Open Magnetic System



Is this motion realistic?



Magnetic field

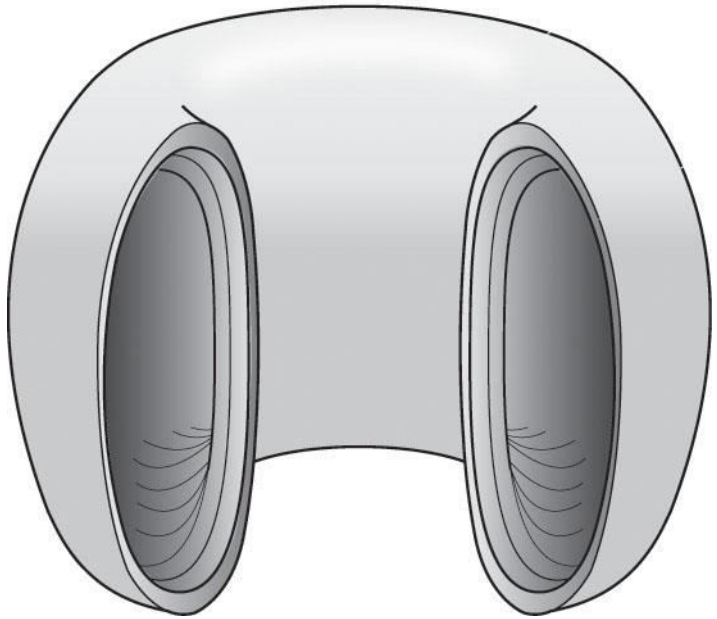
ion

Dunkin donuts (2010)

Closed Magnetic System

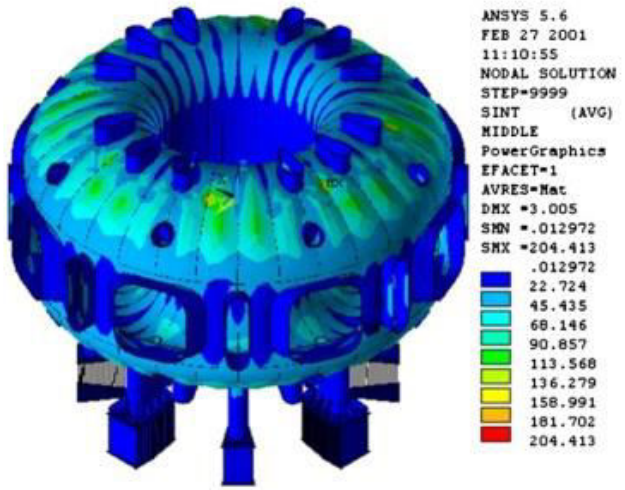
Magnetic field

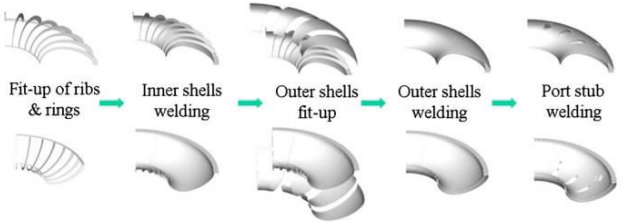
ion



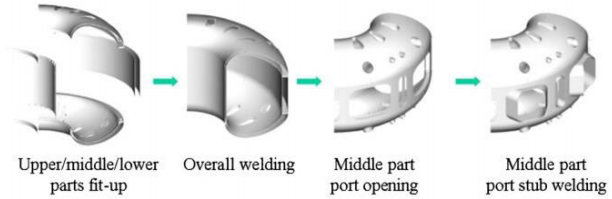
Donut-shaped vacuum vessel

Closed Magnetic System

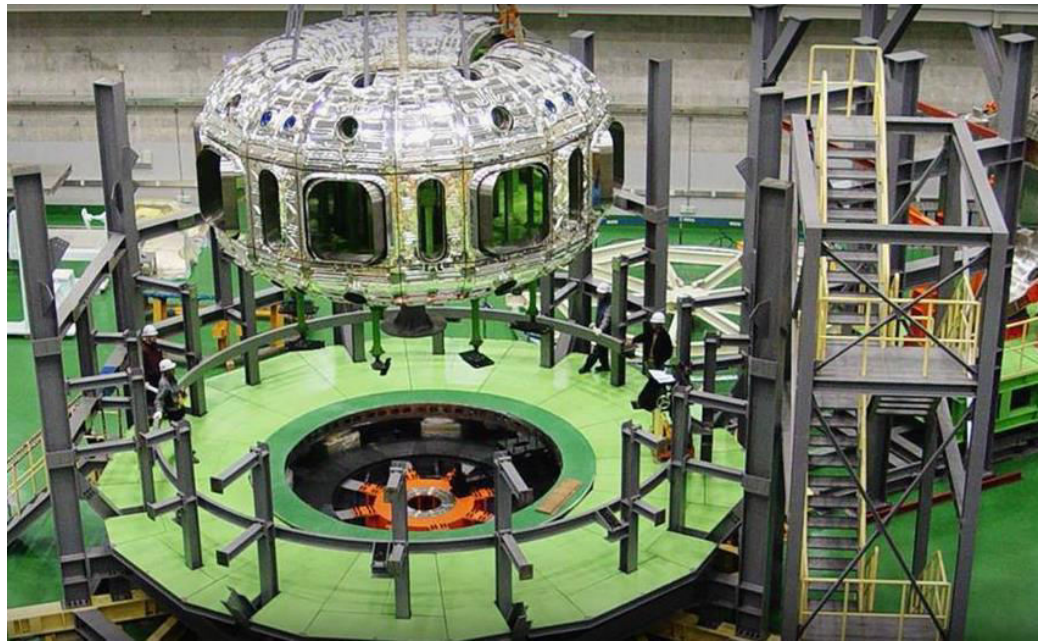




(a) Upper/lower parts fabrication procedures



(b) Quadrant fabrication procedure



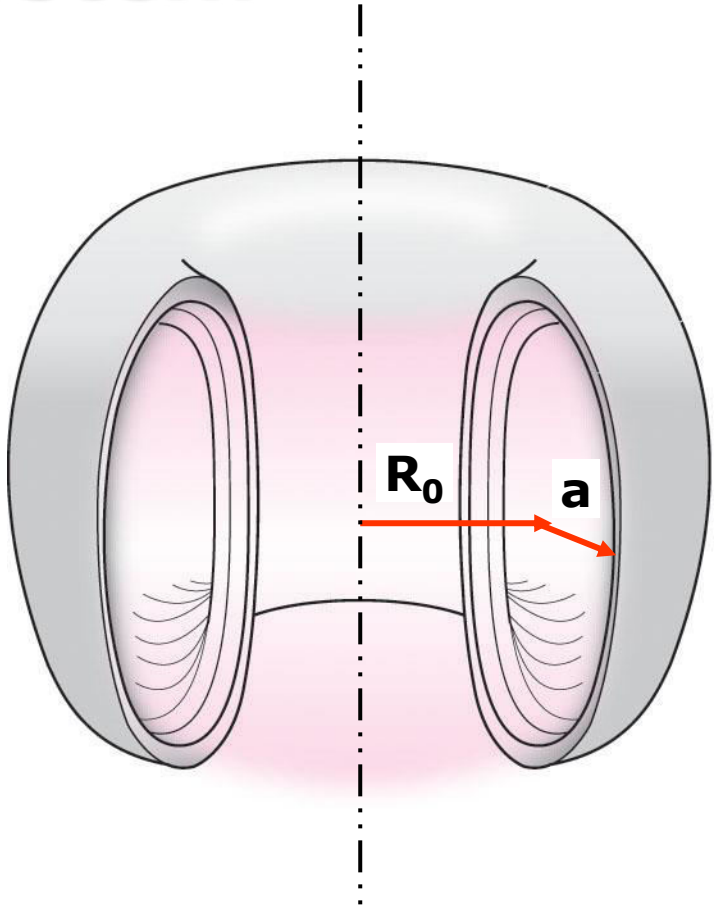
KOTAR

HYUNDAI
SAMHO HEAVY INDUSTRIES CO.,LTD.

Closed Magnetic System

Magnetic field

ion

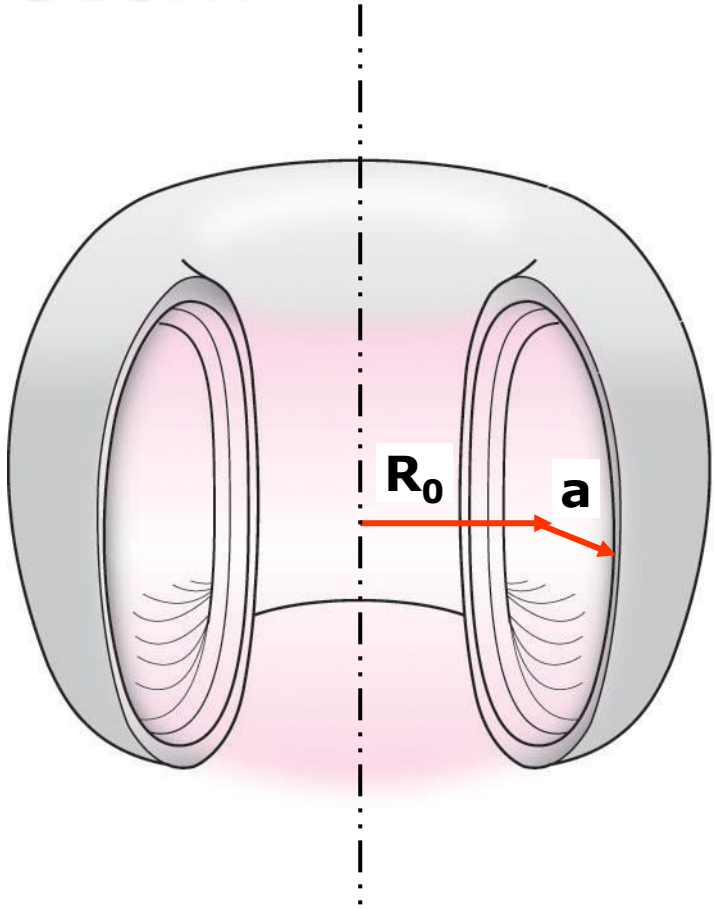


Plasma needs to be confined
R_0 = 1.8 m, a = 0.5 m in KSTAR

Closed Magnetic System

Magnetic field

ion



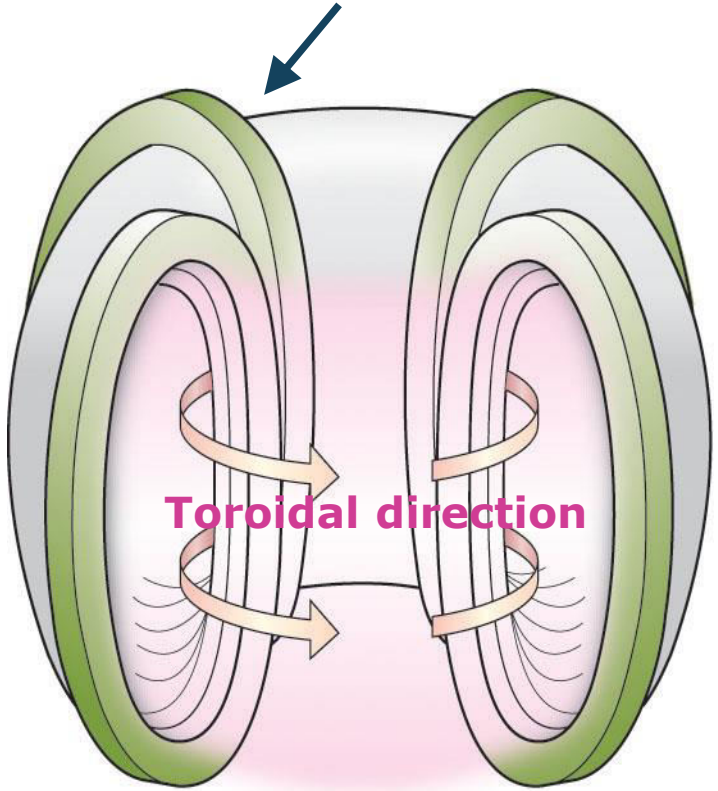
Plasma needs to be confined
R_0 = 6.2 m, a = 2.0 m in ITER

Closed Magnetic System

Magnetic field

ion

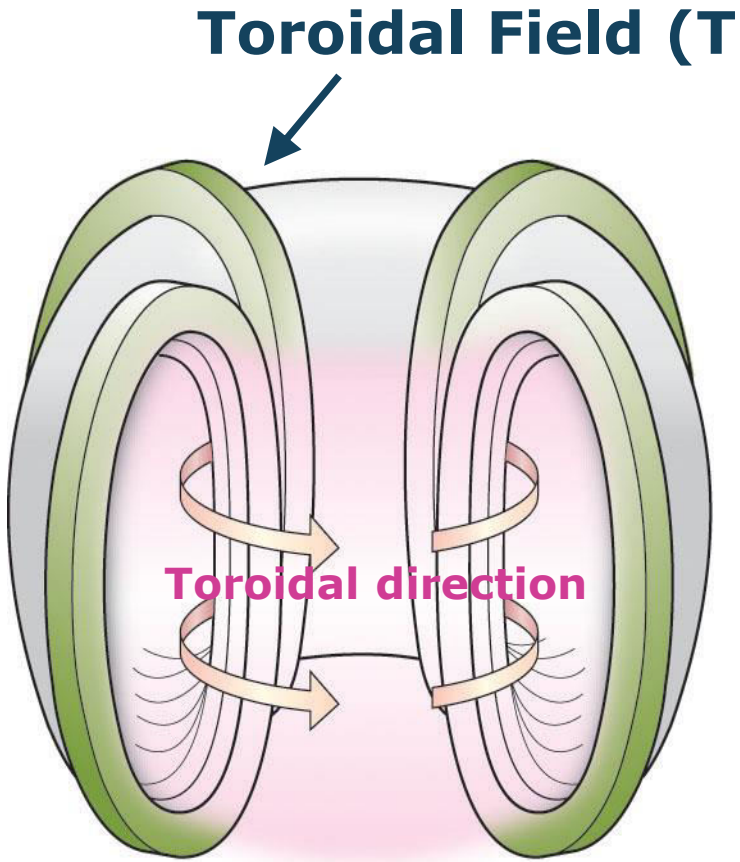
Toroidal Field (TF) coil



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

Closed Magnetic System

KSTAR



Applying toroidal magnetic field
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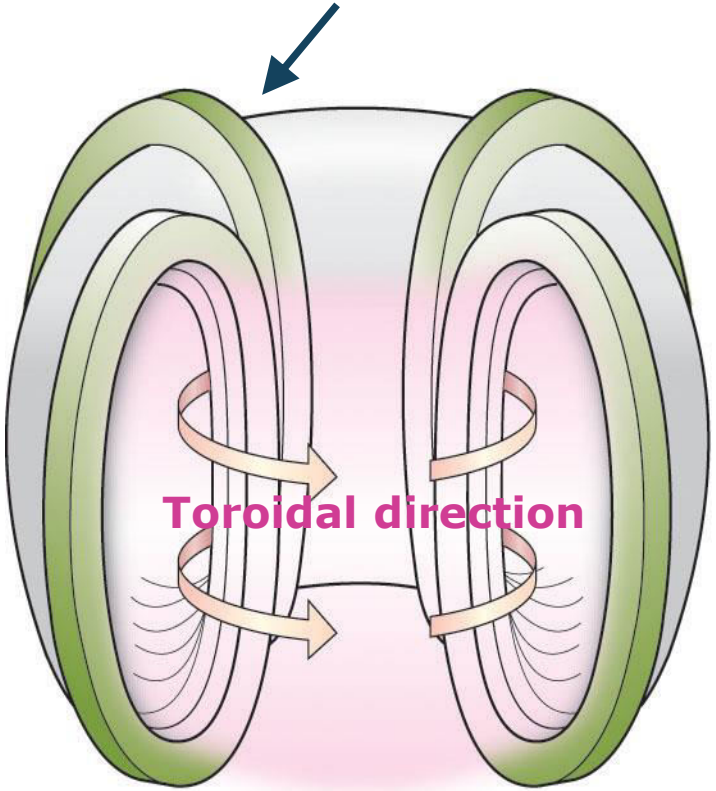
Closed Magnetic System

Magnetic field

ion

Toroidal Field (TF) coil



Magnetic field of earth?

