Fusion Reactor Technology 2
(459.761, 3 Credits)

Prof. Dr. Yong-Su Na

(32-206, Tel. 880-7204)

Introduction

- **Reference**

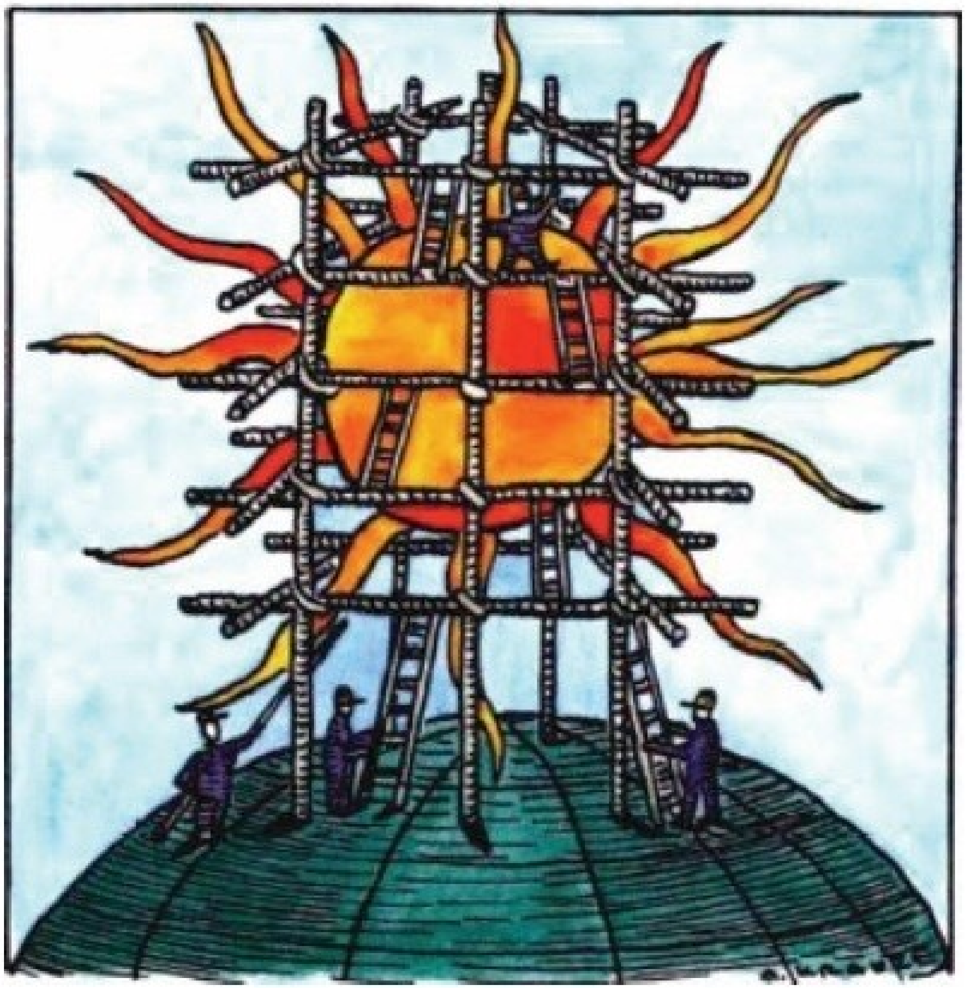
- B. B. Kadomtsev, "Tokamak Plasma: A Complex Physical System", Institute of Physics Publishing, Bristol and Philadelphia (1992)
- L. C. Woods, "Theory of Tokamak Transport - New Aspects for Nuclear Fusion Reactor Design", WILEY-VCH (2006)
- A. A. Harms, K. F. Schoepf, G. H. Miley, D. R. Kingdon, "Principles of Fusion Energy", World Scientific Publishing Co. Pte. Ltd. (2000)
- J. Wesson, "Tokamaks", Oxford University Press, 3rd Edition (2004)
- J. Feidberg, "Plasma Physics and Fusion Energy", Cambridge (2007)
- R. O. Dendy, "Plasma Physics: An Introductory Course", Cambridge University Press (February 24, 1995)

Introduction

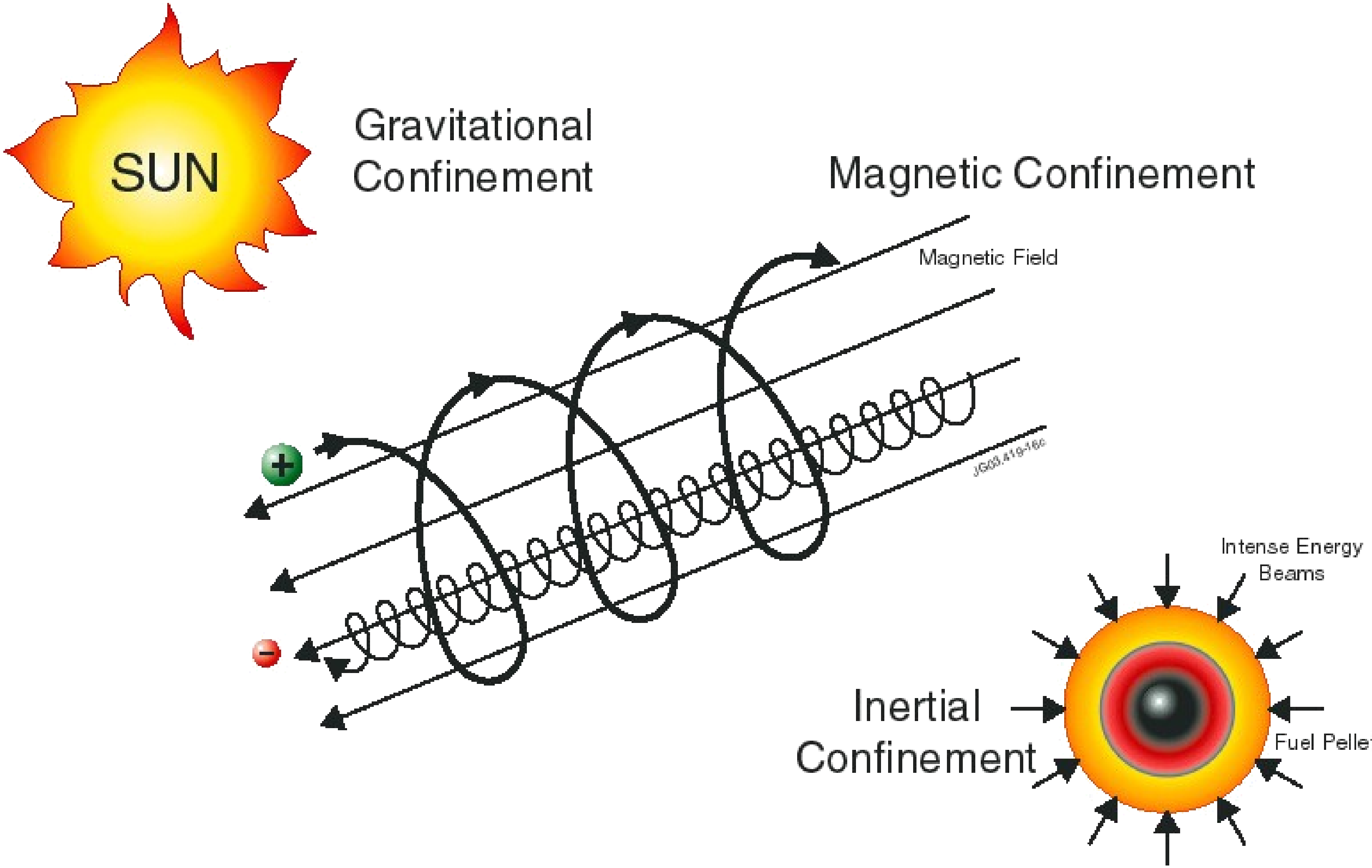
Evaluation

- Attendance & Course Participation: 10%
- Homework: 10%
- Midterm exam: 40%
- Final exam: 40%

To build a sun on earth



To build a sun on earth



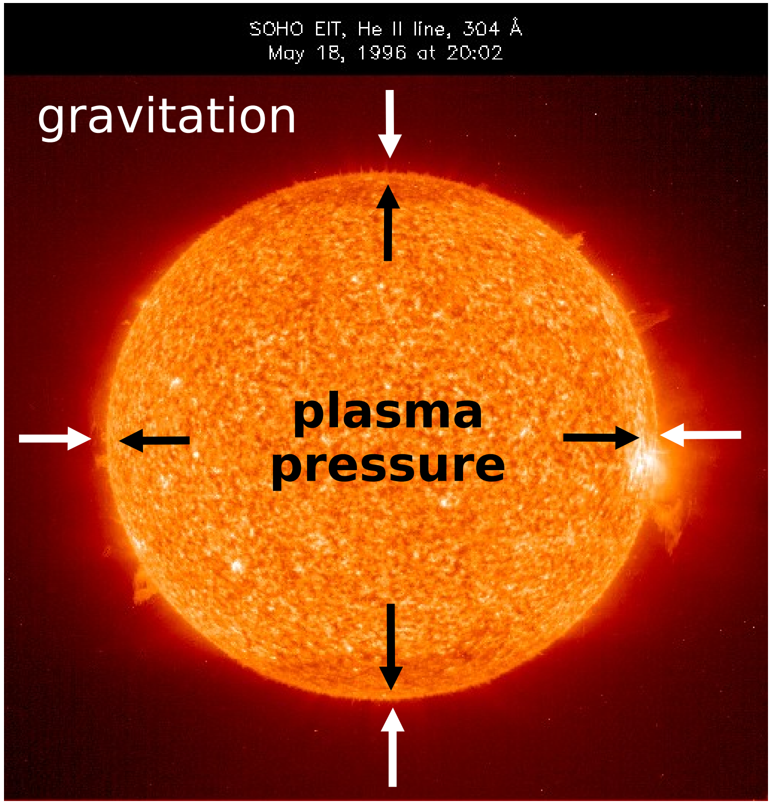
Magnetic Confinement

"To keep the ions from hitting the wall, some type of force is required that will act at a distance. A magnetic field seems to offer the only promise."

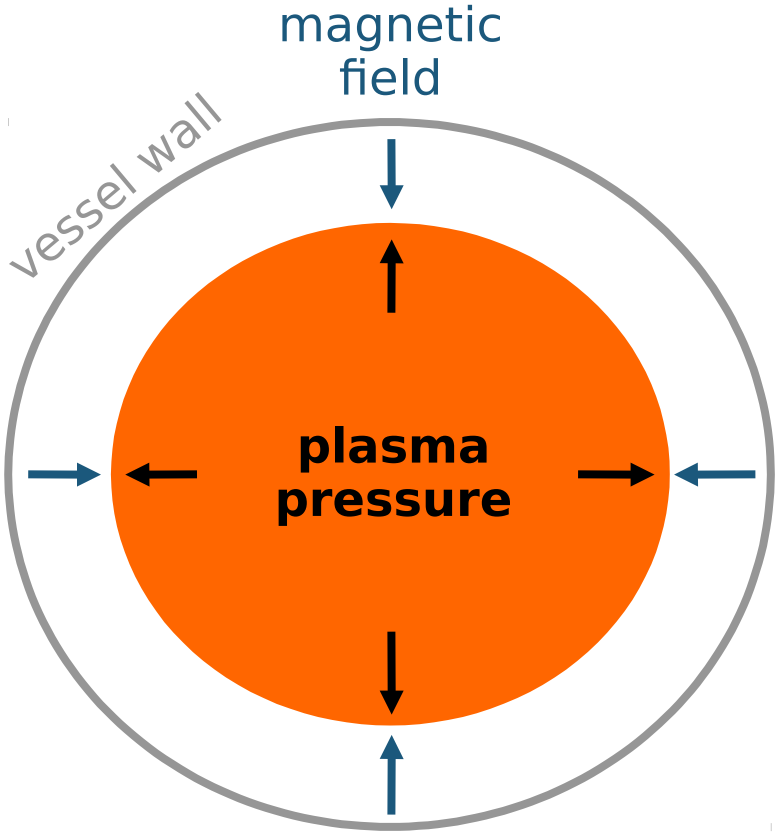
L. Spitzer, Jr.