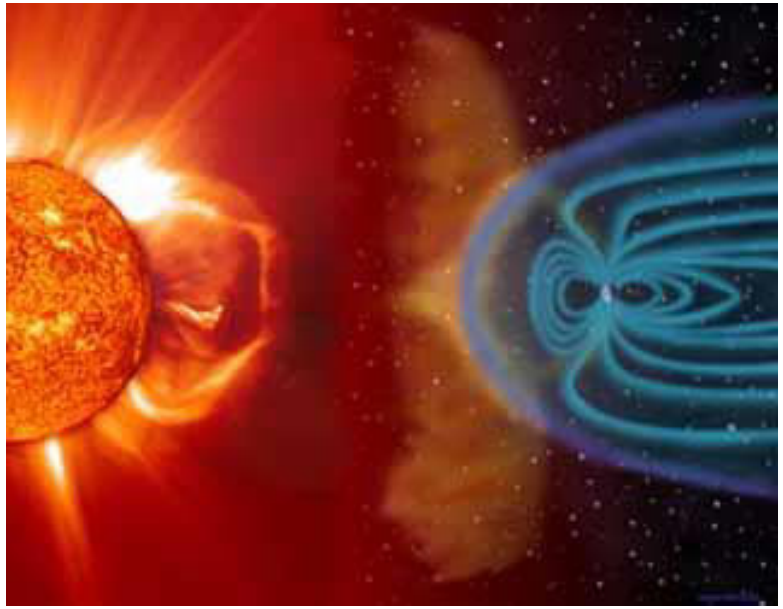
0.5 Gauss = 0.00005 T

http://www.crystalinks.com/earthsmagneticfield.html

Closed Magnetic System

Magnetic field

ion



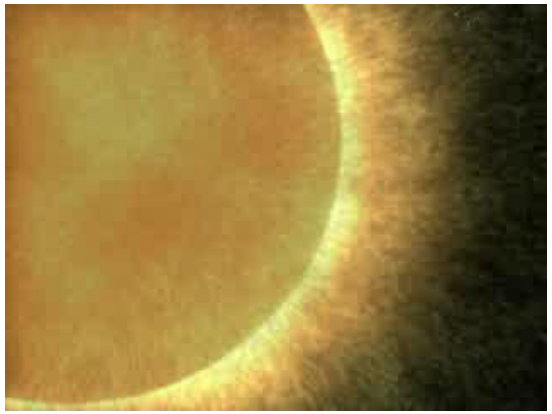
Magnetic field of earth?

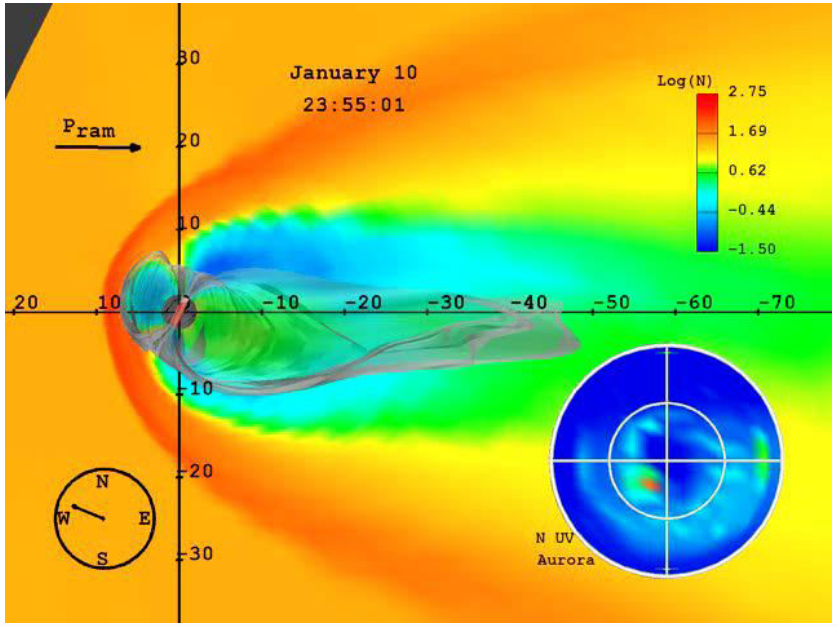
0.5 Gauss = 0.00005 T

http://www.transformacionconciencia.com/archives/2384

Closed Magnetic System

Magnetic field

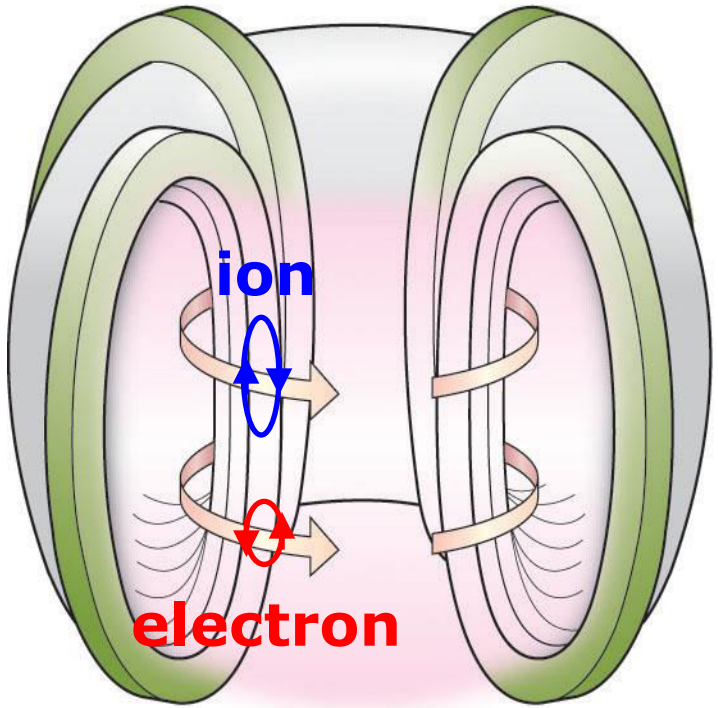




ion

Lesch, Astrophysics, IPP Summer School (2008)

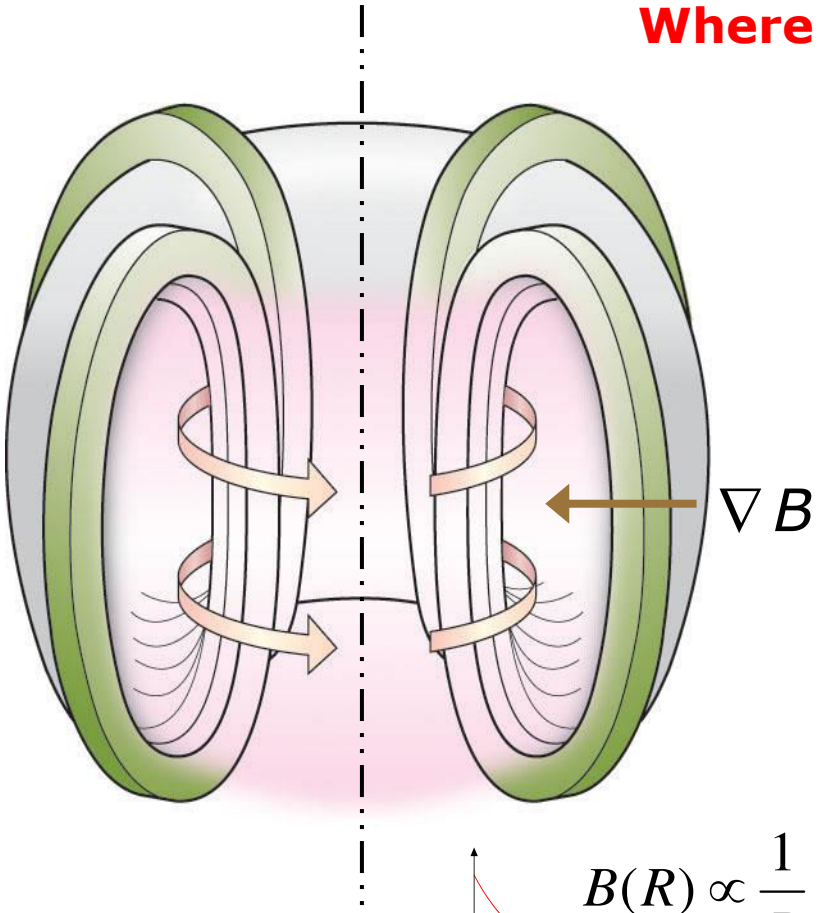
Closed Magnetic System

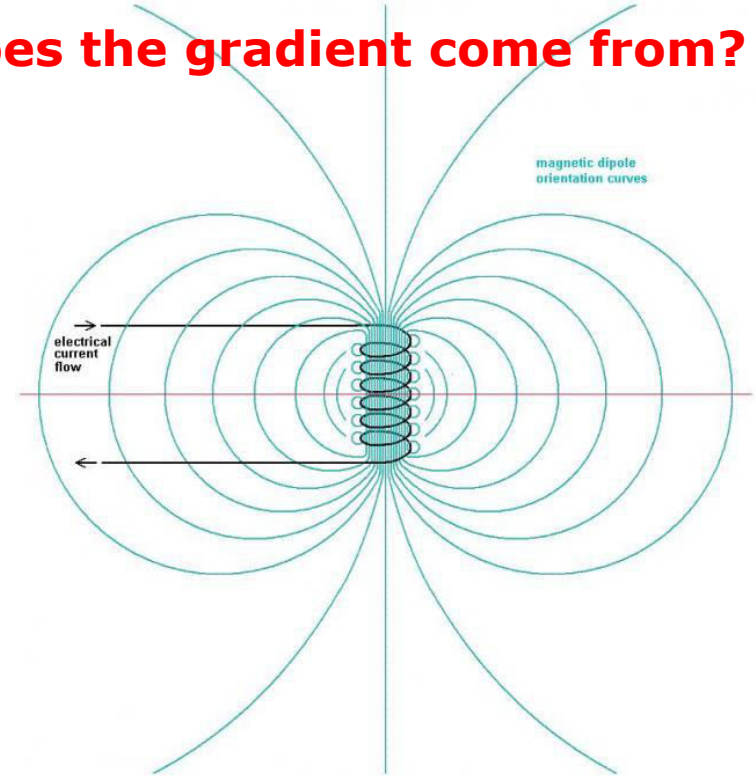


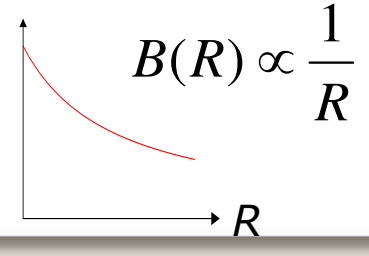
What kind of drift motions?

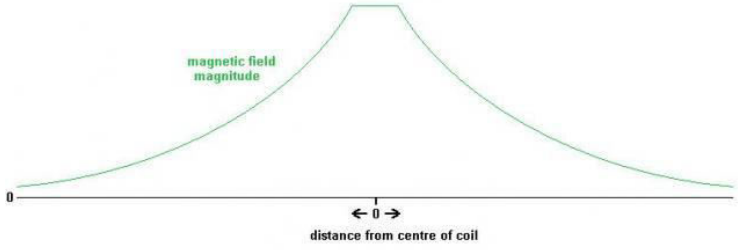
Closed Magnetic System

Where does the gradient come from?





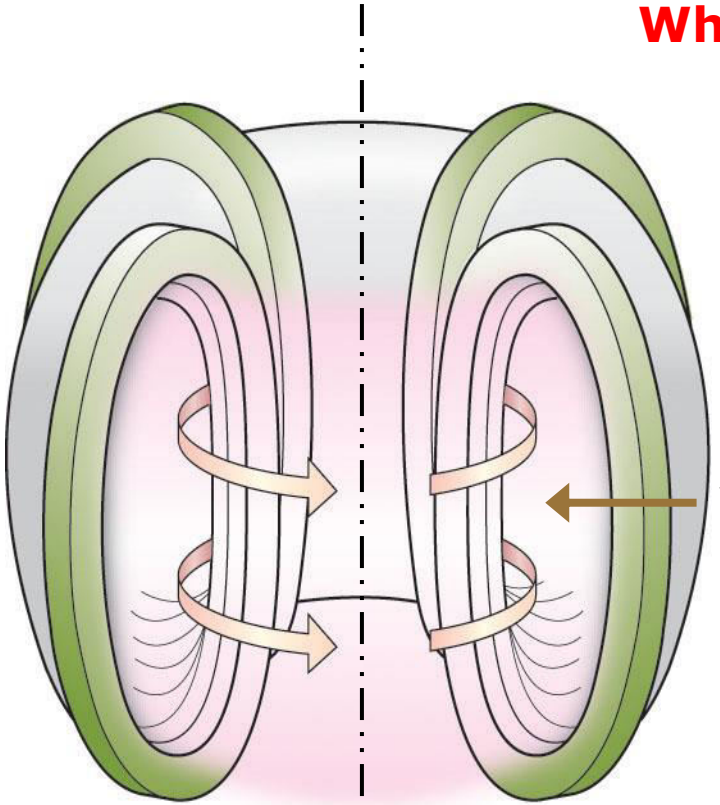




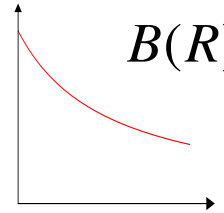
http://magnetoglide.wordpress.com/

Closed Magnetic System

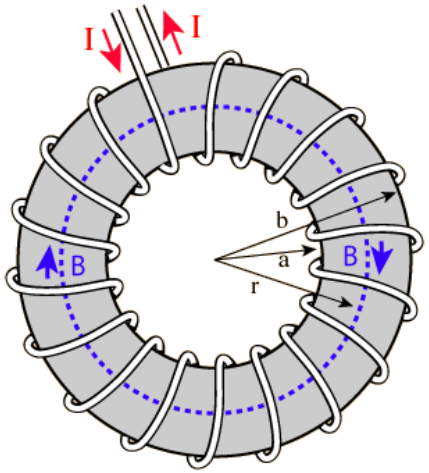
Where does the gradient come from?