Magnetic Confinement

- **Imitation of the Sun on Earth**



Equilibrium in the sun



Plasma on earth
much, much smaller & tiny mass!

Magnetic Confinement

- **Bring the Sun on the Earth**

Quantity	ITER	Sun	Ratio
Diameter	16.4 m	140x10^4 km	~ 1/10^8
Central temp.	200 Mdeg	15 Mdeg	10
Central density	~10^{20}/m^3	~10^{32}/m^3	~1/10^{12}
Central press.	~5 atm	~10^{12} atm	~1/10^{11}
Power density	~0.6 MW/m^3	~0.3 W/m^3	~2x10^6
Reaction	DT	pp	
Plasma mass	0.35 g	2x10^{30} kg	1/6x10^{33}
Burn time const.	200 s	10^{10} years	10^{15}

M. Kikuch, “steady state tokamak reactor and its physics issues”, Talk at SNU, Korea, September 30, 2011

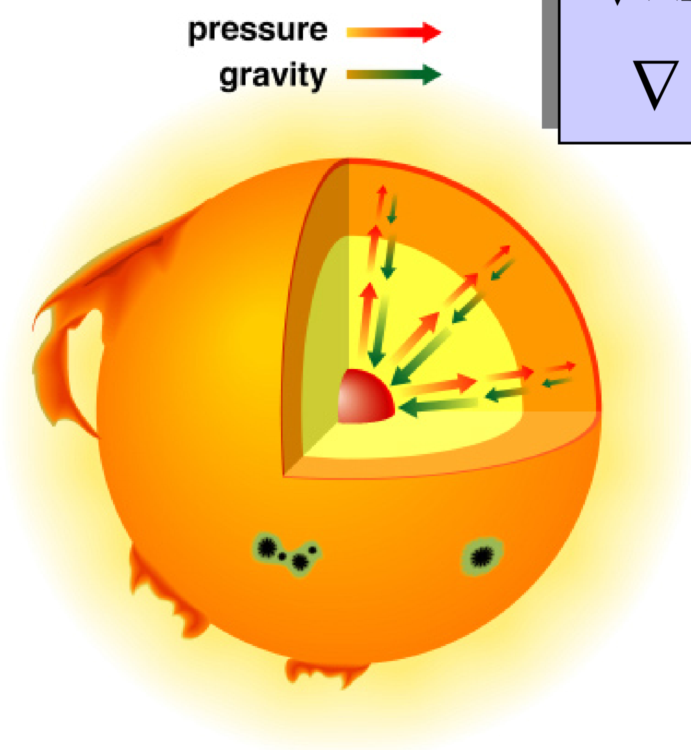
Magnetic Confinement

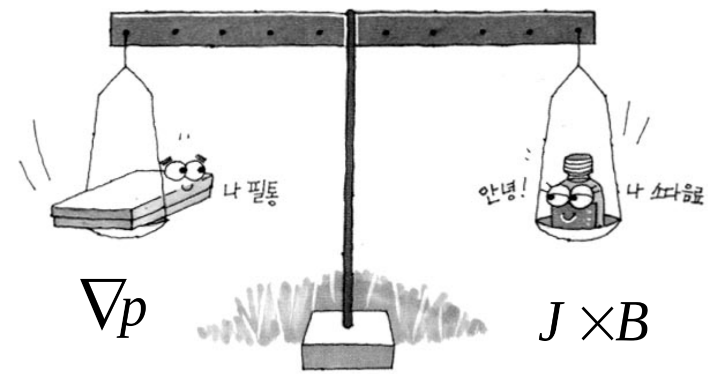
- **Radial Force Balance**

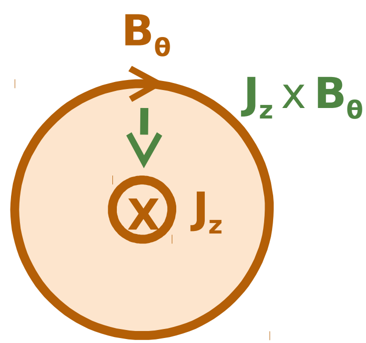
$$\nabla p = J \times B$$

$$\nabla \times B = \mu_0 J$$

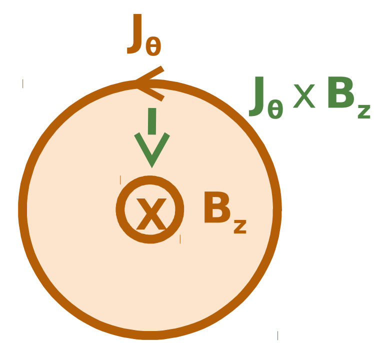
$$\nabla \cdot B = 0$$







Z pinch



θ pinch

Magnetic Confinement - History

Inspecting the torus at John Jay Hopkins Laboratory's fusion research building are, from left to right: Richard Courant, Hideki Yukawa, Marshall N. Rosenbluth, Marcus Oliphant, Niels Bohr, Edward C. Creutz, and Donald W. Kerst, General Atomic, Division of General Dynamics Corporation Courtesy of AIP's Emilio Segrè Visual Archives

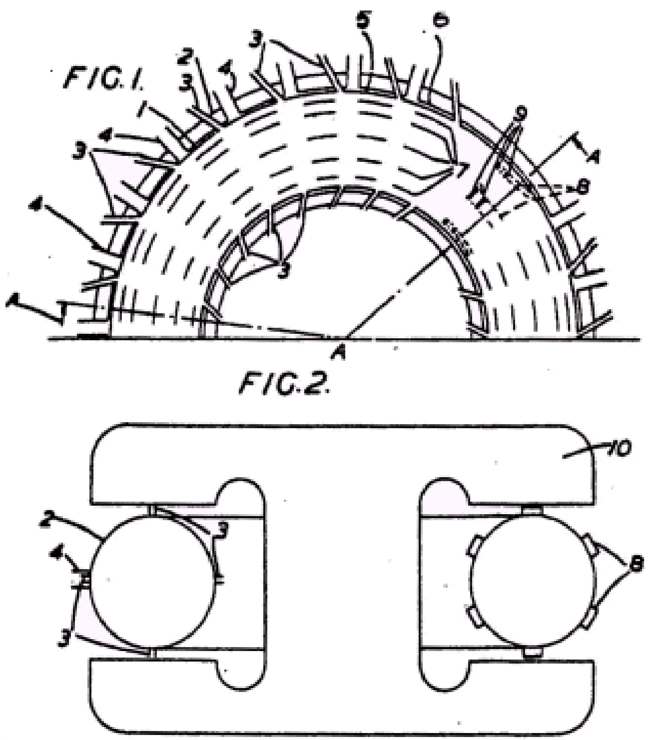
http://pop.aip.org/article_archive_2009/09_16_09_selected_highly_cited_papers_from_50_years_of_plasma_physics

1946: Fusion Reactor Patent

- **Fusion Reactor Patent**

- G. P. Thomson and M. Blackman, of the University of London, filed a patent for a fusion reactor in 1946.

- Although the scale of this device was overly optimistic, the device already featured a vacuum chamber in a torus shape and current generation by radio-frequency waves, two important aspects found on today's tokamaks!



- Major radius R_0 = 1.3 m
- Minor radius a = 0.3 m
- Plasma current 0.5 MA, created by 3 GHz radiofrequency waves

G. P. Thompson and M. Blackman
1946 British Patent 817681

1946: Fusion Reactor Patent

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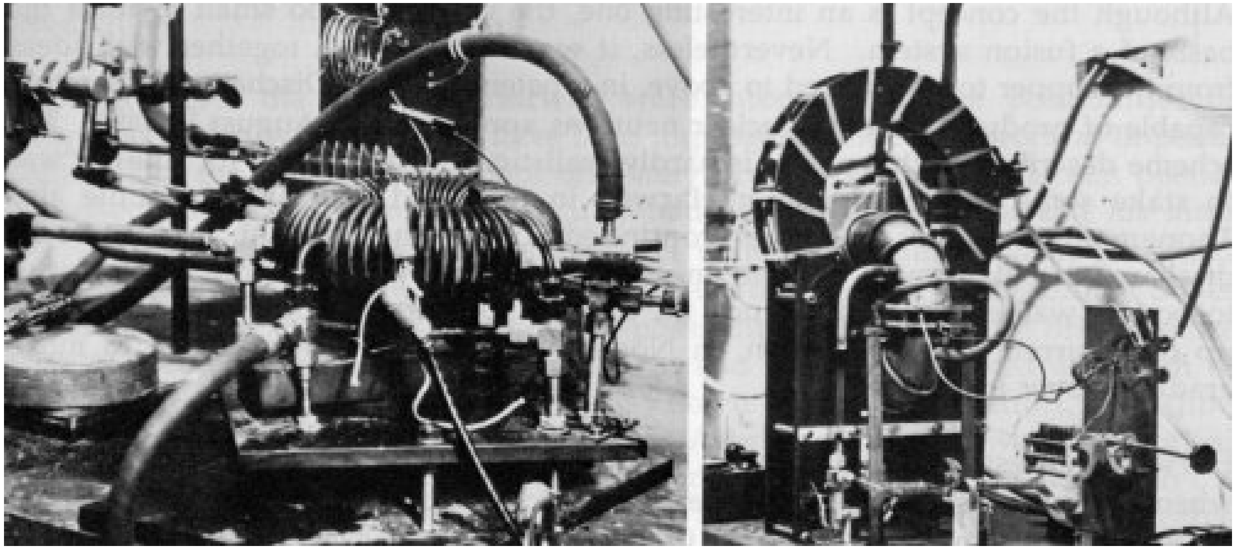
- Although the scale of this device was overly optimistic, the device already featured a vacuum chamber in a torus shape and current generation by radio-frequency waves, two important aspects found on today's tokamaks!