∇B



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



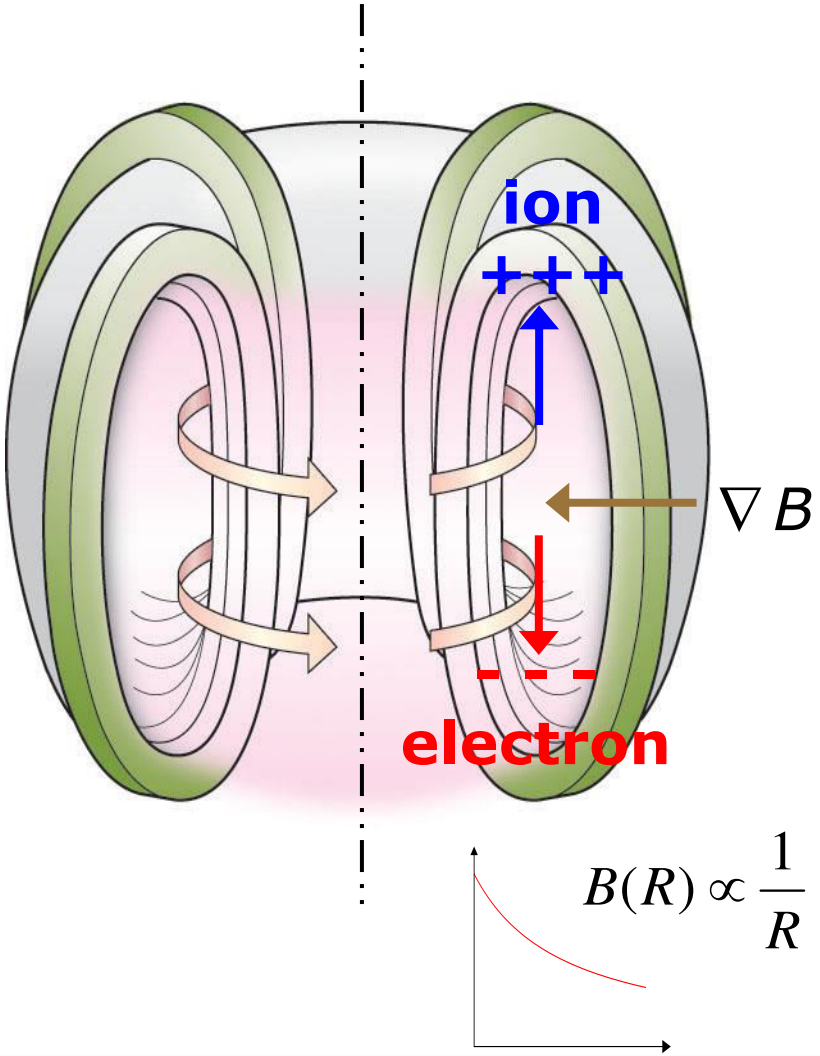
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

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

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

http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/toroid.html

Closed Magnetic System

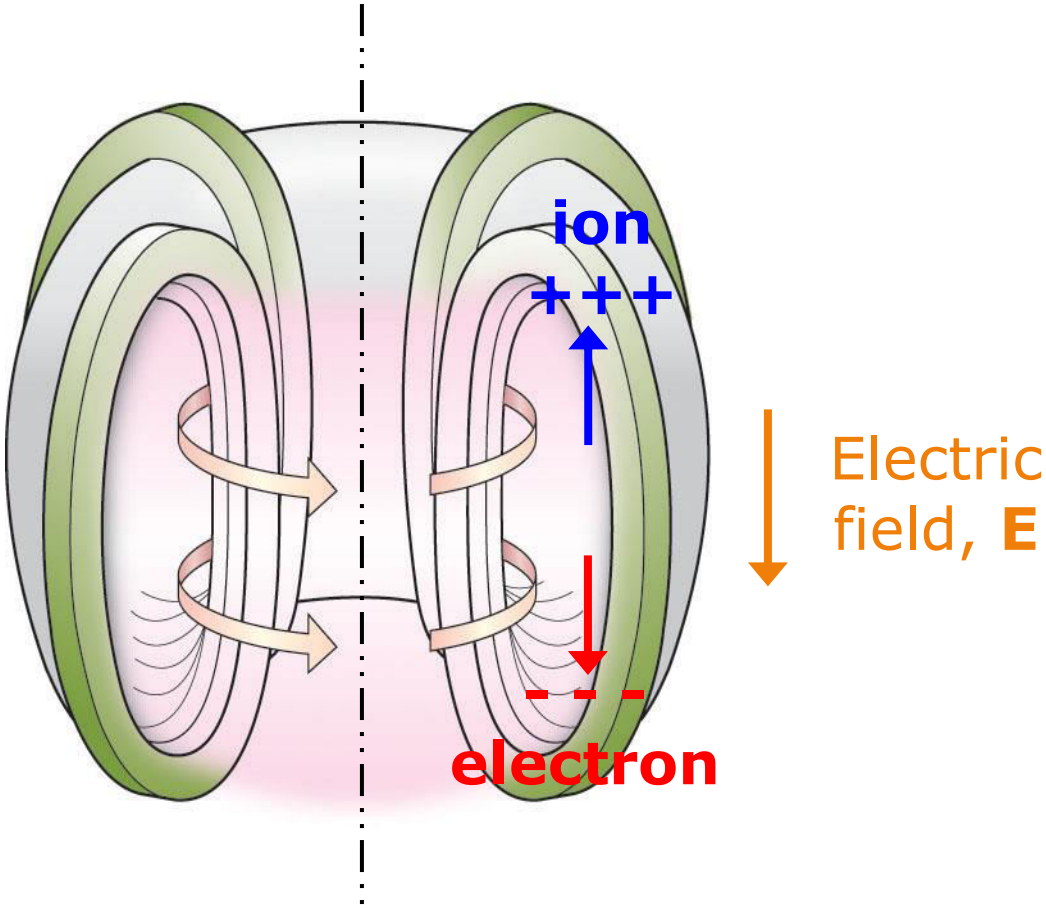


$$\mathbf{v}_{D,R} = \frac{mv_{\parallel}^2}{qB_0^2}\frac{\mathbf{R}_0 \times \mathbf{B}_0}{R^2}$$

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

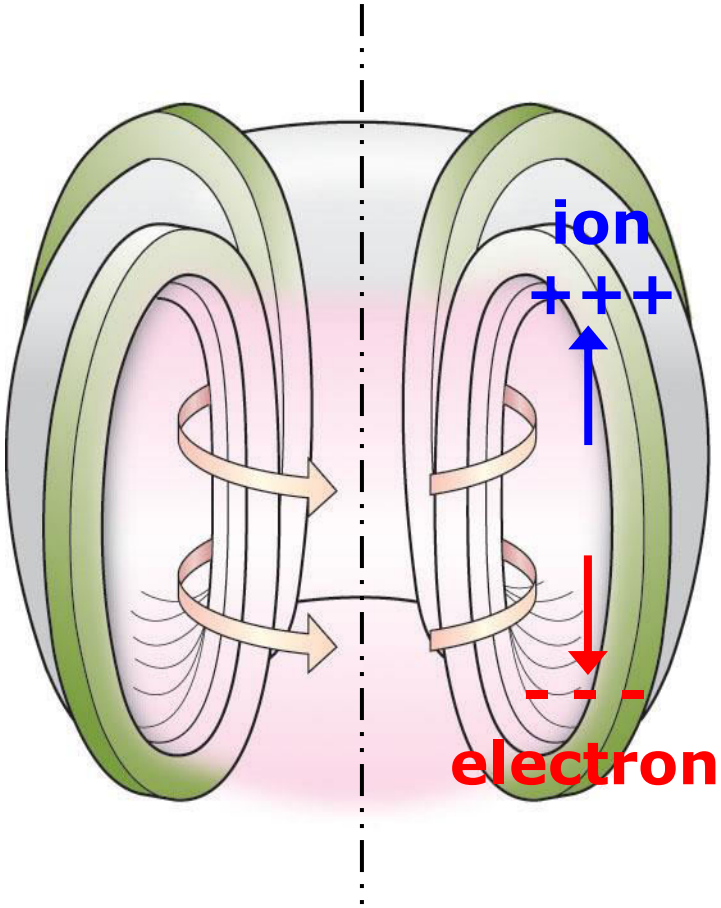
$$\mathbf{v}_D = \frac{m}{q}\frac{1}{R_0 B_{\phi}(R_0)}\left[v_{\parallel}^2 + \frac{v_{\perp}^2}{2}\right]\mathbf{e}_Z$$

Closed Magnetic System



Electric field, **E**

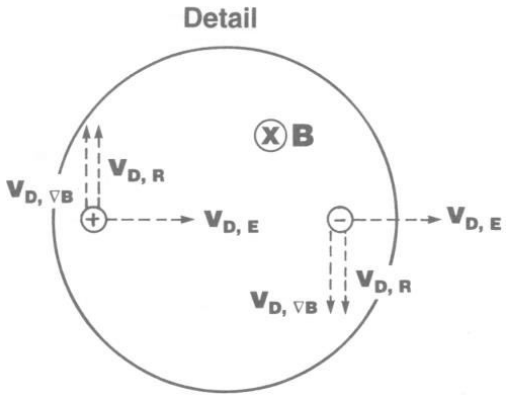
Closed Magnetic System



ExB drift

Electric field, **E**

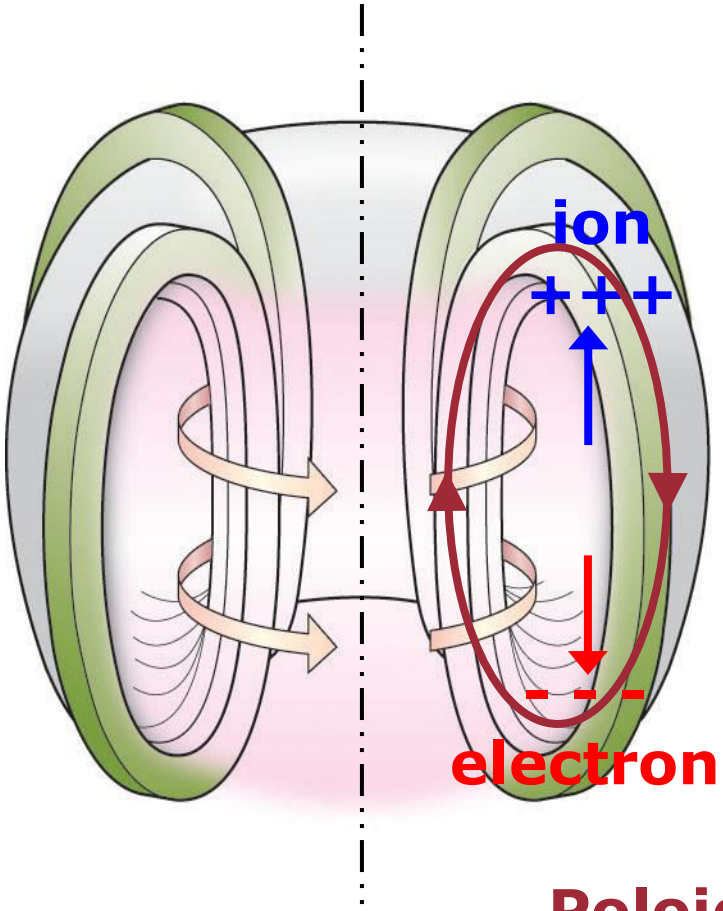
ExB drift



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

A. A. Harms et al, "Principles of Fusion Energy", World Scientific (2000)

Closed Magnetic System



ExB drift

Electric field, **E**

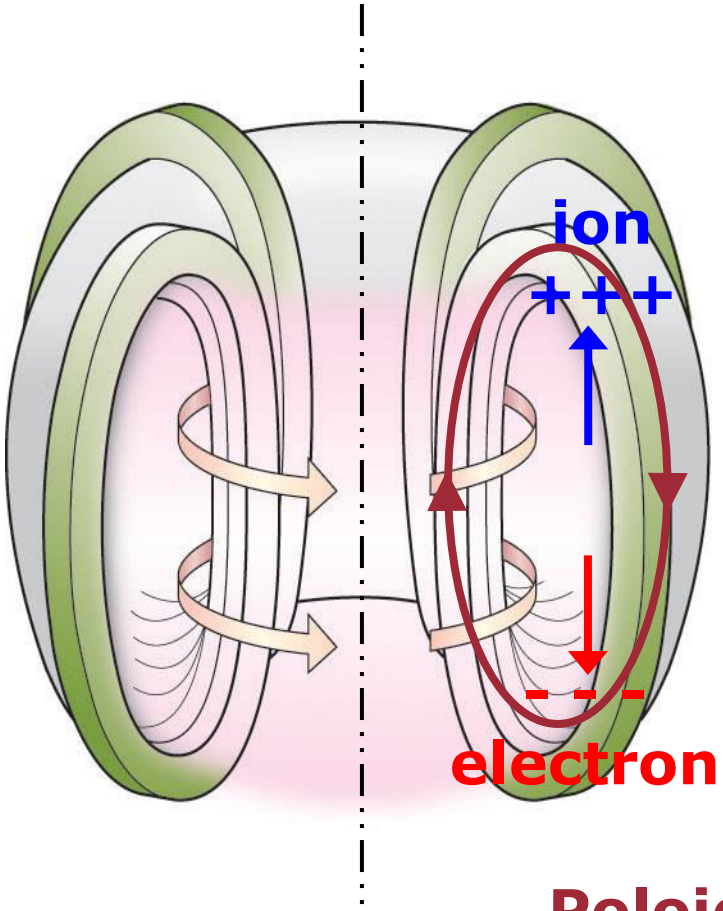
ExB drift

Poloidal magnetic field required

Tokamak .VS. Stellarator

What is a tokamak?

Closed Magnetic System



Will be the plasma current driven if a toroidal magnetic field is applied?

ExB drift

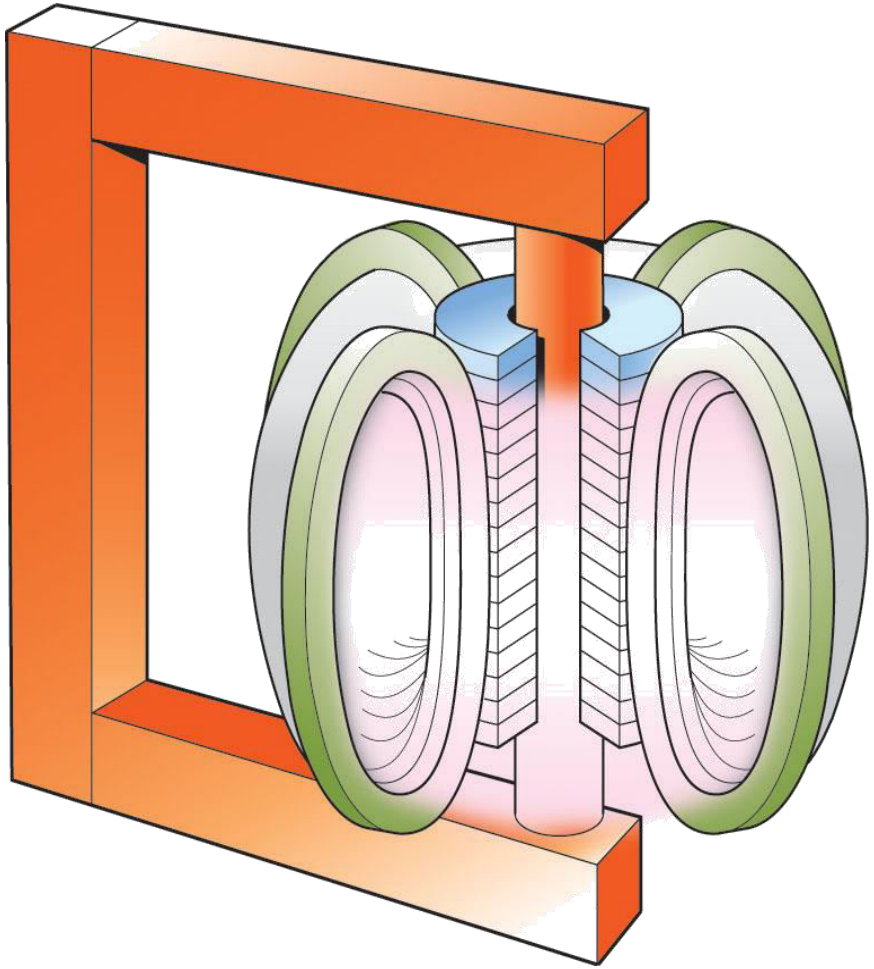
Electric field, **E**

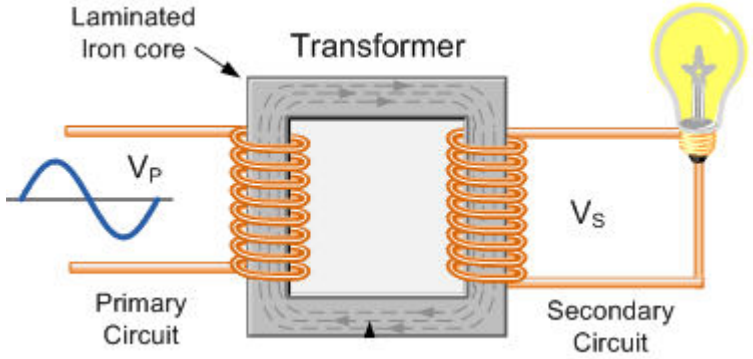
ExB drift

Poloidal magnetic field required

How to drive plasma current?