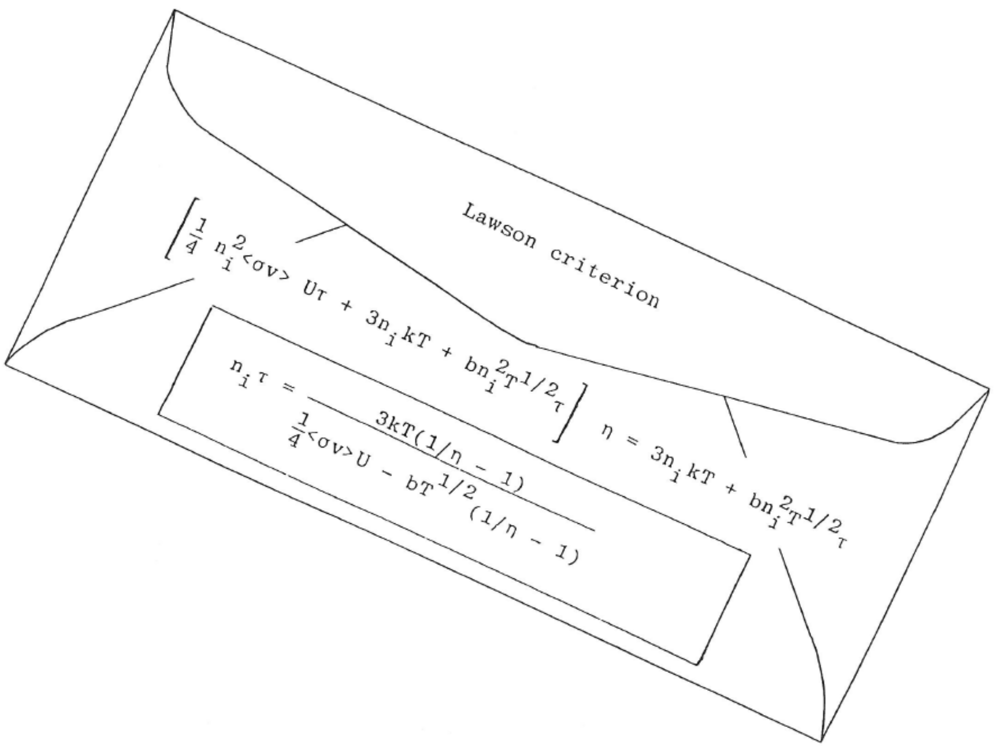


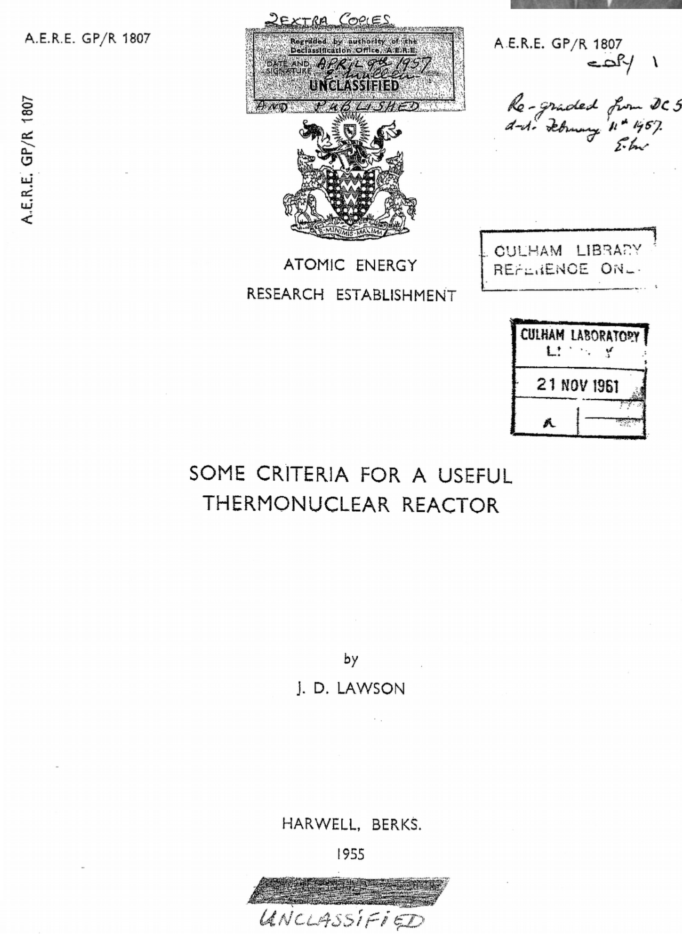
1946: the magnetic confinement devices tested by Thoneman (tori made of glass and metal), in the Clarendon laboratory (Oxford, United Kingdom)

1955: Lawson Criterion

- **Lawson Criterion**

- Building a fusion reactor is a very challenging task.
- Simple criterion found by Lawson

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Regraded by authority of the Declassification Office, A.E.R.E.

DATE AND SIGNATURE APRIL 9th 1957

UNCLASSIFIED

AND PUBLISHED

A.E.R.E. GP/R 1807

copy 1

ATOMIC ENERGY RESEARCH ESTABLISHMENT

SOME CRITERIA FOR A USEFUL THERMONUCLEAR REACTOR

by

J. D. LAWSON

HARWELL, BERKS.

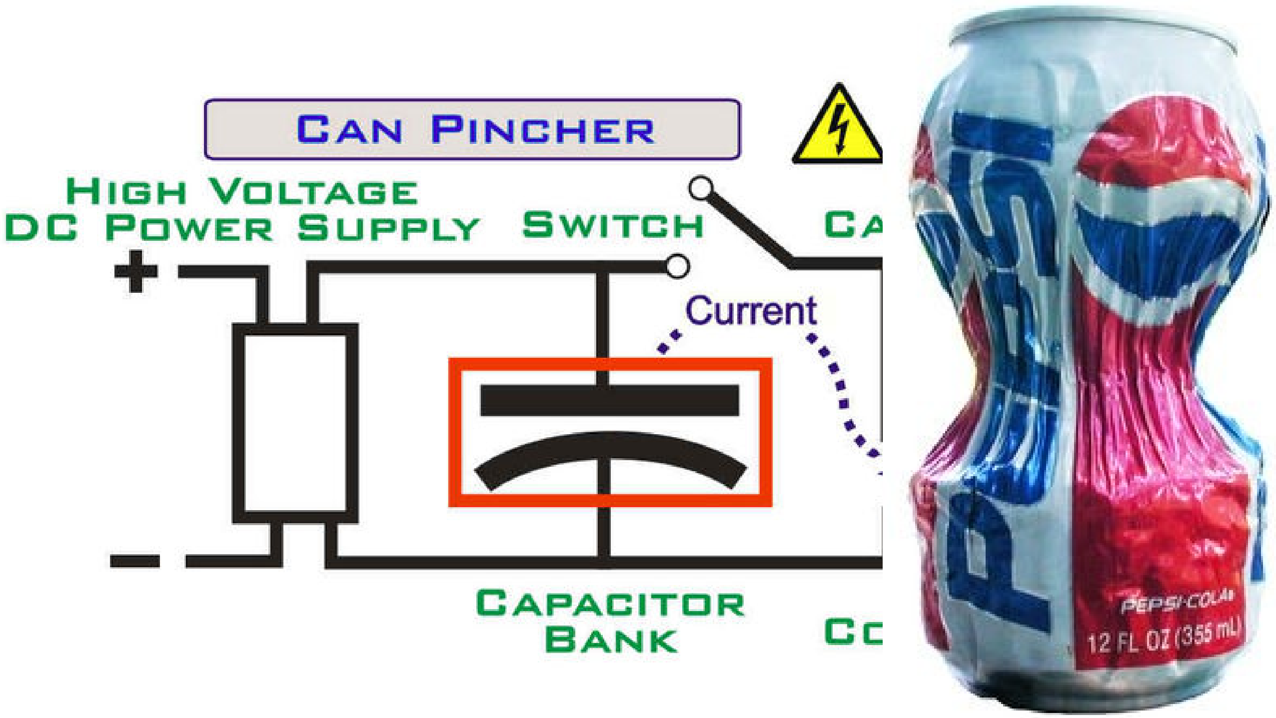
1955

[redacted]

UNCLASSIFIED

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **Pinches**



A theta pinch capable of crushing an aluminium soft drink can

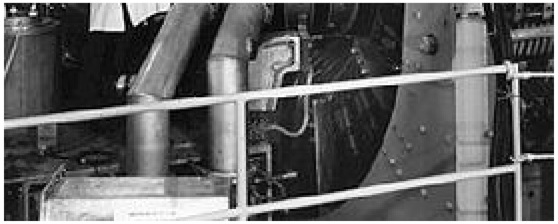
http://www.plasma-universe.com/Pinch

1950-1965: Configurations under Study in the Early Years of Fusion Research

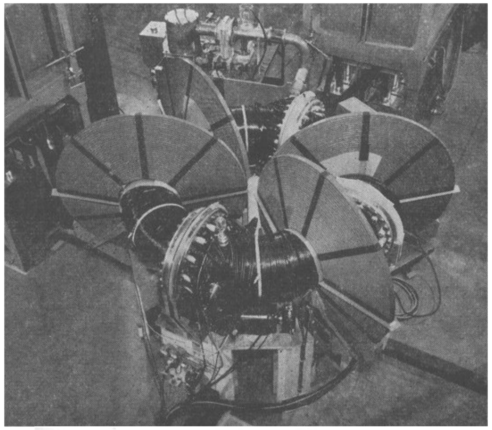
- **Toroidal Pinches, e.g.**

- Z-pinch: ZETA (Culham, UK), Perhapsatron S-3/S-4/S-5 (Los Alamos, USA), ...
- Confinement properties and reactor prospects disappointing

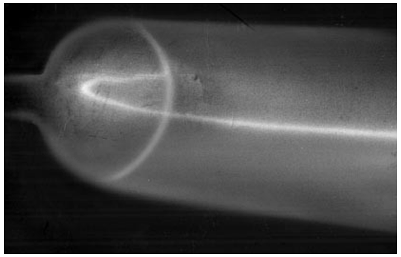
“Zero Energy" refers to the aim of producing copious numbers of fusion reactions, but releasing no net energy.



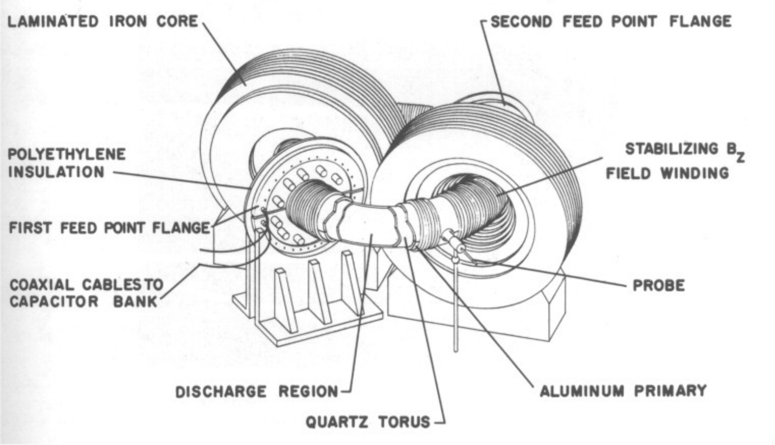
ZETA (Zero Energy Thermonuclear Assembly) (1954-58, UK)



Perhapsatron (1952-1961, USA)



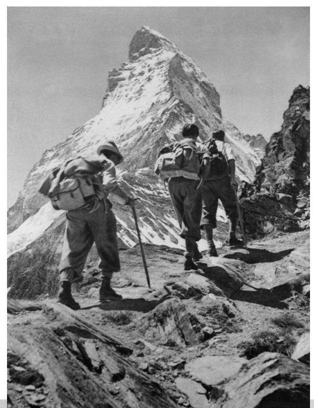
Xenon pinched discharge

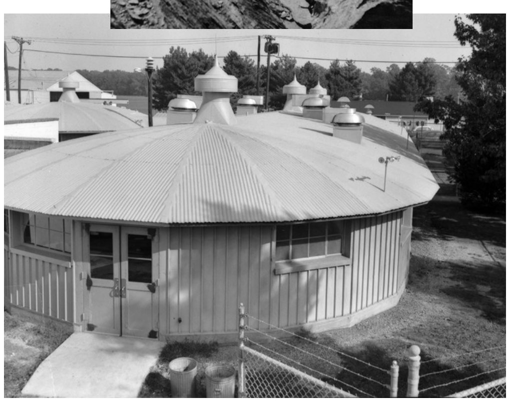


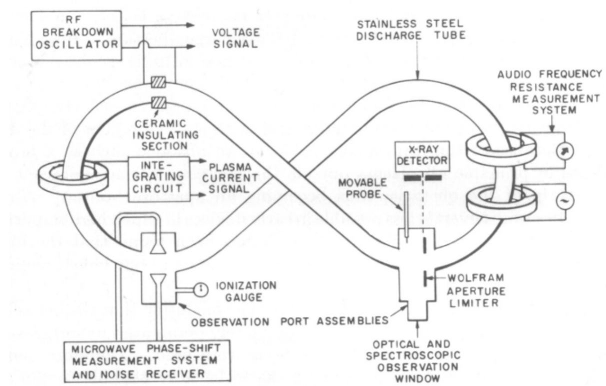
1950-1965: Configurations under Study in the Early Years of Fusion Research

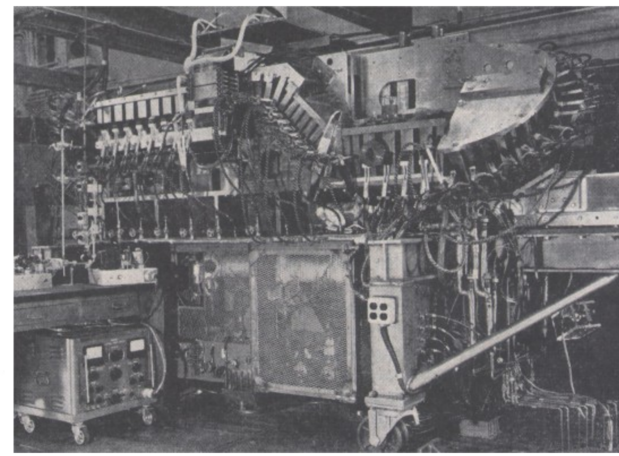
- **Stellarators, e.g.**

- C-Stellarator (Spitzer, Princeton, USA - later converted into the ST tokamak), Sirius (USSR), Initial Wendelsteins (IPP-Garching), ….
- Initial results very disappointing









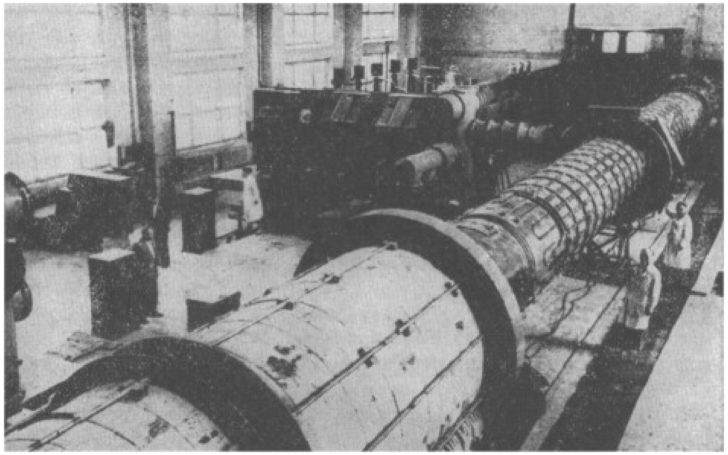
The Model B-3 stellarator (the last figure-8 stellarator) (USA)

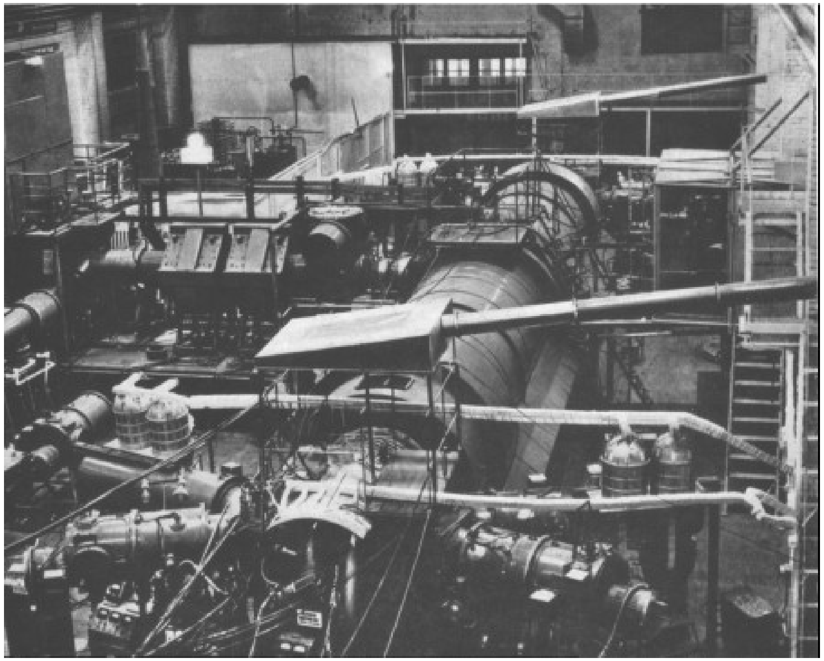
Mattherhorn project (1951, USA)

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **Mirror Machines, e.g.**

- USSR: OGRA fitted with Ioffe's magnetic wells (Institute of Physics of Moscow)
  France: DECA I, II, III (later withdrawn) and MMII (CEA)
  USA: Table Top and Toy Top, MFTF-B (abandoned) (Livermore)





The OGRA Device (1957, USSR)

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **Mirror Machines, e.g.**

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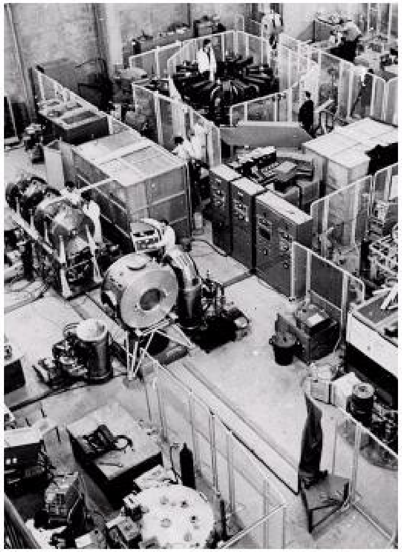
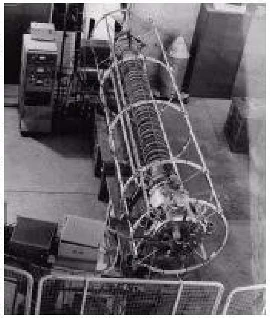
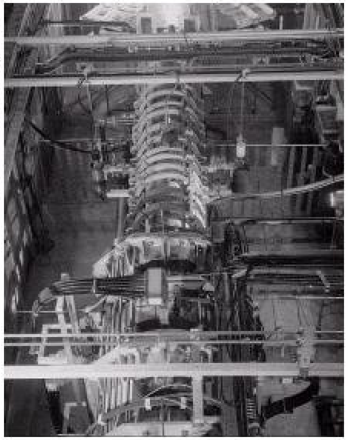


Fusion research laboratory (CEA-1962)



Capel B (CEA - 1966)



DECA 2B (CEA - 1966)

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **Fundamental Difficulties**

- Several instabilities discovered reducing confinement:
  Kink instabilities, flute instabilities, …
  M. D. Kruskal and Schwarzchild "Some Instabilities of a Completely Ionized Plasma" 1954 Proc. R. Soc. Lond. A 223 348
  M. N. Rosenbluth and C. L. Longmire “Stability of Plasmas Confined by Magnetic Fields”, Ann. Phys. **1** 120 (1957)

- Most toroidal machines followed the so-called Bohm scaling for the confinement time:

$$\tau \propto \frac{BR^2}{T}$$

Very low confinement times predicted by this formula (for JET this would predict 10-40 μs)

- Need for better machine configurations

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **1958**

- By mid-1958 nuclear fusion research had been virtually freed from all security restrictions, in the UK, the USA and the USSR.

No. 4604 January 25, 1958 NATURE

PRODUCTION OF HIGH TEMPERATURES AND NUCLEAR REACTIONS IN A GAS DISCHARGE

By Dr. P. C. THONEMANN, E. P. BUTT, R. CARRUTHERS, Dr. A. N. DELLIS, D. W. FRY, Dr. A. GIBSON, G. N. HARDING, D. J. LEES, R. W. P. McWHIRTER, R. S. PEASE, Dr. S. A. RAMSDEN and S. WARD

Atomic Energy Research Establishment, Harwell

Conclusion

These preliminary results demonstrate that it is possible to produce a stable highly ionized plasma isolated from the walls of a toroidal tube. Hydrogen gas has been maintained in a state of virtually complete ionization with a particle density lying between 10^{13} and 10^{14} per cm.^{3}, for times of milli-seconds. The mean energy of the ions in the plasma is certainly of the order of 300 eV., and there are many indications that the electron temperature is of the same order. The containment time and the high electrical conductivity are both adequate for the detailed study of magnetohydrodynamical processes.

To identify a thermonuclear process it is necessary to show that random collisions in the gas between deuterium ions are responsible for the nuclear reactions. In principle, this can be done by calculating the velocity distribution of the reacting deuterium ions from an exact determination of both the energy and direction of emission of the neutrons. The neutron flux so far obtained is insufficient to attain the desired accuracy of measurement.

1950-1965: Configurations under Study in the Early Years of Fusion Research

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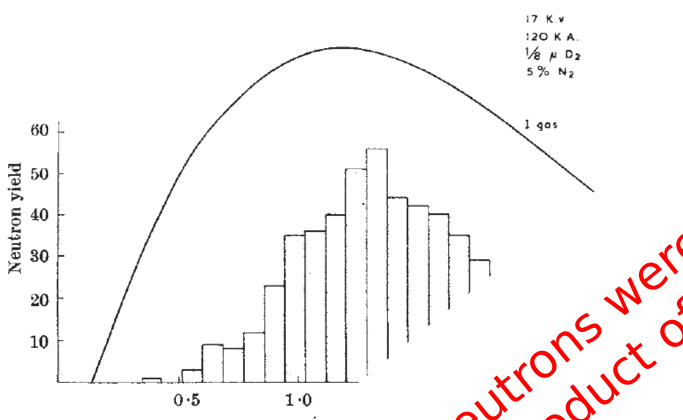


Fig. 4. Histogram show... times

The neutrons were later explained as the byproduct of instabilities in the fuel!

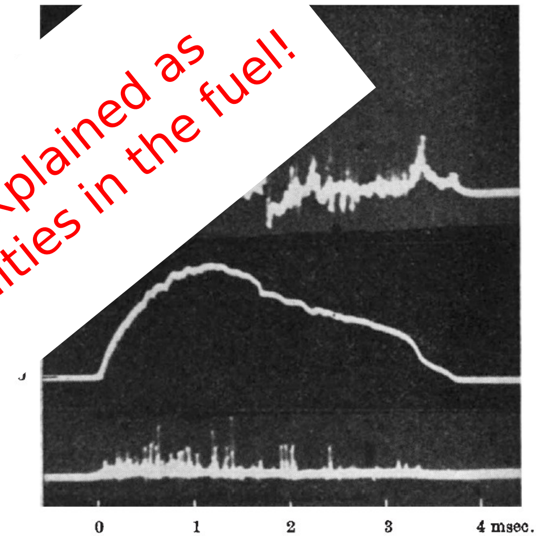


Fig. 2. Oscillograph recordings of the voltage per turn of the transformer, and the secondary current I_2. The lower trace shows the pulses produced by proton recoil in a scintillation neutron counter. Conditions: gas, deuterium + 5 per cent nitrogen + 10 per cent oxygen; pressure, $0\cdot13 \times 10^{-3}$ mm. mercury; axial field, 160 gauss

*P. C. Thonemann et al, Nature **181** 217 (1958)*

1950-1965: Configurations under Study in the Early Years of Fusion Research

- **September 1958 "Atoms for Peace" (IAEA, Geneva)**
  - 1957 Eisenhower's UN speech
  - IAEA established in 1957

"to make of the atom a peaceful servant of humanity, I shortly shall ask the Congress to authorize full United States participation in the International Atomic Energy Agency."