Tokamak



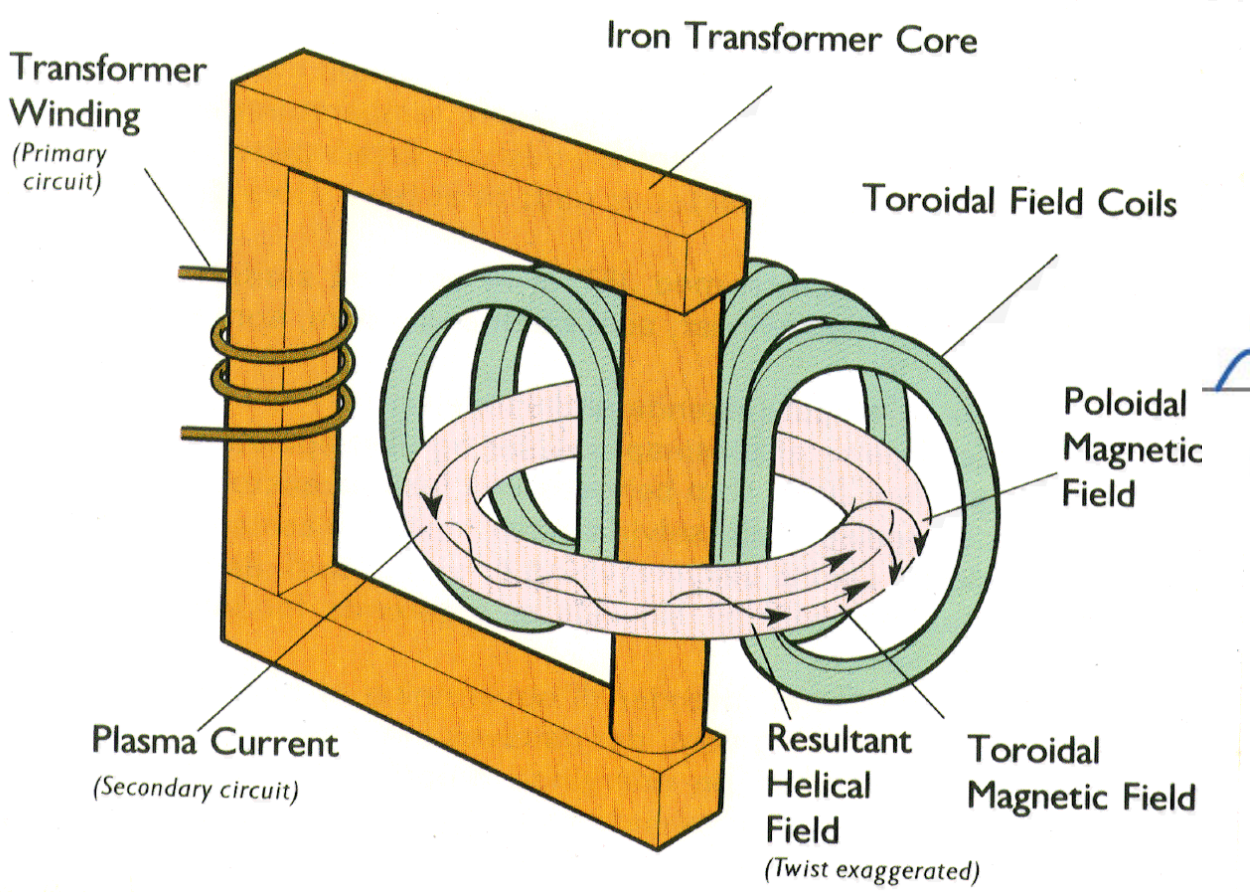


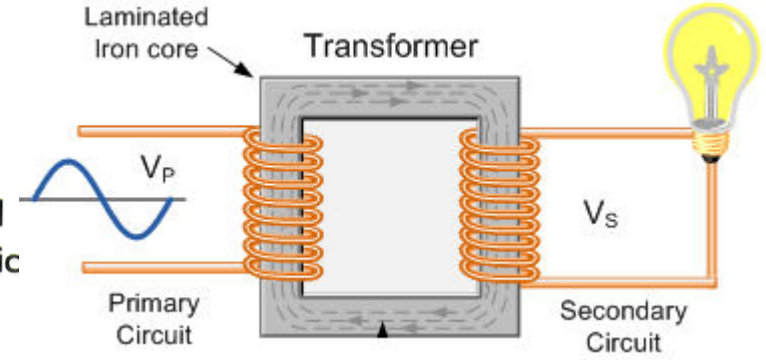
Faraday's law

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

http://www.electronics-tutorials.ws/electromagnetism/electromagnetic-induction.html

Tokamak





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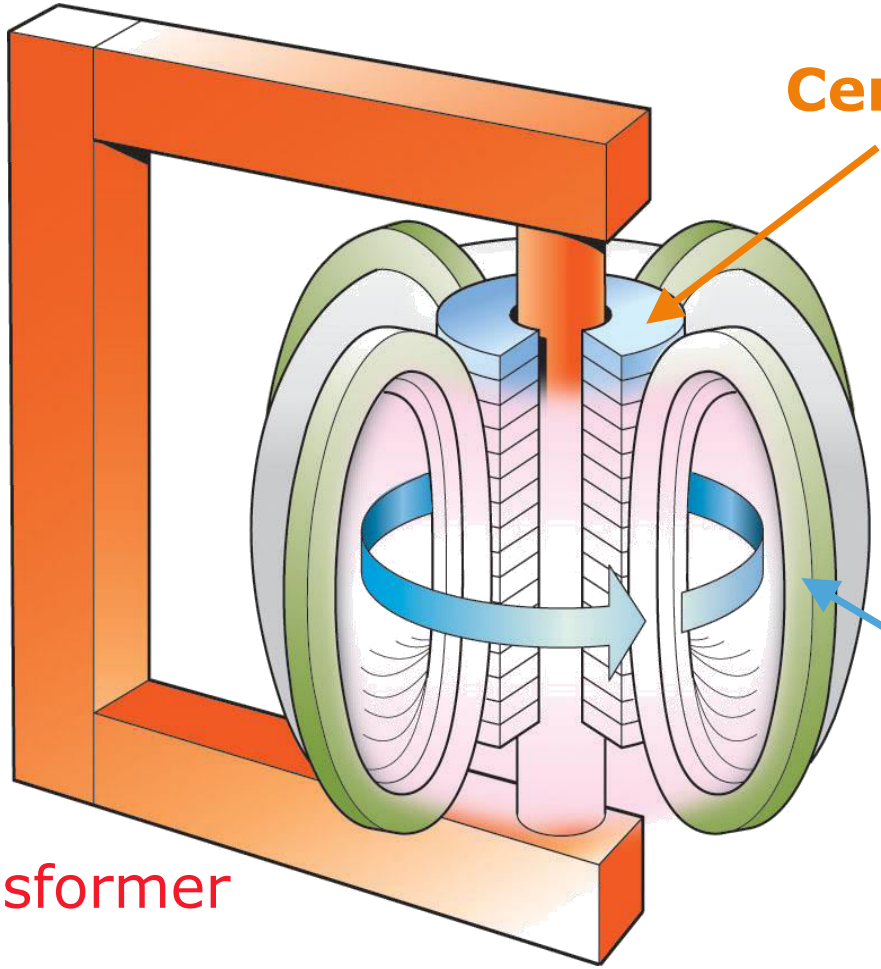
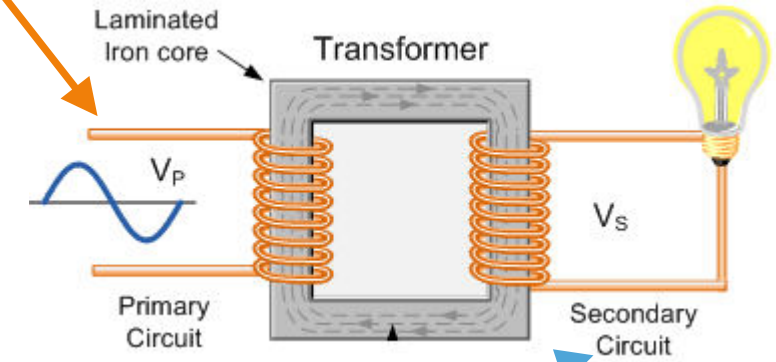
Tokamak



Transformer

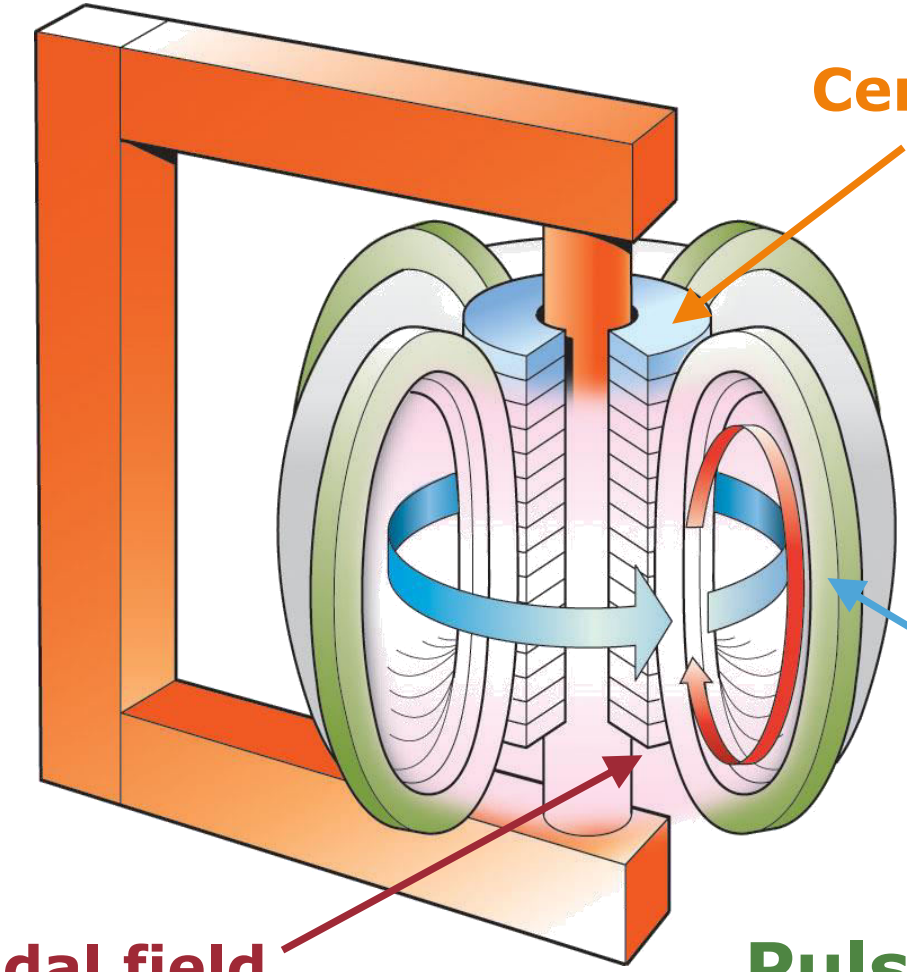
Central Solenoid (CS)



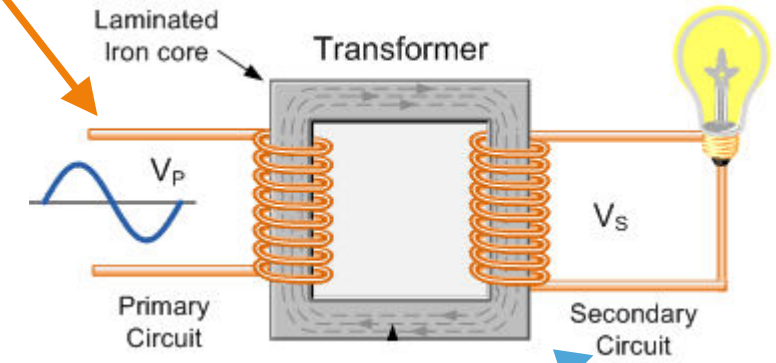
Plasma

http://www.electronics-tutorials.ws/electromagnetism/electromagnetic-induction.html

Tokamak



Central Solenoid (CS)



Plasma

Poloidal field

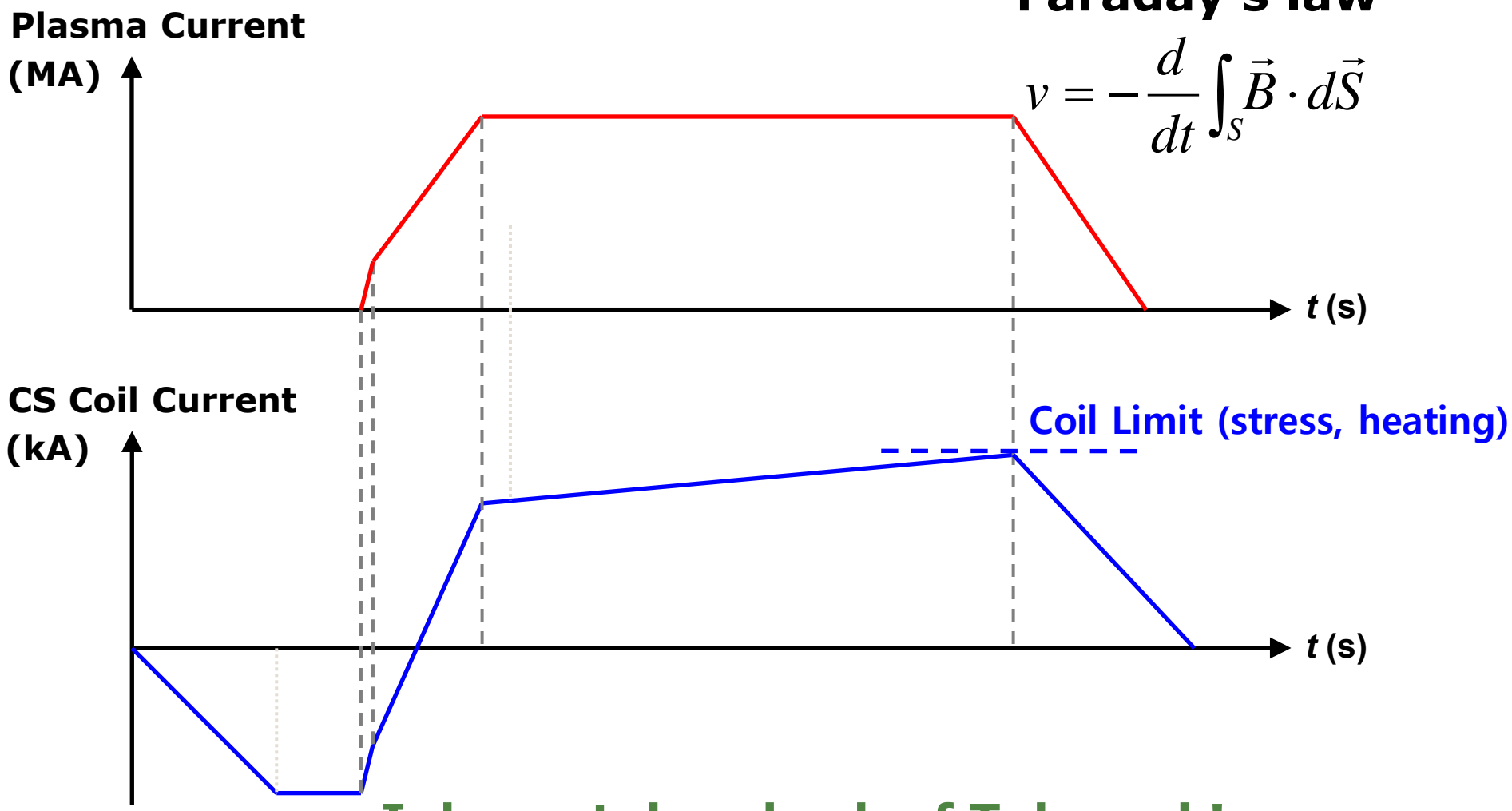
Pulsed Operation!

http://www.electronics-tutorials.ws/electromagnetism/electromagnetic-induction.html