Dwight D. Eisenhower 1957

IAEA
International Atomic Energy Agency

1950-1965: Configurations under Study in the Early Years of Fusion Research

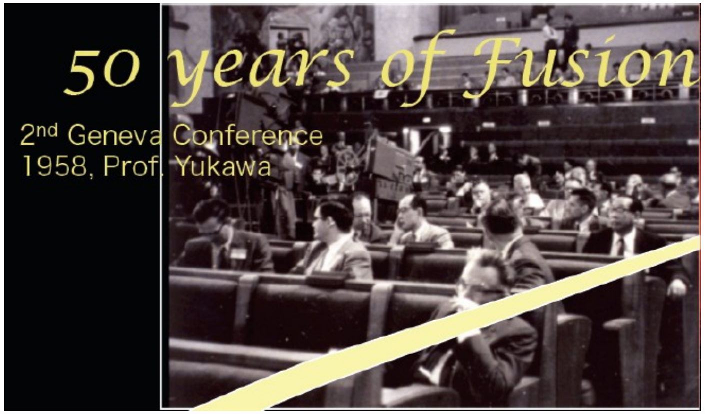
- **September 1958 “Atoms for Peace” (IAEA, Geneva)**

Proceedings of the Second
United Nations International Conference
on the Peaceful Uses of Atomic Energy

Held in Geneva
1 September - 13 September 1958

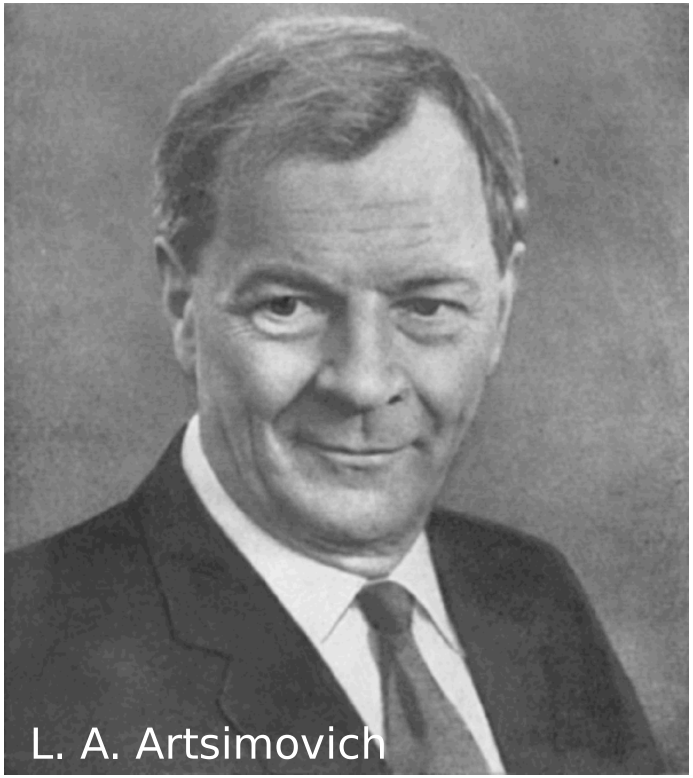
Volume 32
Controlled Fusion Devices

UNITED NATIONS
Geneva
1958



1950-1965: Configurations under Study in the Early Years of Fusion Research

- **September 1958 “Atoms for Peace” (IAEA, Geneva)**



“Plasma physics is very difficult. Worldwide collaboration needed for progress.”

“Fusion technology is very complex. It is almost impossible to build a fusion reactor in this century.”

1968: A Turning Point for Fusion Physics
Emergence of the Tokamak

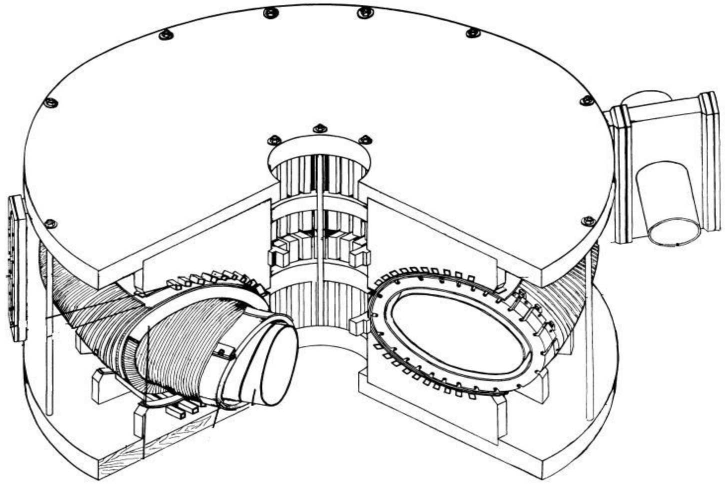


Diagram of the Kurchatov Institute's
T1 tokamak in Moscow

IAEA Novosibirsk
(August 1968)
T3 reaches 1 keV

1968: A Turning Point for Fusion Physics
Emergence of the Tokamak

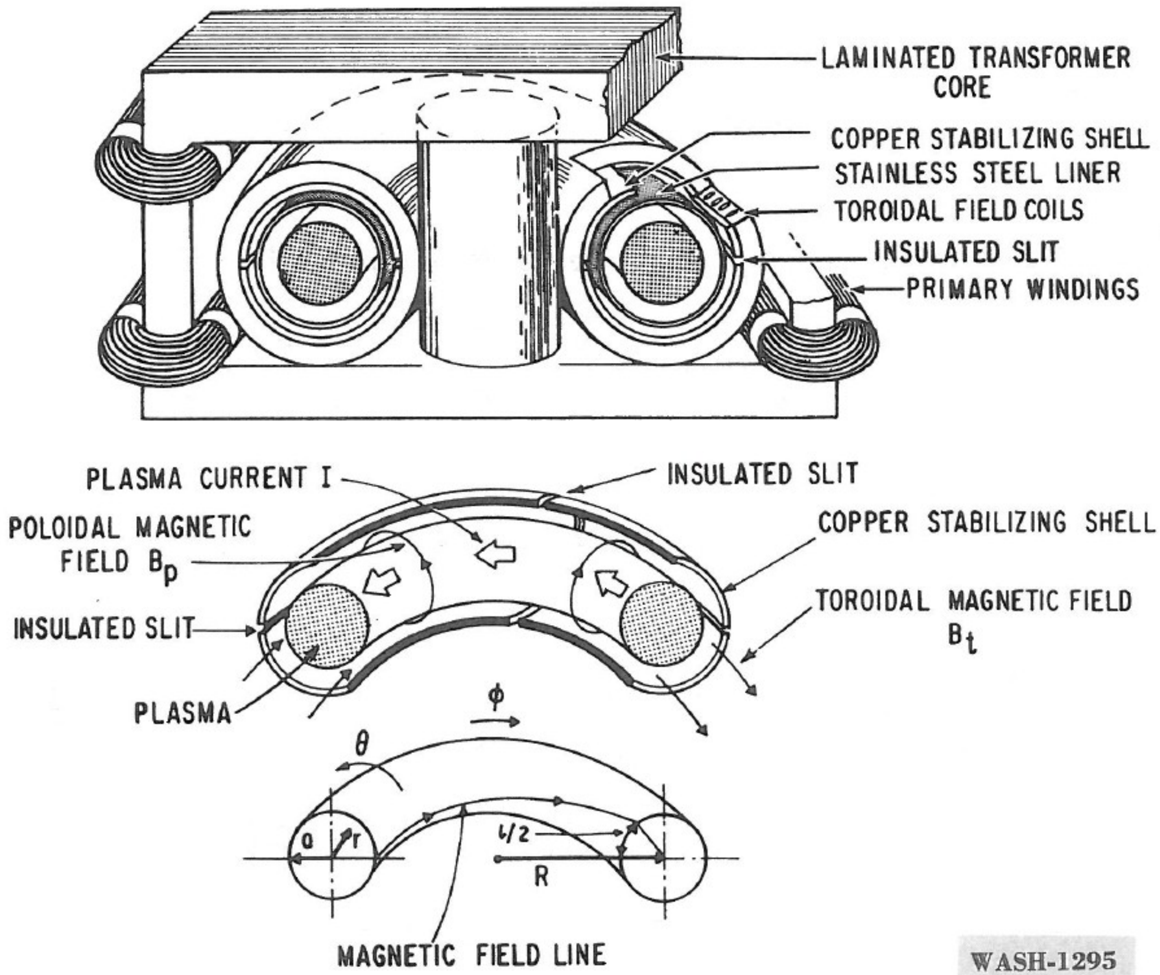
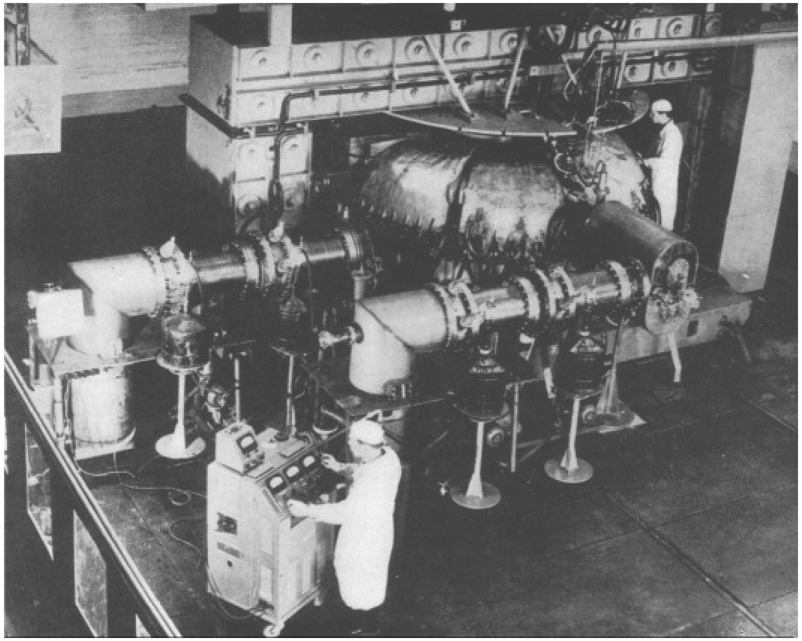
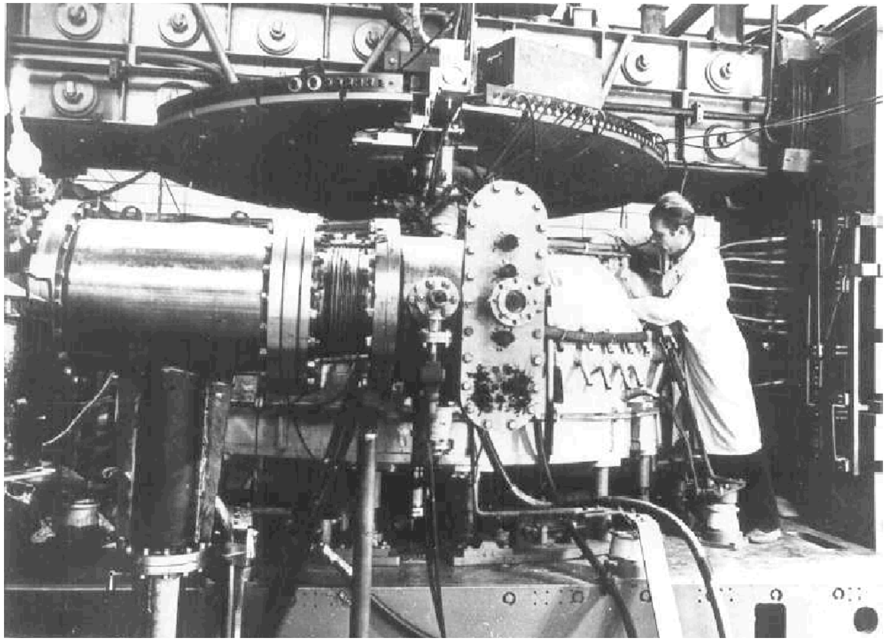


Figure 1. Basic tokamak apparatus: a toroidal plasma confined in a helical magnetic field created by the superposition of a strong, externally generated toroidal field and the poloidal field generated by the plasma current. The plasma current, induced by transformer action, resistively heats the plasma.