Pulsed Operation

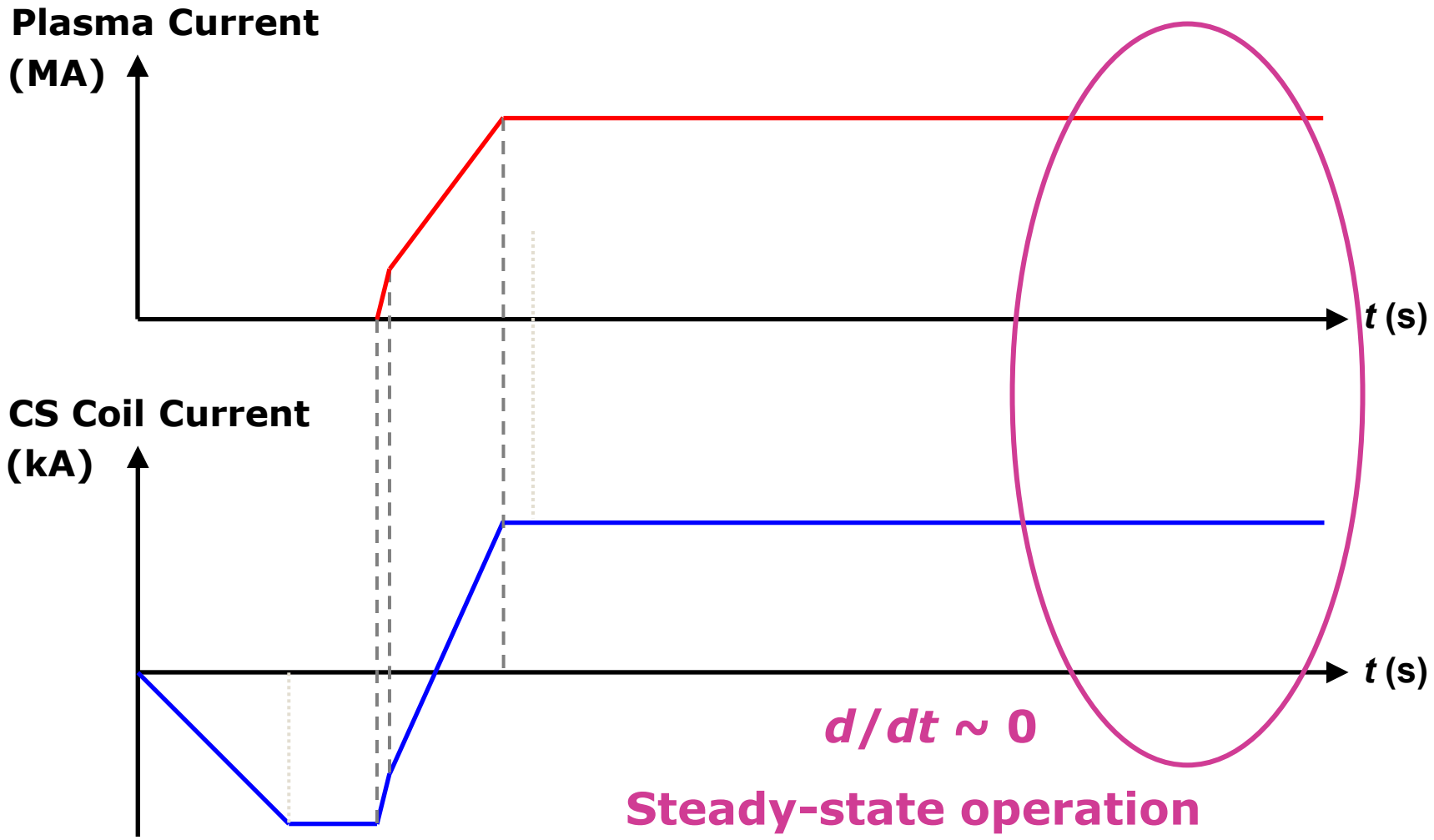
Faraday's law

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



Inherent drawback of Tokamak!

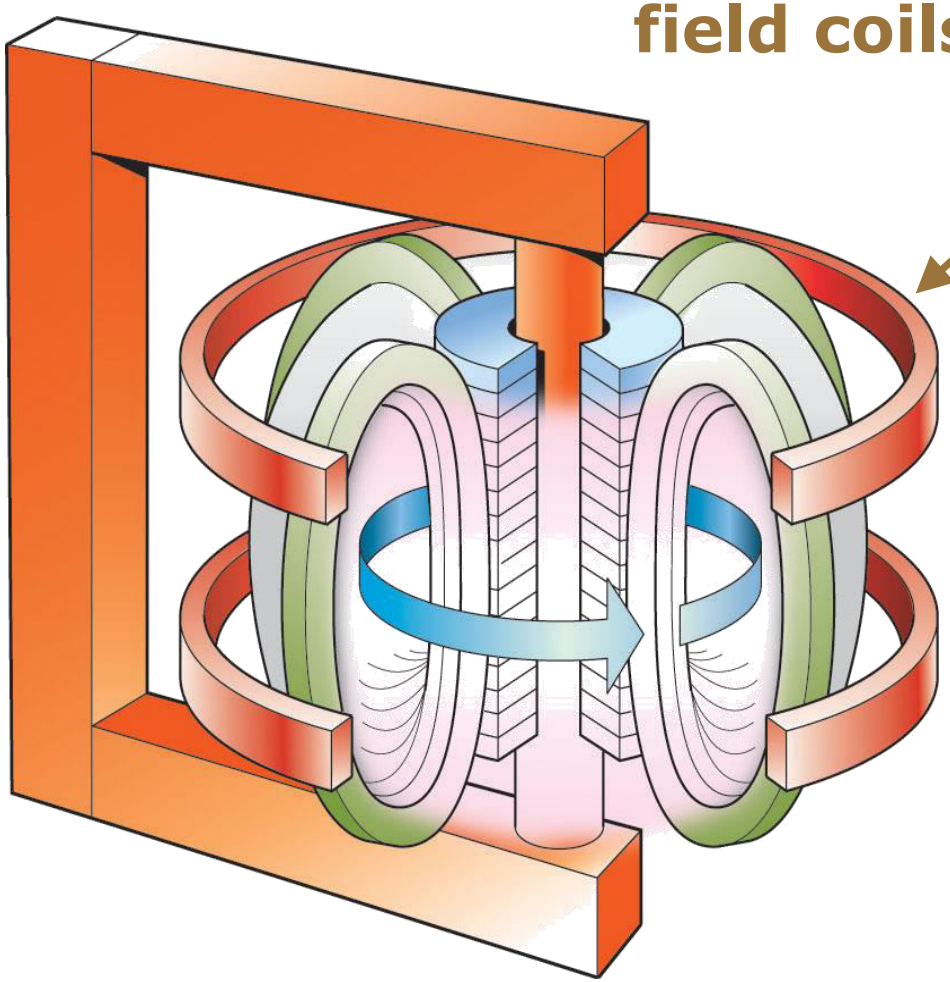
Steady-State Operation

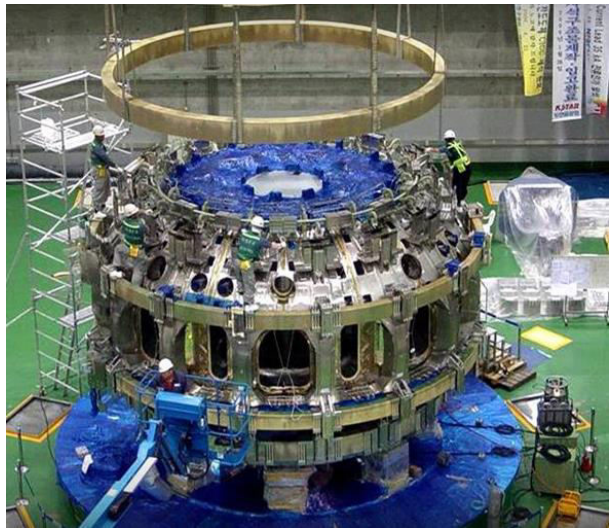


Steady-state operation
by self-generated and externally driven current

Tokamak

Adding vertical (equilibrium) field coils (PF: Poloidal Field)

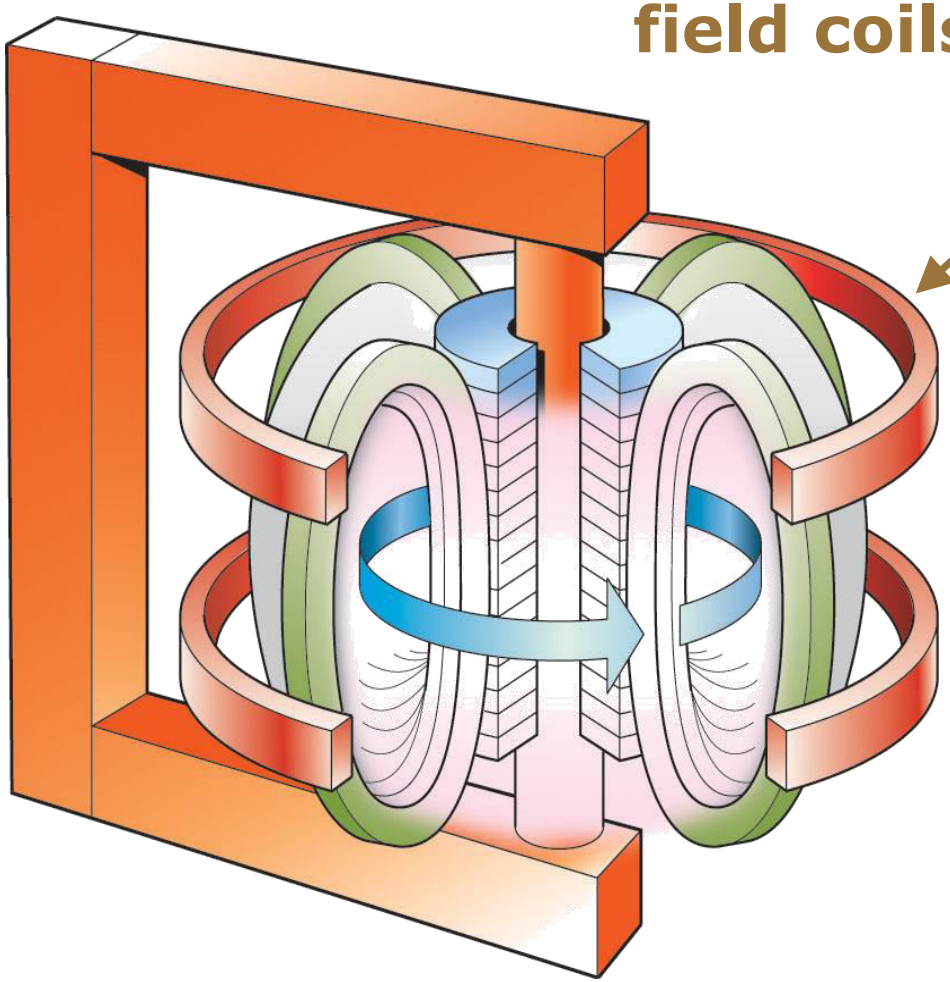




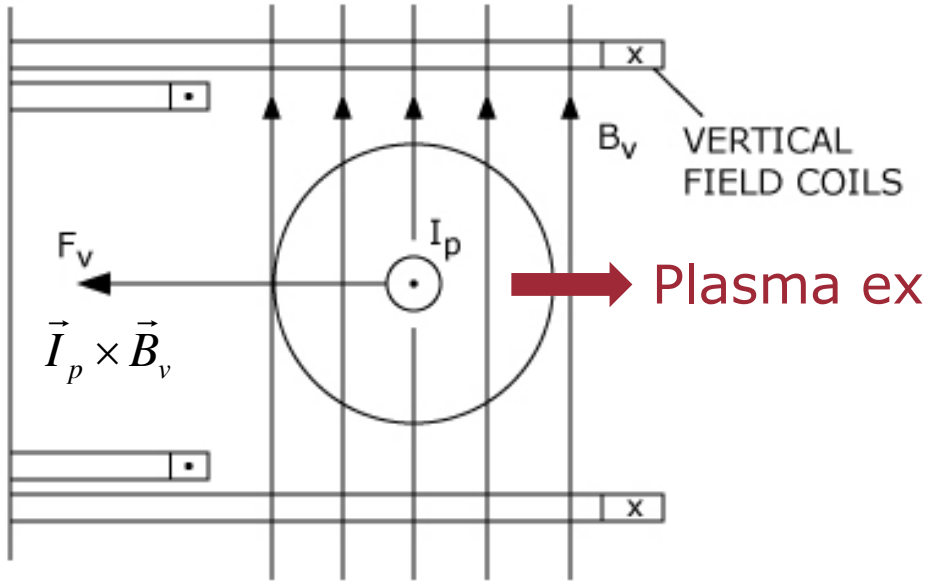
KSTAR

Tokamak

Adding vertical (equilibrium) field coils (PF: Poloidal Field)