WASH-1295

1968: A Turning Point for Fusion Physics
Emergence of the Tokamak

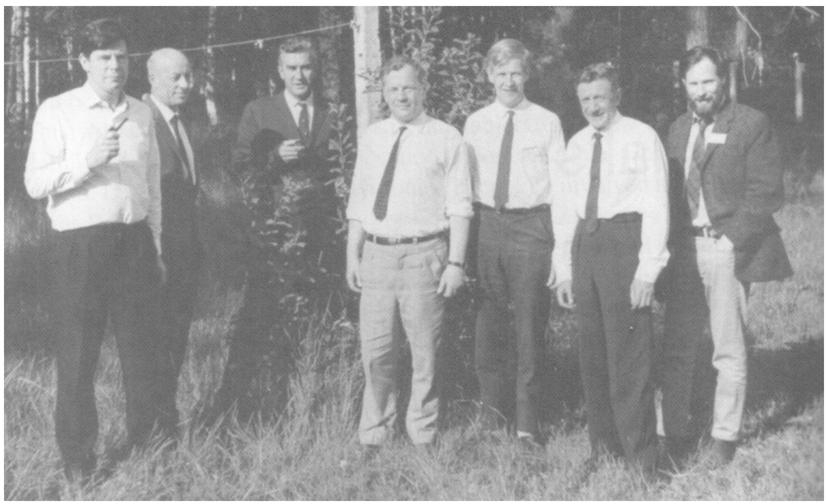




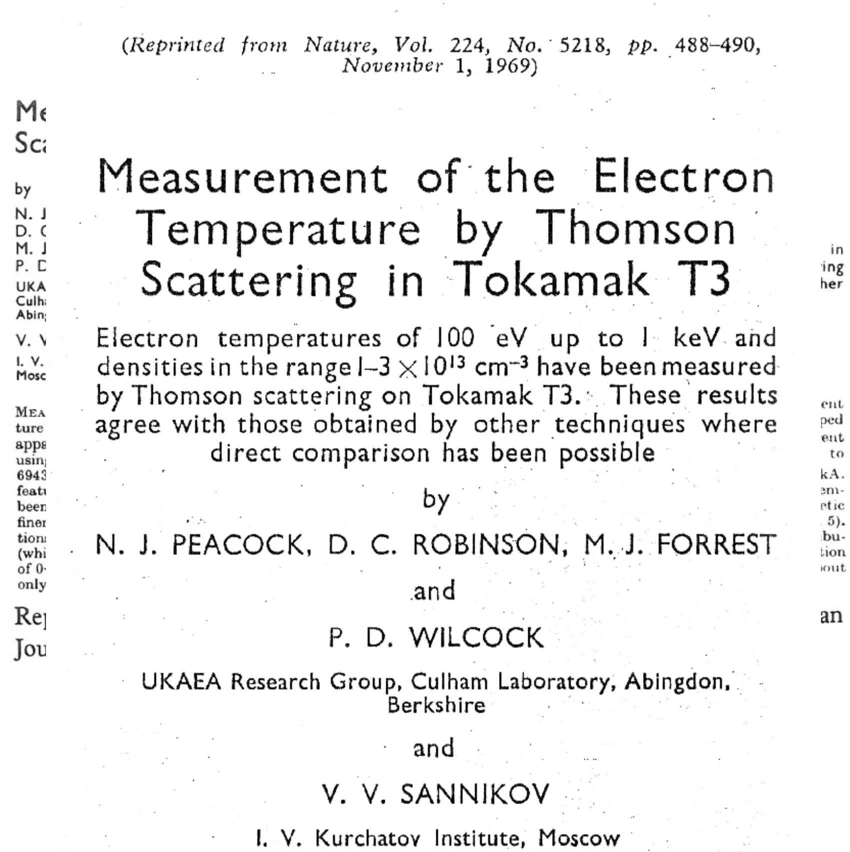
Tokamak T-3
(USSR)

1968: A Turning Point for Fusion Physics Emergence of the Tokamak

- Confirmed by 1969 Culham mission to Moscow



A group of Soviet and British scientists during the Novosibirsk conference (1968)



(*Reprinted from Nature, Vol. 224, No. 5218, pp. 488–490, November 1, 1969*)

Measurement of the Electron Temperature by Thomson Scattering in Tokamak T3

Electron temperatures of 100 eV up to 1 keV and densities in the range 1–3 × 10^{13} cm^{-3} have been measured by Thomson scattering on Tokamak T3. These results agree with those obtained by other techniques where direct comparison has been possible

by

N. J. PEACOCK, D. C. ROBINSON, M. J. FORREST

and

P. D. WILCOCK

UKAEA Research Group, Culham Laboratory, Abingdon, Berkshire

and

V. V. SANNIKOV

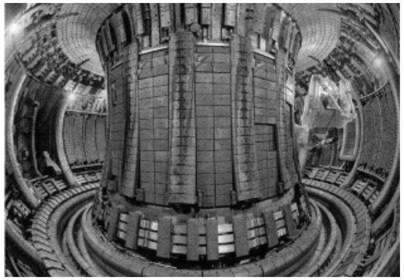
I. V. Kurchatov Institute, Moscow

1969- Success of Tokamak

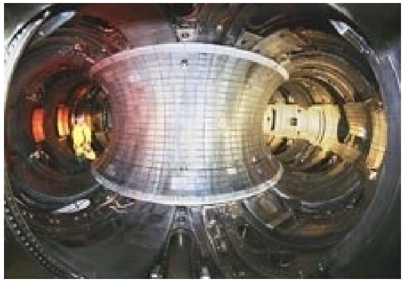
- **Tokamaks**

- Showing much better confinement than all other configurations
- T-3 (Kurchatov Institute, USSR):
  First device with temperatures in the keV range
  Confinement time (70 ms) more than 30 times higher than predicted by Bohm scaling
- 1969: General redirection towards the tokamak (‘Tokamakitis’)
- Diagnostic development on smaller devices
- Data acquisition, feedback, and heating techniques had become available.
- It appeared then that a large device could and had to be build to make further progress: JET, TFTR, JT-60U

JET



TFTR

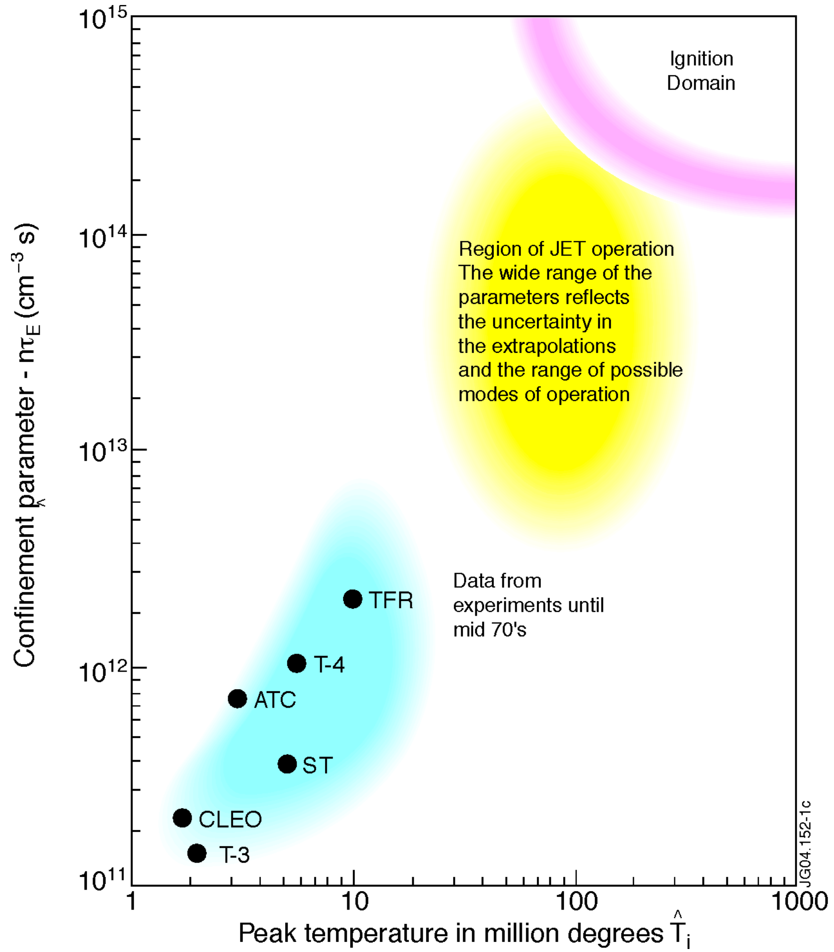


JT-60U

1969- Success of Tokamak

- **Lawson Diagram in mid 1970 s**

- Parameter domain foreseen for JET

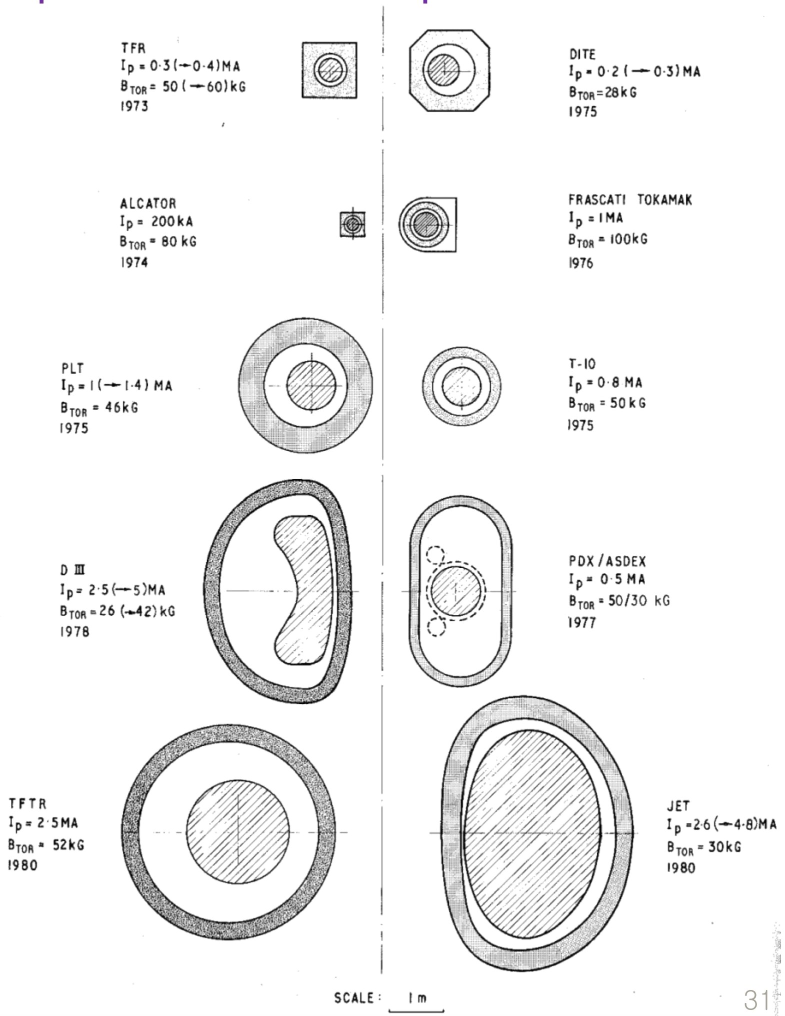


1969- Success of Tokamak

- **JET**

- Much larger plasma compared to existing or planned tokamak plasma at that time
- D-shaped plasma