Tokamak

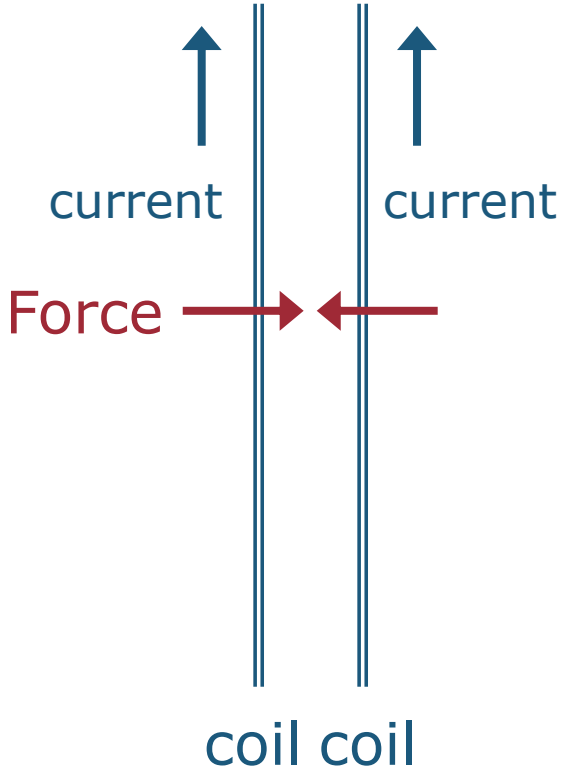


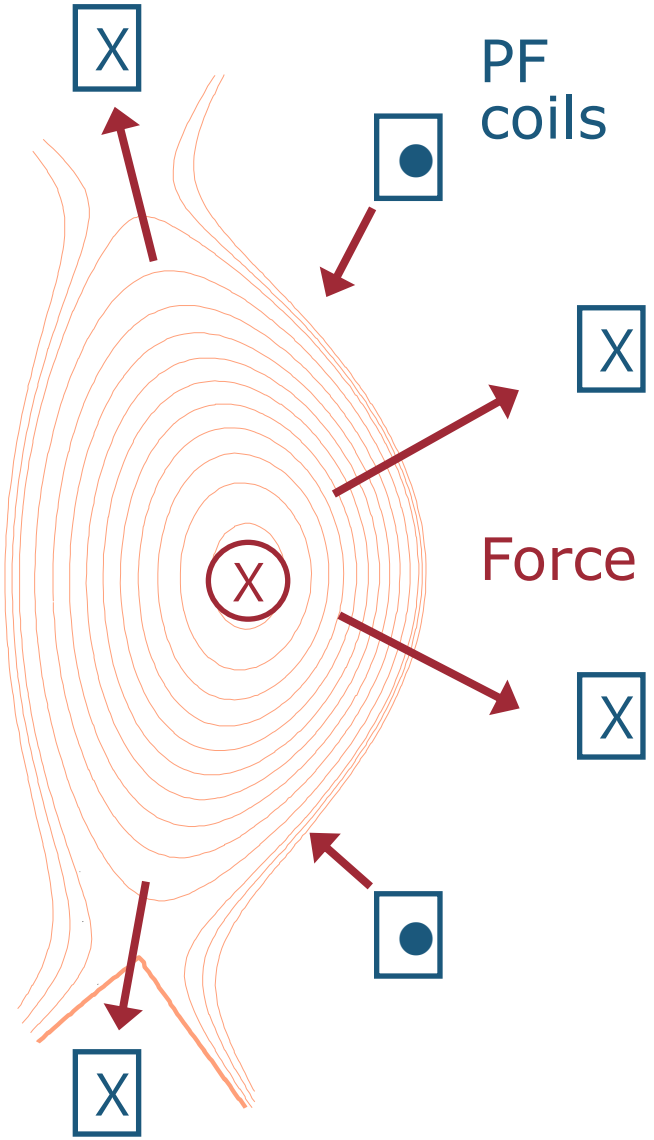
Plasma expansion force

Force balance by vertical field coils:
Plasma positioning

J.P. Freidberg, "Ideal Magneto-Hydro-Dynamics", lecture note

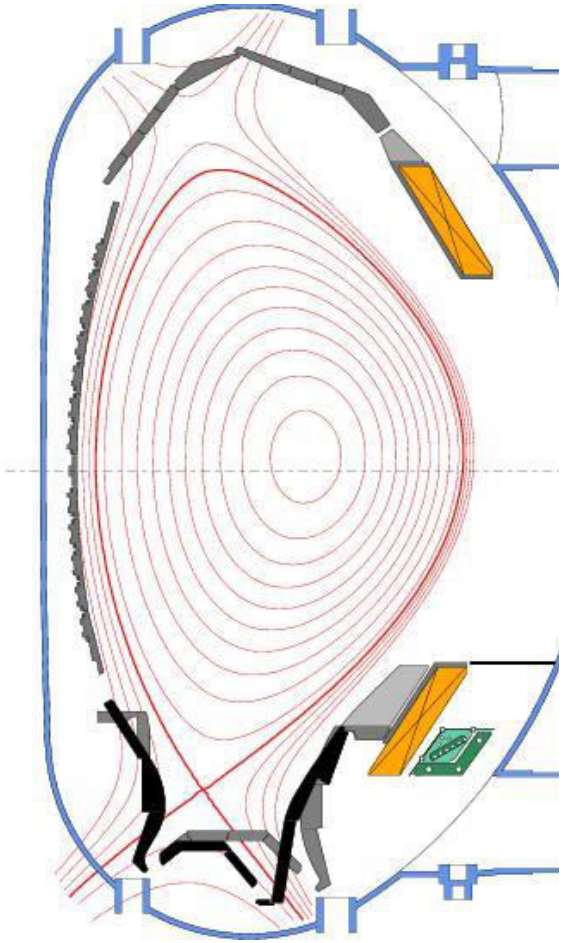
Tokamak

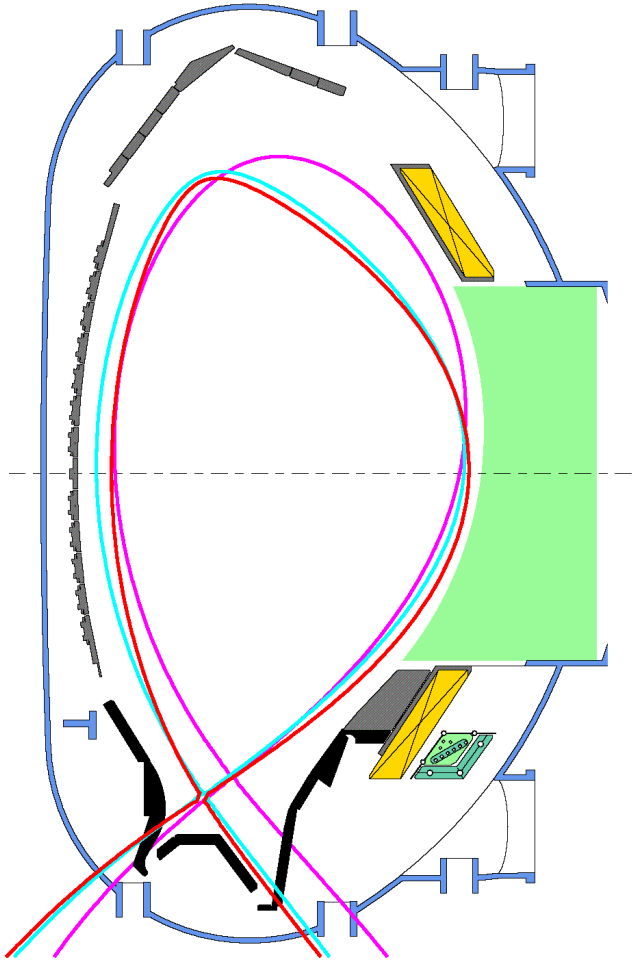




Plasma shaping by PF coils

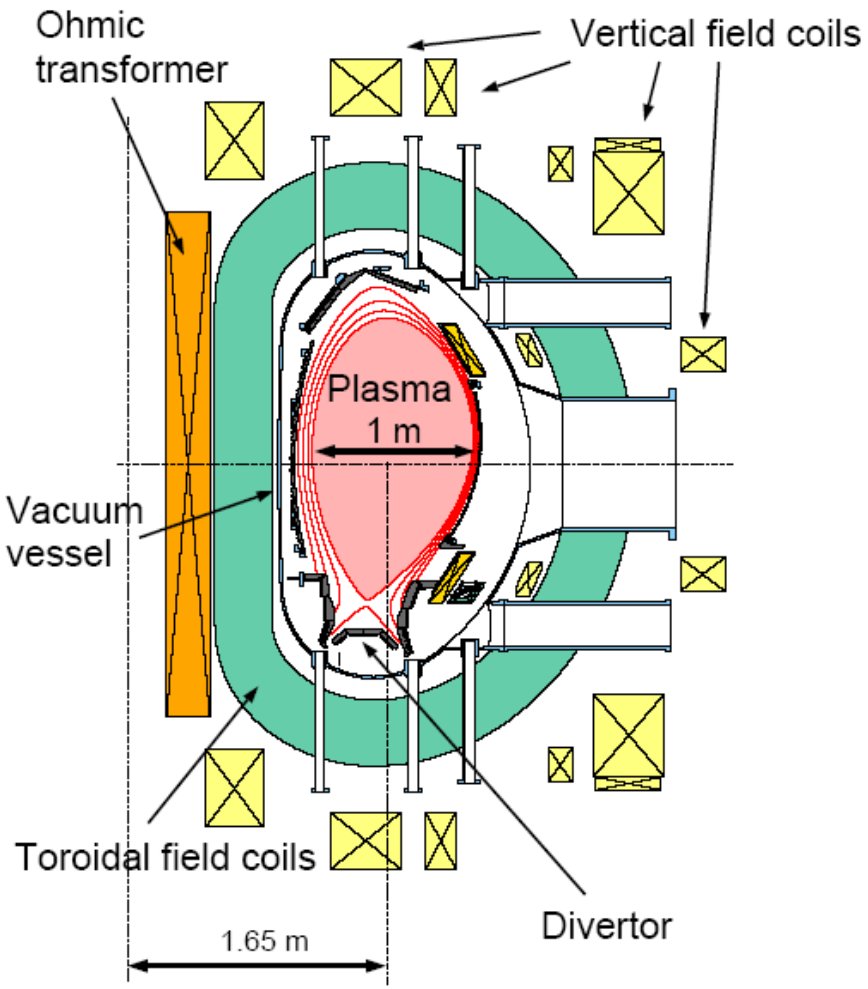
Tokamak

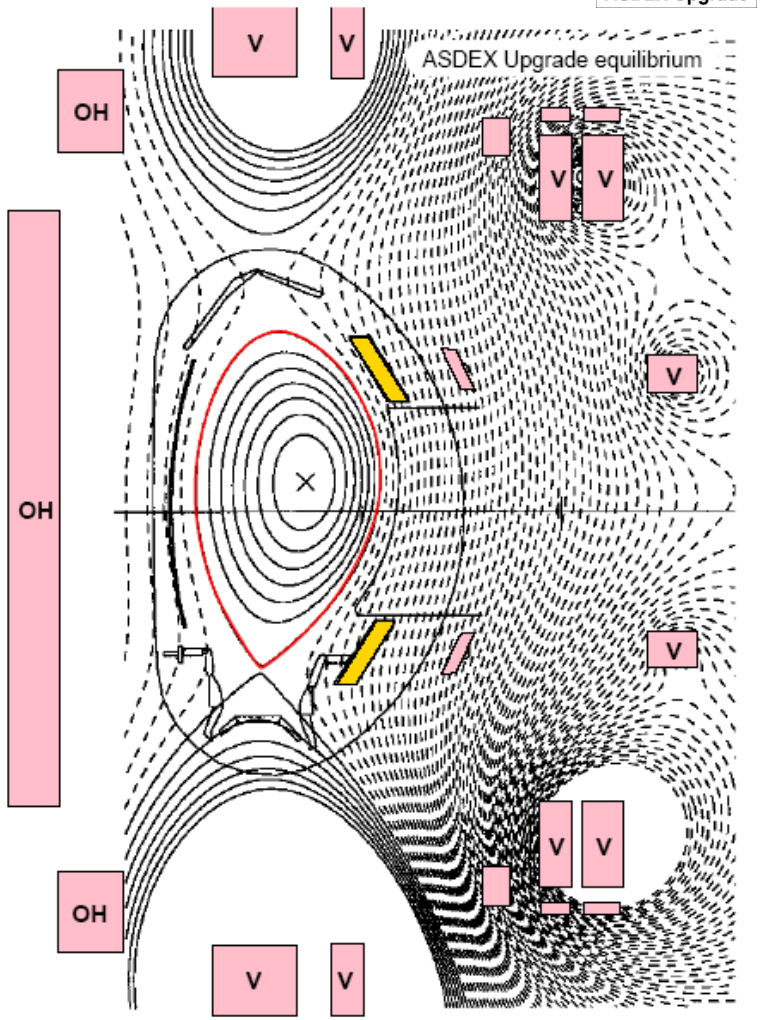




The plasma shape can be modified by PF coil currents.

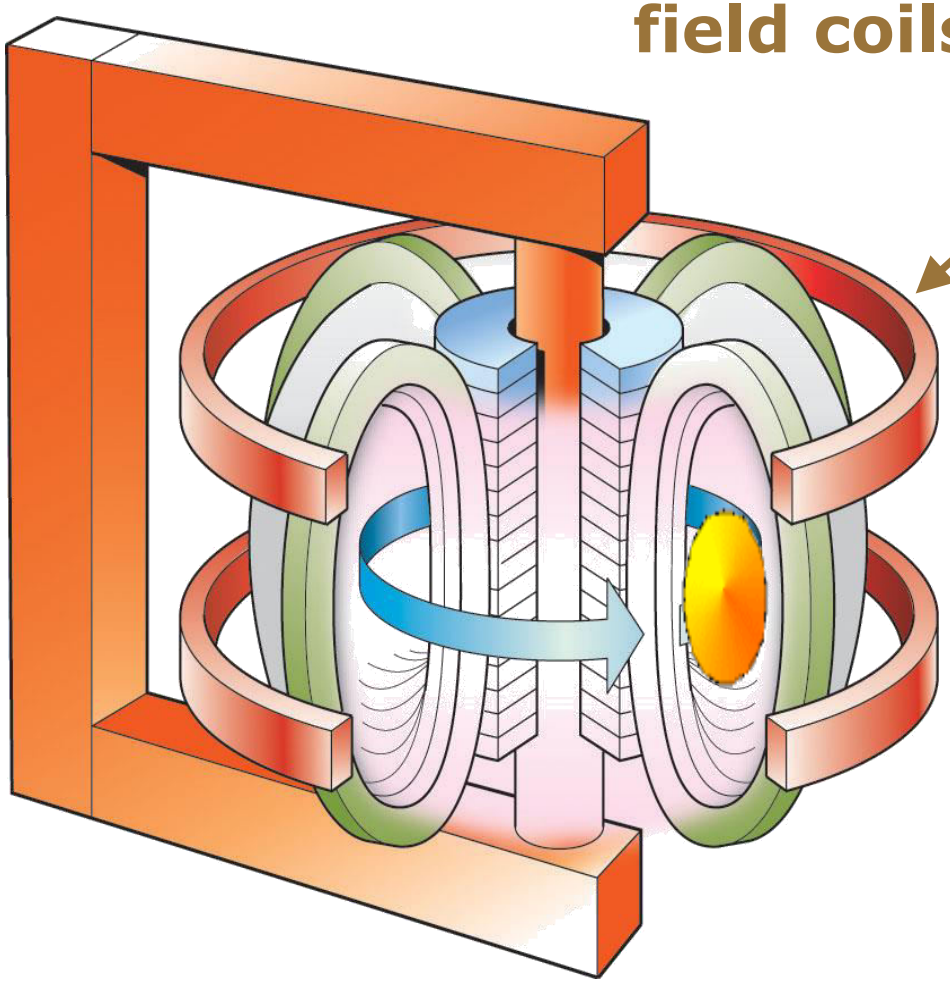
Tokamak

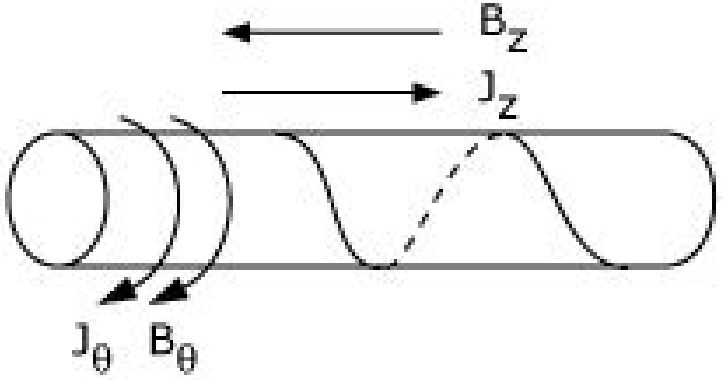

Ohmic
transformer
Vertical field coils
Plasma
1 m
Vacuum
vessel
Toroidal field coils
Divertor
1.65 m


ASDEX Upgrade equilibrium
OH
OH
OH
V
V
V
V
V
V
V
V
V
V

Tokamak

Adding vertical (equilibrium) field coils (PF: Poloidal Field)