Design Phase of JET (1973-1975)



1991- DT Operation

- First D-T experiments: JET (Nov. 1991)

PRÉSIDENCE
DE LA
RÉPUBLIQUE

Le Conseiller Technique

1er janvier 1992

Cher Monsieur,

Monsieur le Président a été très sensible à votre lettre du 15 novembre 1991 lui annonçant la réussite de la première fusion thermonucléaire obtenue avec la machine JET que vous dirigez. Il me demande de vous transmettre ses félicitations pour vous et l'ensemble du personnel impliqué dans ce beau succès.

Je profite de cette lettre pour vous adresser tous mes voeux personnels pour la nouvelle année et pour vous dire que je ne désespère pas de trouver un créneau dans mon emploi du temps pour visiter vos installations.

Veuillez agréer, cher Monsieur, l'expression de mes sentiments les meilleurs.

Jean AUDOUZE

Monsieur Paul-Henri REBUT
JET Joint Undertaking
ABINGDON
Oxfordshire OX14 3EA
ANGLETERRE

BUCKINGHAM PALACE

22nd November, 1991

Dear Dr. Rebut,

I am commanded by The Queen to thank you for your letter of 15th November. Her Majesty remembers with pleasure her visit to the Joint European Torus in April 1984 and appreciated your thoughtfulness in letting her know of the controlled experiment which took place recently at your headquarters which produced a quantity of fusion power. The Queen sends her congratulations and best wishes to you and all members of your team.

Yours sincerely,

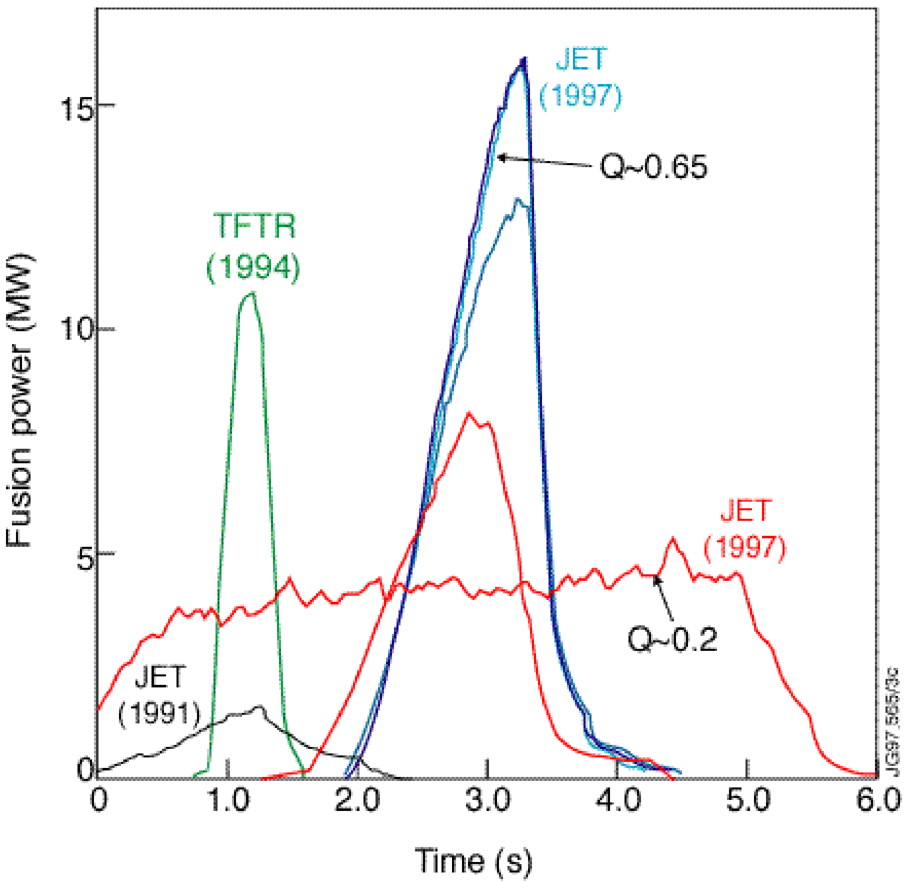
(KENNETH SCOTT)

Dr. P-H Rebut.

- Congratulations from HRH (Her Royal Highness) Queen Elisabeth II and President Mitterand for pioneering and successful D-T experiments

1991- DT Operation

- First D-T experiments: JET (Nov. 1991)



JET 1991 (EU): 1.7 MW

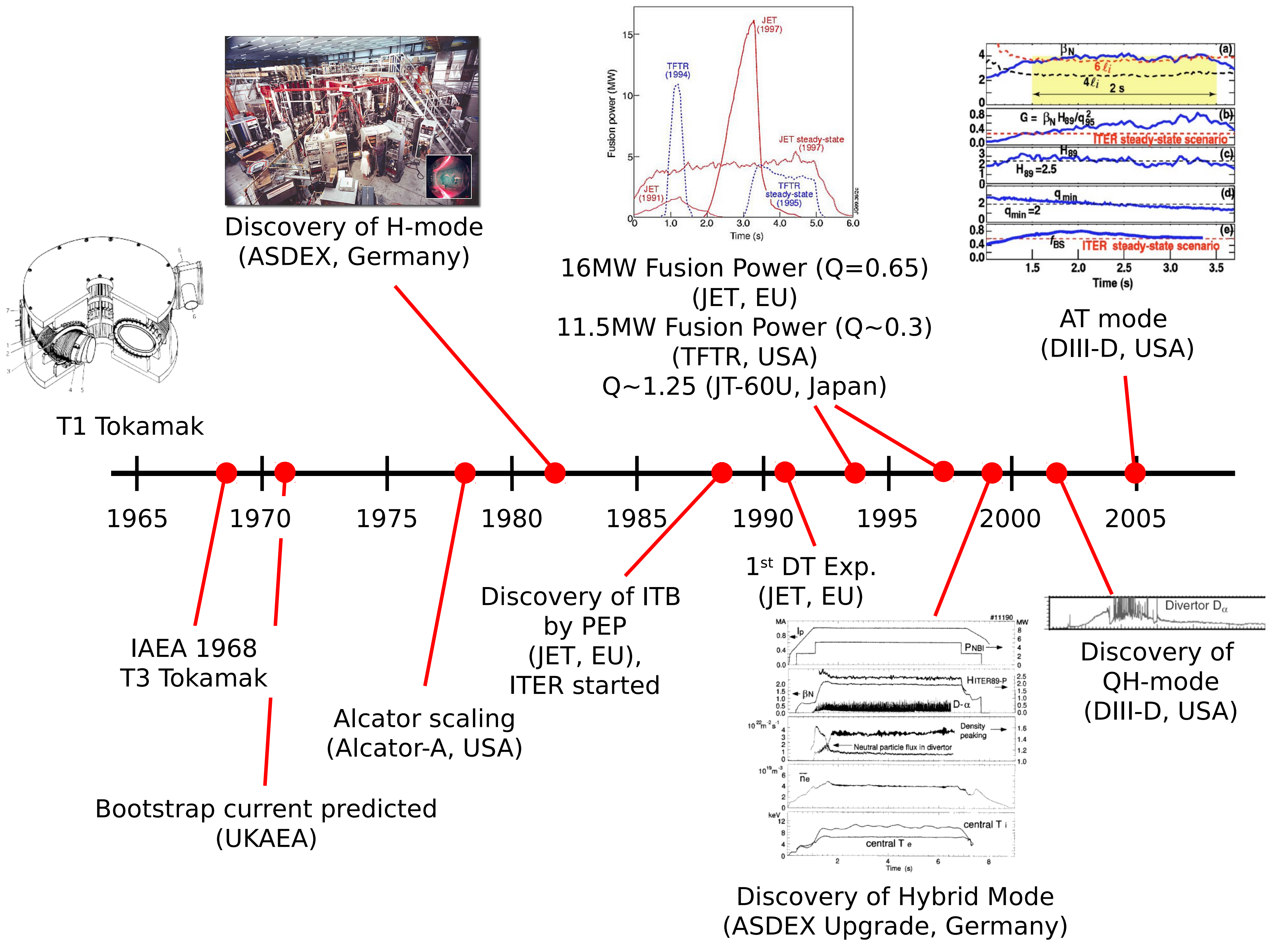
First controlled DT fusion experiments on earth