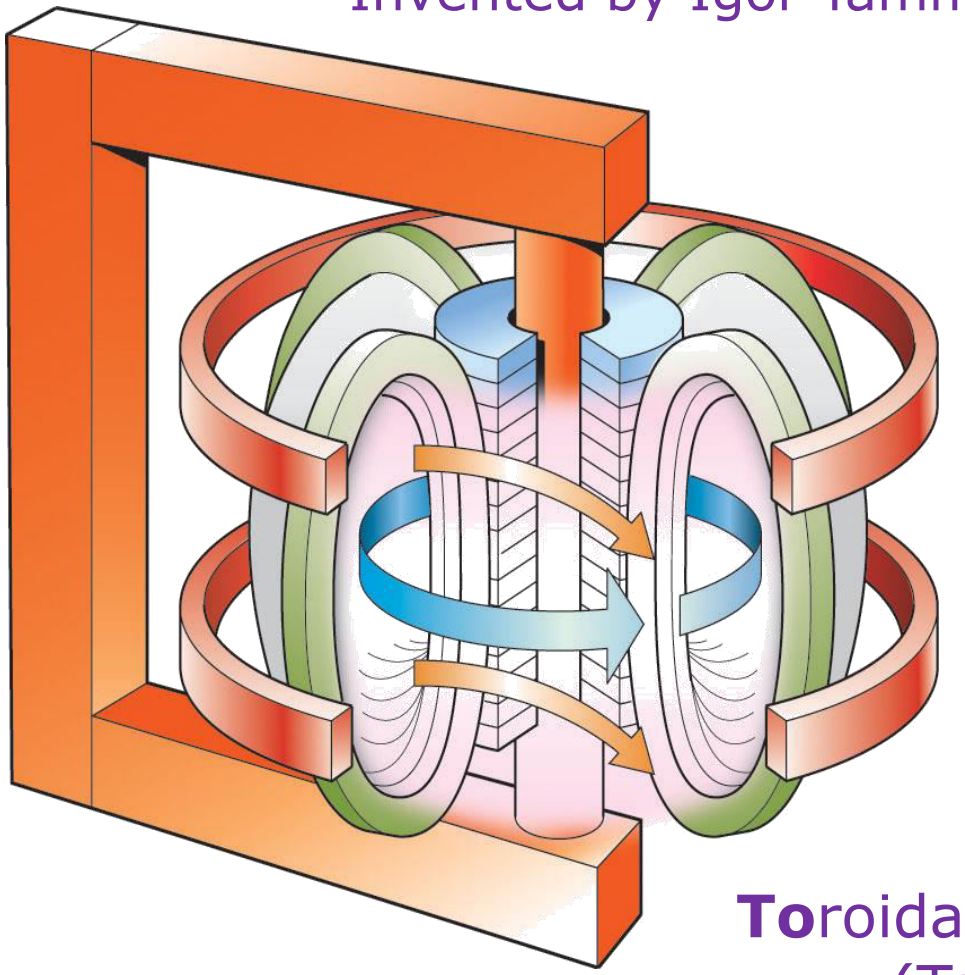
$$B_\phi >> B_\theta$$

$$J_\phi >> J_\theta$$

Plasma positioning & shaping by PF coils

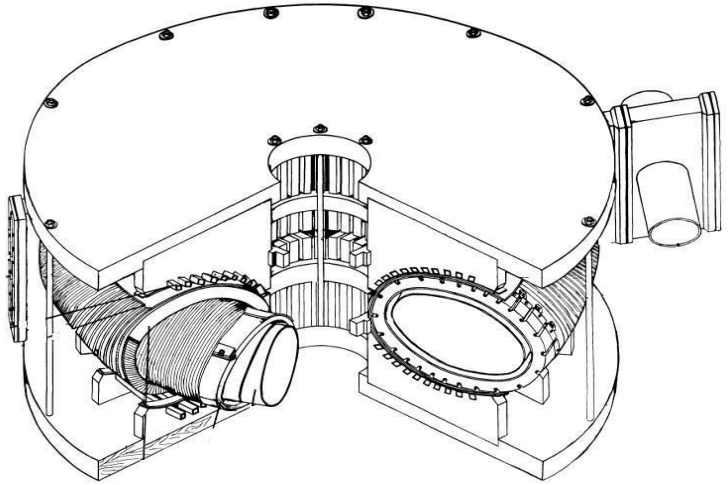
Tokamak

Invented by Igor Tamm and Andrei Sakharov in 1952



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

Tokamak

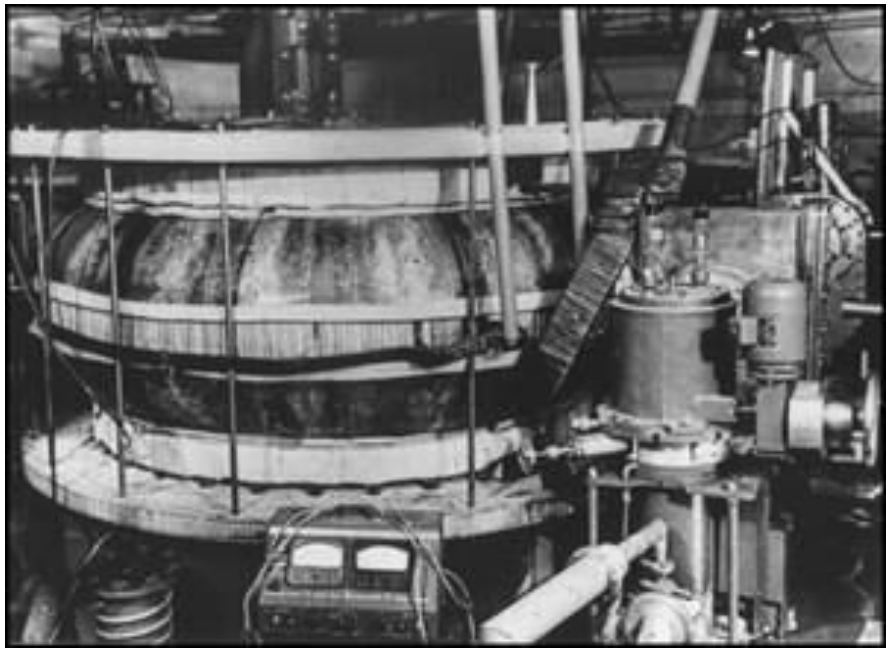


Cutaway of the Toroidal Chamber in Artsimovitch's Paper *Research on Controlled Nuclear Fusion in the USSR*

WIKIPEDIA

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

1958 IAEA FEC, Geneva, Switzerland



T1: The world's first tokamak,
Kurchatov Institute, Moscow Russia

http://www.iter.org/newsline/55/1194

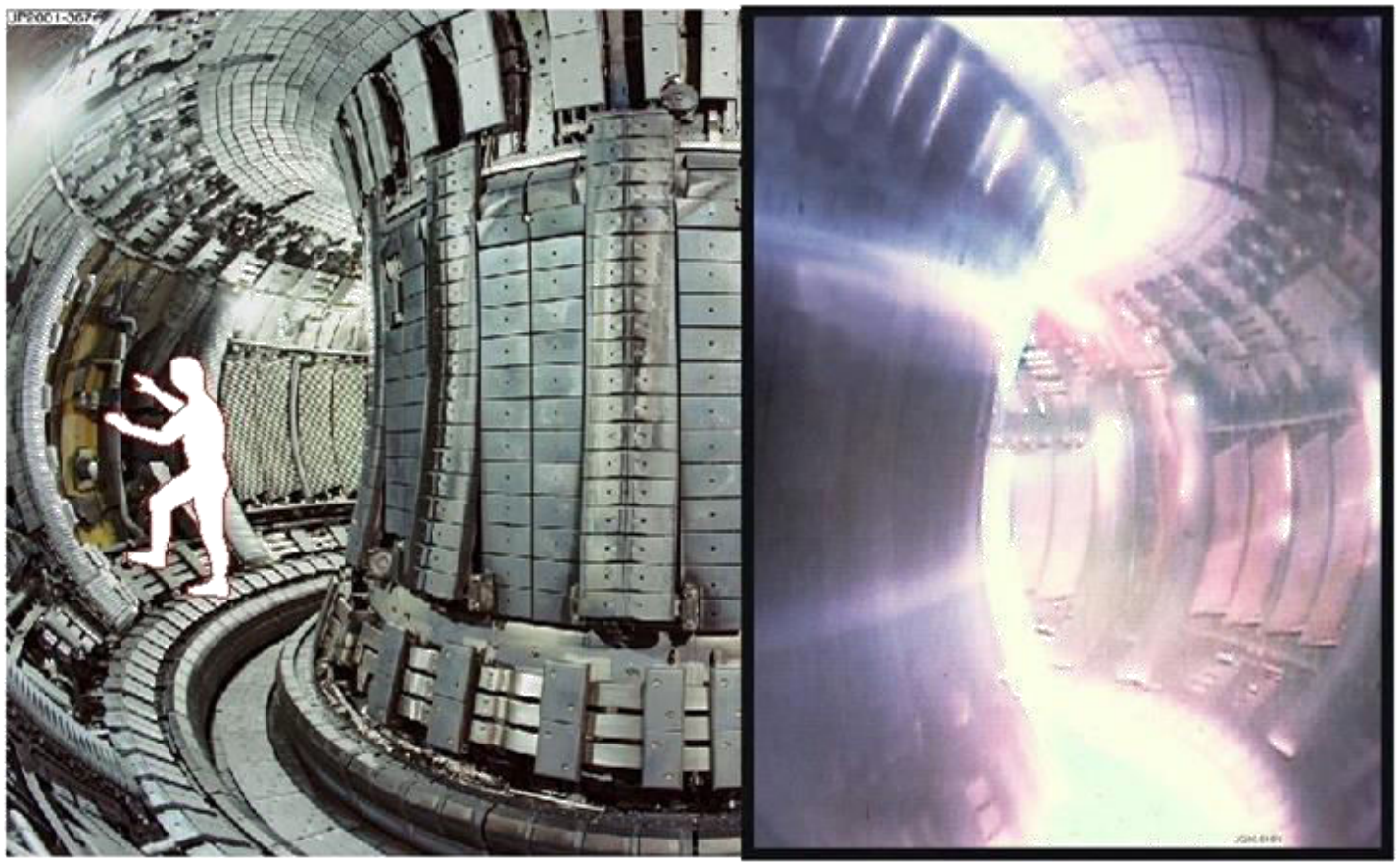
Tokamak

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

http://imgarcade.com/1/spherical-tokamak/

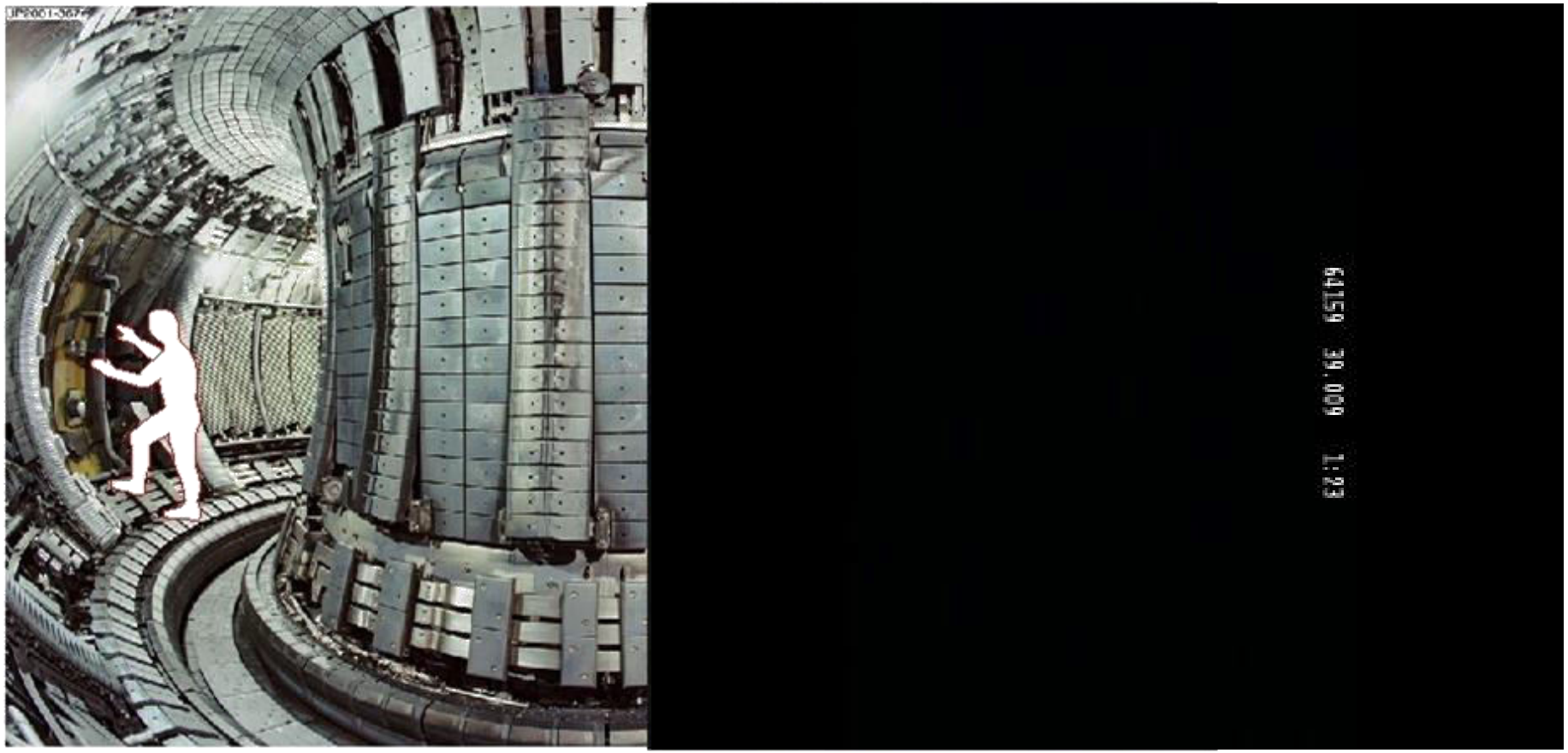
Tokamak

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

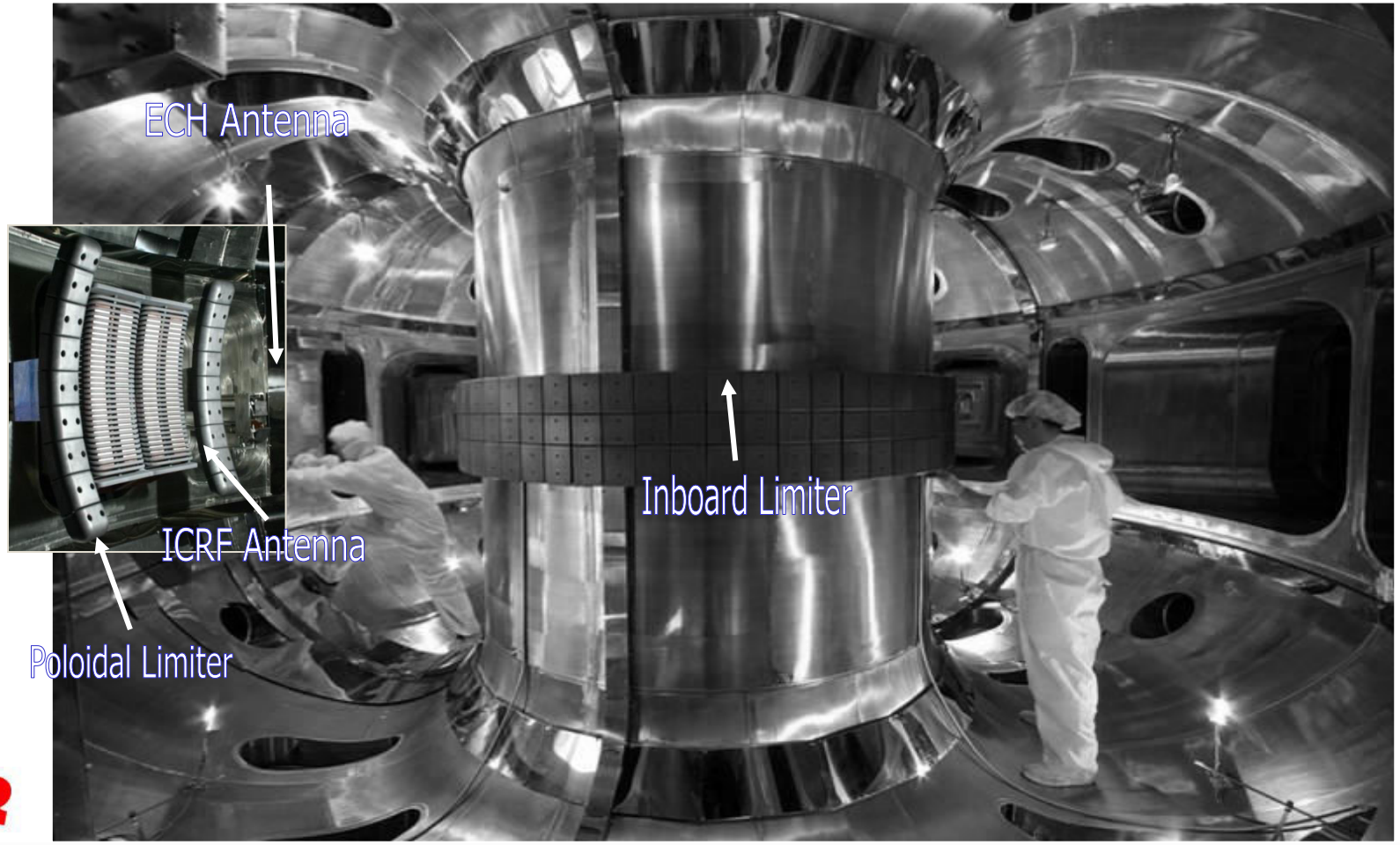


Tokamak

http://cafe.naver.com/gamebox26.cafe?iframe_url=/ArticleRead.nhn%3Farticleid=16140

Tokamak

KSTAR (Korea Superconducting Tokamak Advanced Research):
R_0 = 1.8 m, a = 0.5 m, 2007-today



KSTAR

Tokamak

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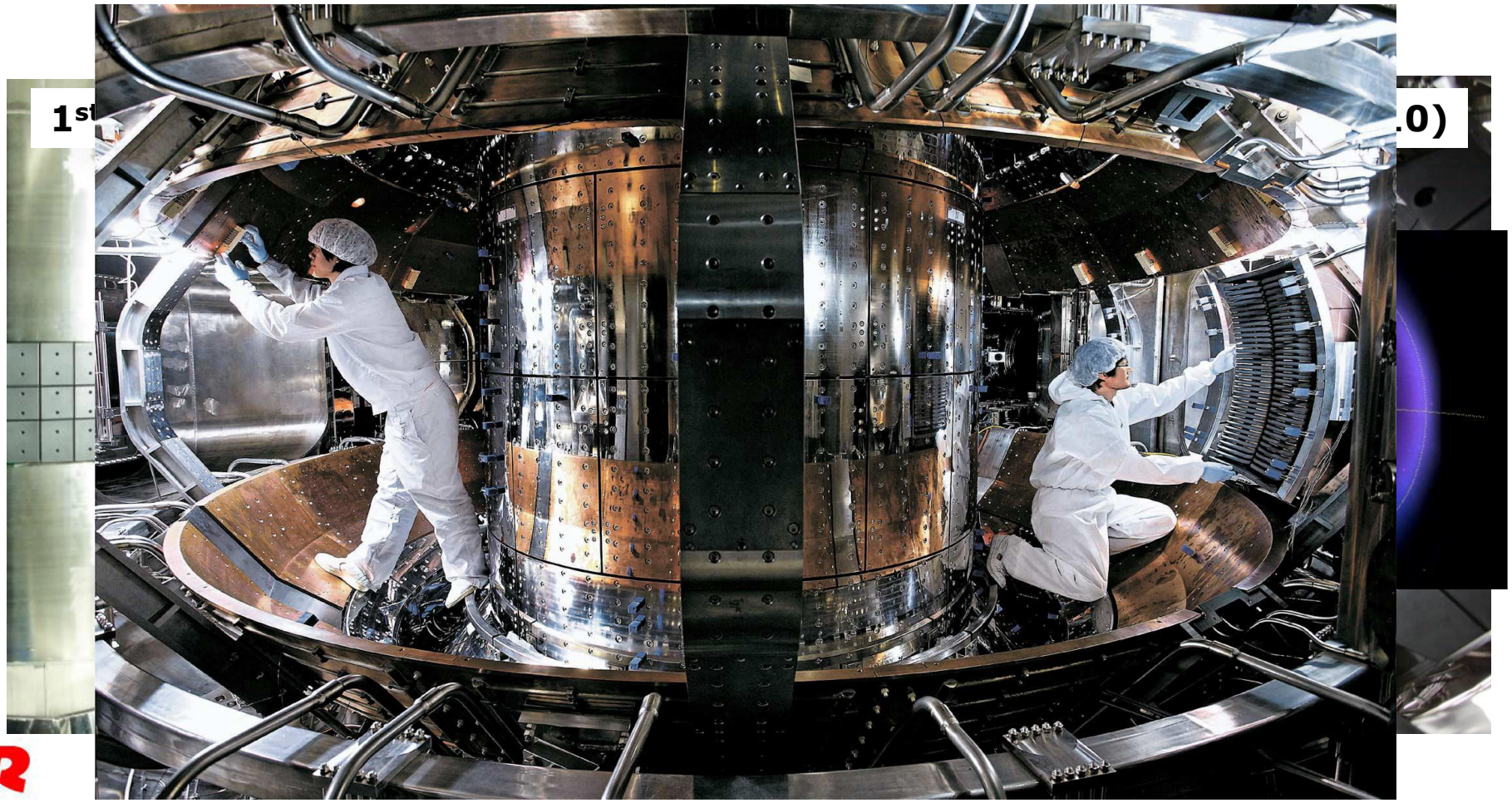

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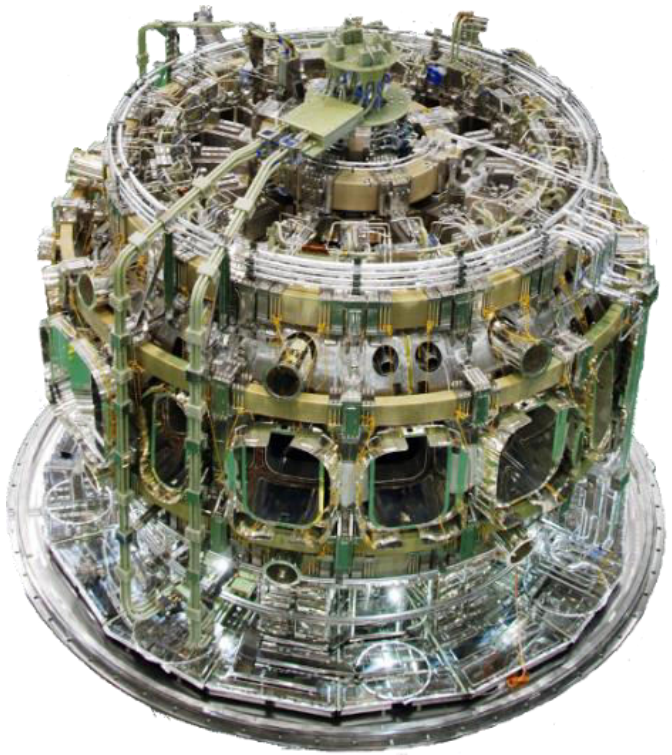

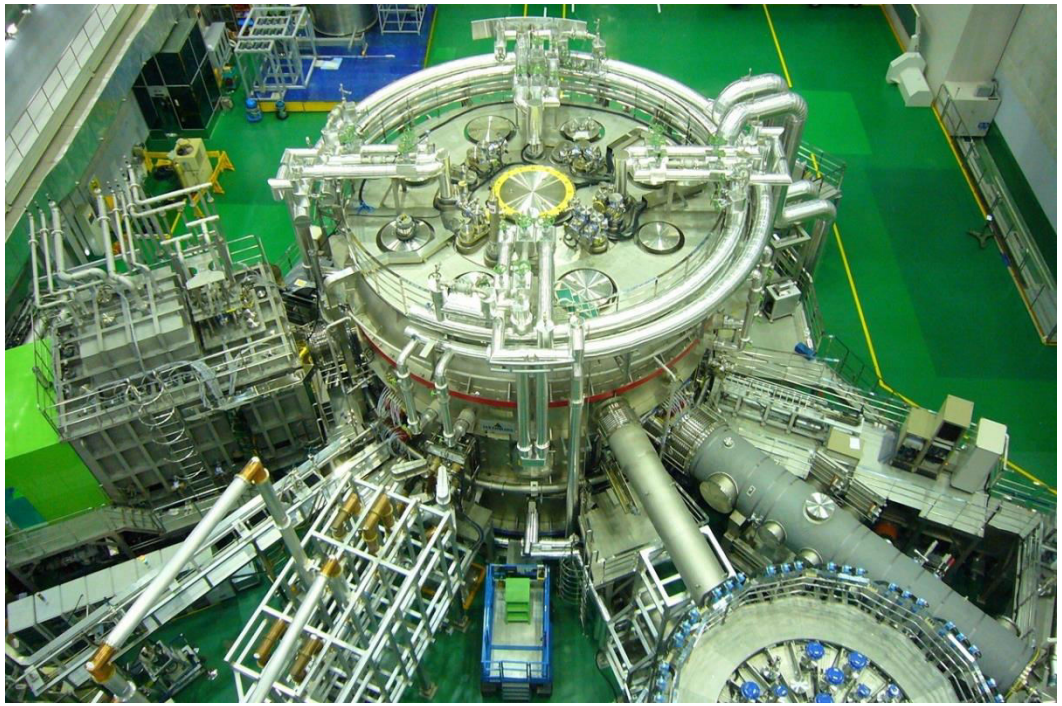

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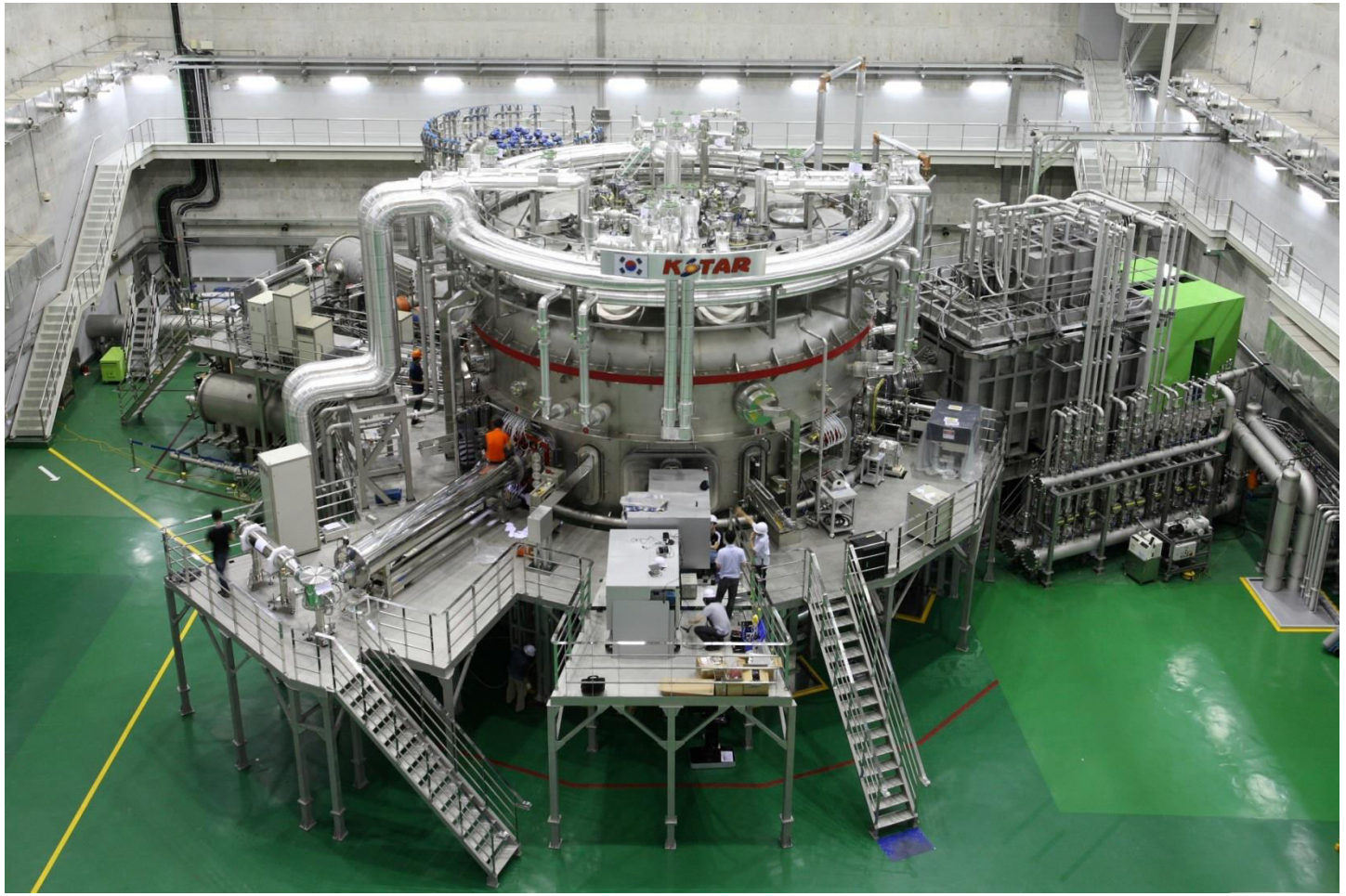


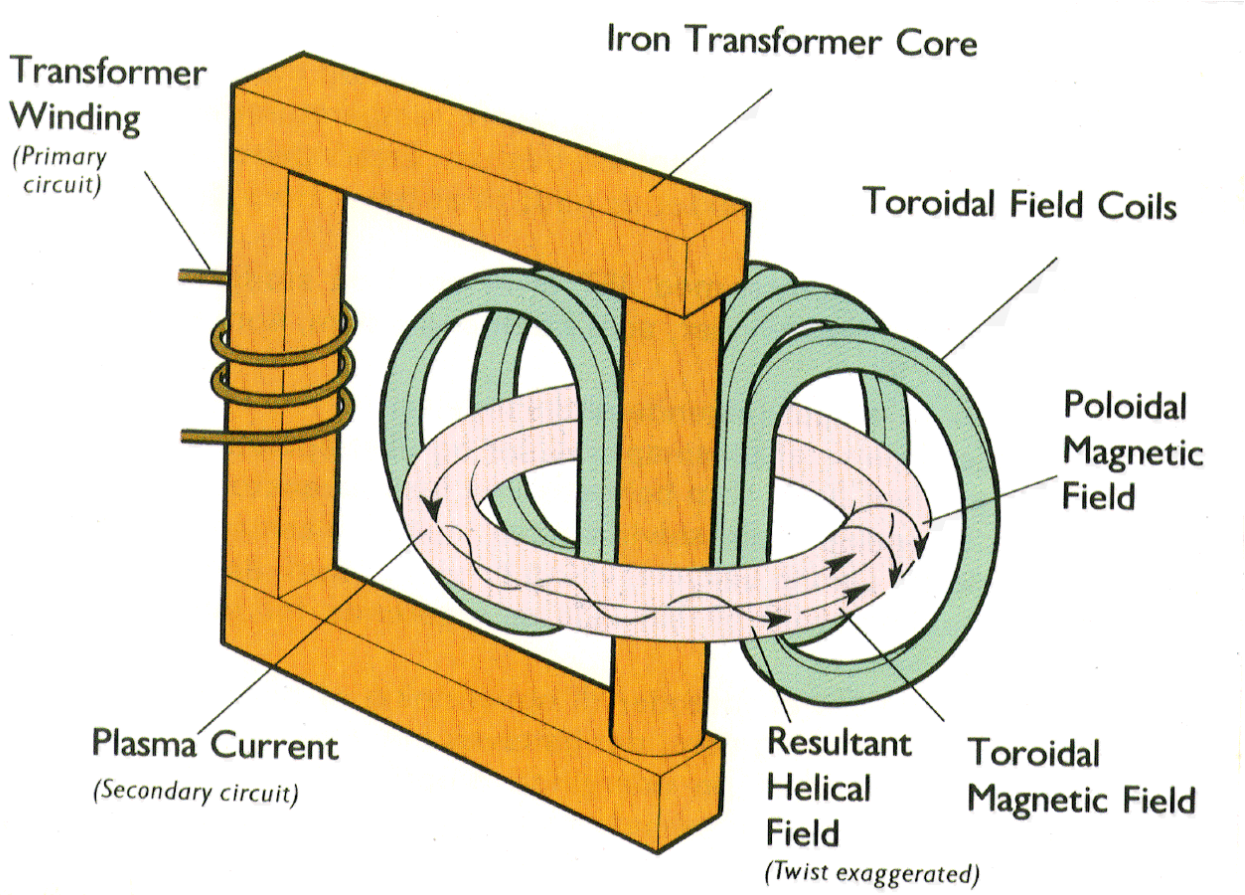
Tokamak

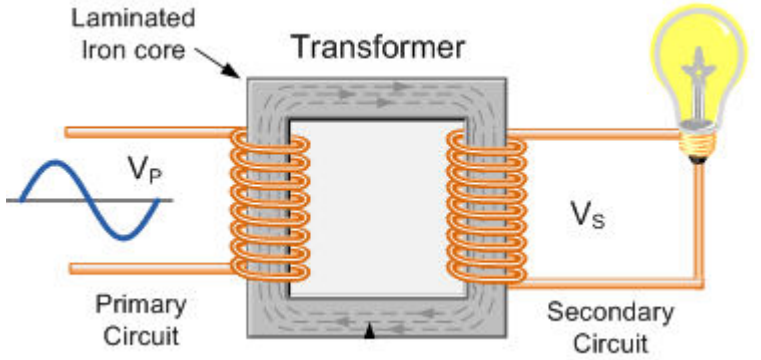
KSTAR (Korea Superconducting Tokamak Advanced Research):
R_0 = 1.8 m, a = 0.5 m, 2007-today

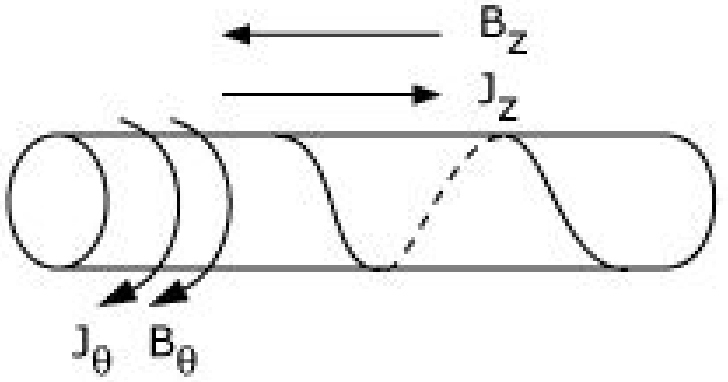
KSTAR 1st plasma

Analyse the KSTAR 1st plasma

Tokamak







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