TFTR 1994 (US): 11.5 MW

JET 1997 (EU): 16 MW

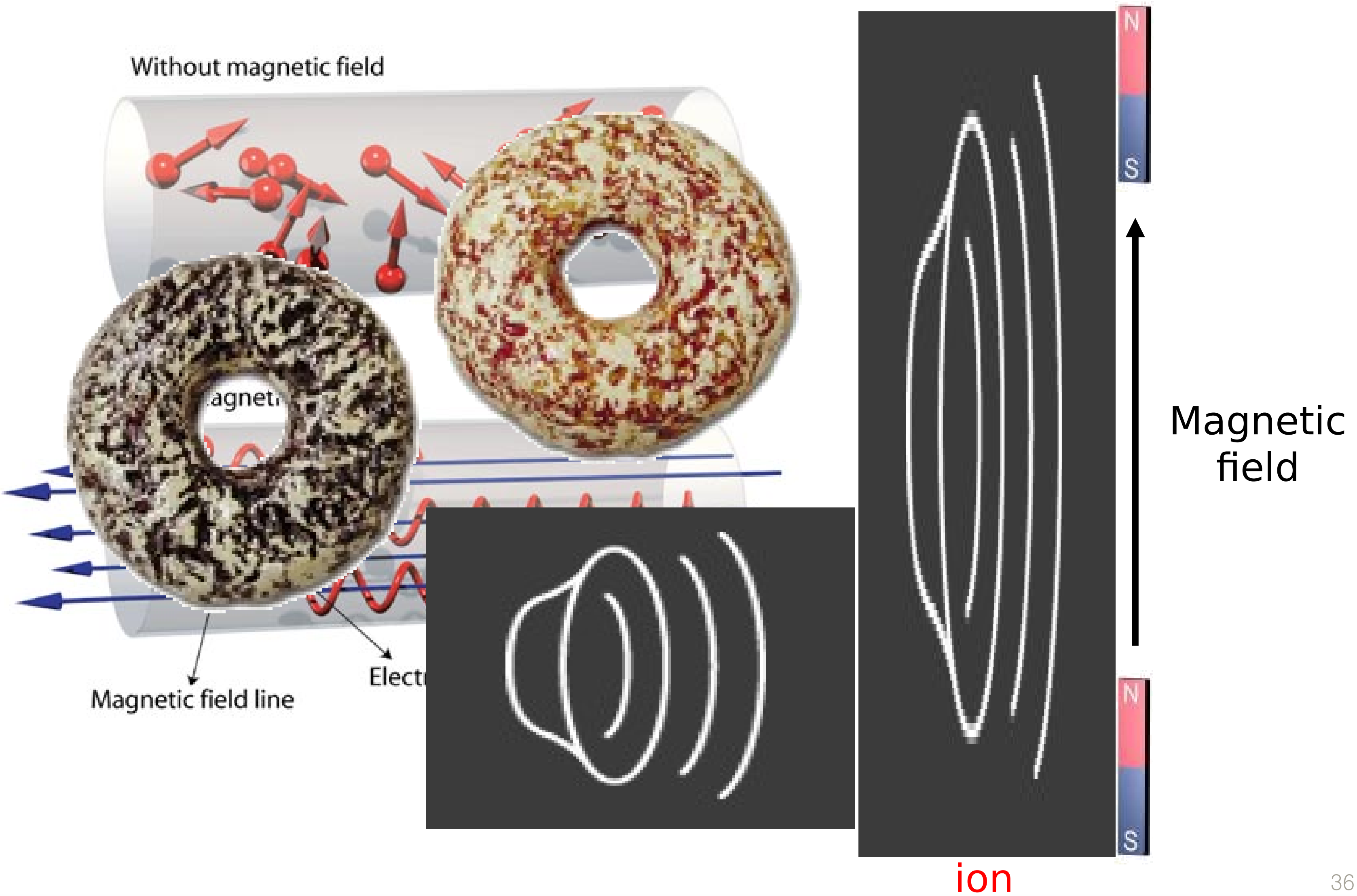
energy amplification $Q \sim 0.65$

Alpha particle heating clearly observed consistent with theory

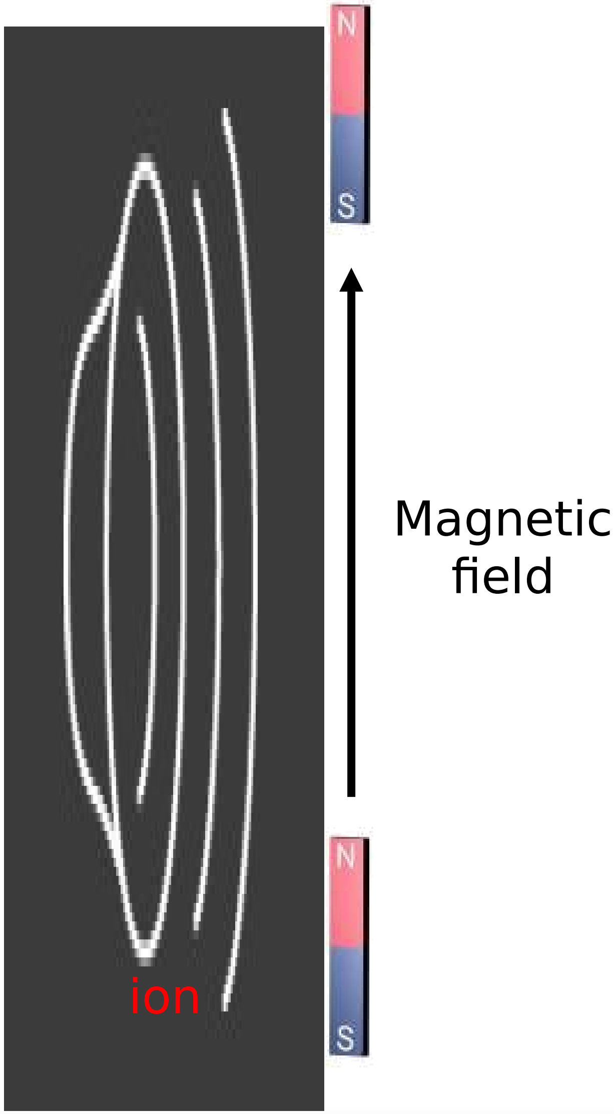


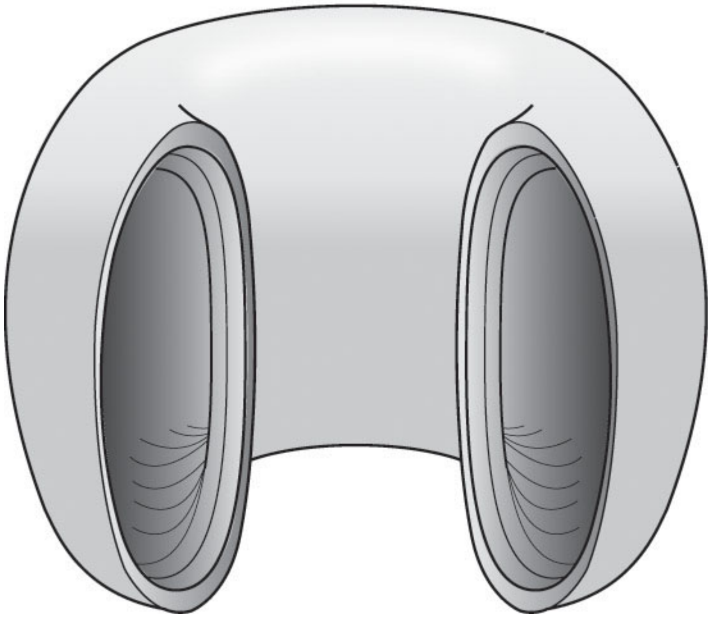
T1 Tokamak
Discovery of H-mode
(ASDEX, Germany)
16MW Fusion Power (Q=0.65)
(JET, EU)
11.5MW Fusion Power (Q~0.3)
(TFTR, USA)
Q~1.25 (JT-60U, Japan)
AT mode
(DIII-D, USA)
1965
1970
1975
1980
1985
1990
1995
2000
2005
IAEA 1968
T3 Tokamak
Bootstrap current predicted
(UKAEA)
Alcator scaling
(Alcator-A, USA)
Discovery of ITB
by PEP
(JET, EU),
ITER started
1st DT Exp.
(JET, EU)
Discovery of Hybrid Mode
(ASDEX Upgrade, Germany)
Discovery of
QH-mode
(DIII-D, USA)
Divertor Dα
Fusion power (MW)
Time (s)
JET (1997)
TFTR (1994)
JET steady-state (1997)
TFTR steady-state (1995)
JET (1991)
G = βN H89/q95²
ITER steady-state scenario
H89 =2.5
qmin =2
Time (s)
Neutral particle flux in divertor
Density peaking
central Ti
central Te

Open Magnetic Systems



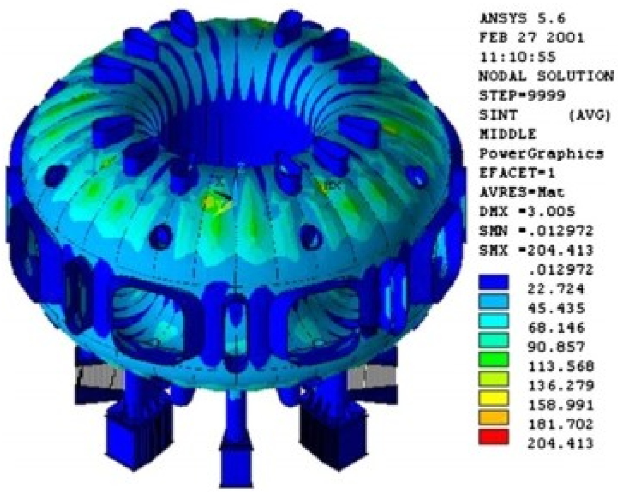
Closed Magnetic Systems

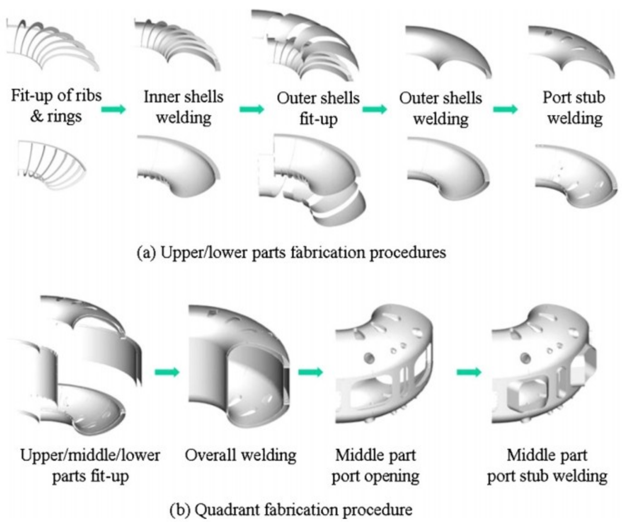


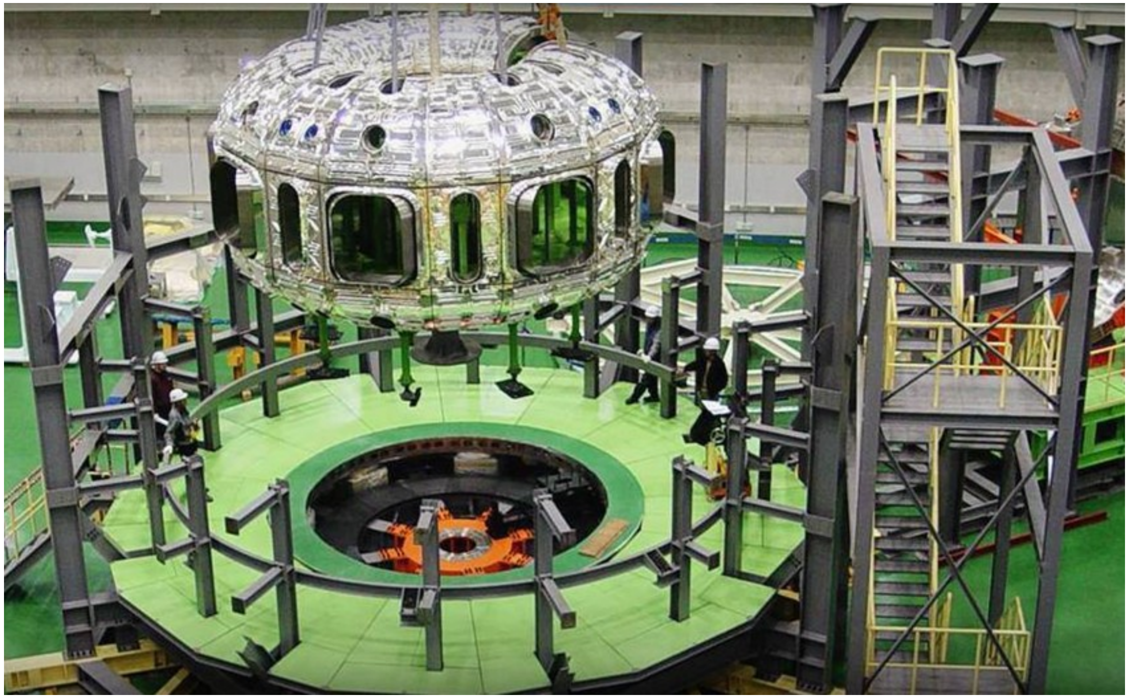


Donut-shaped vacuum vessel

Closed Magnetic Systems

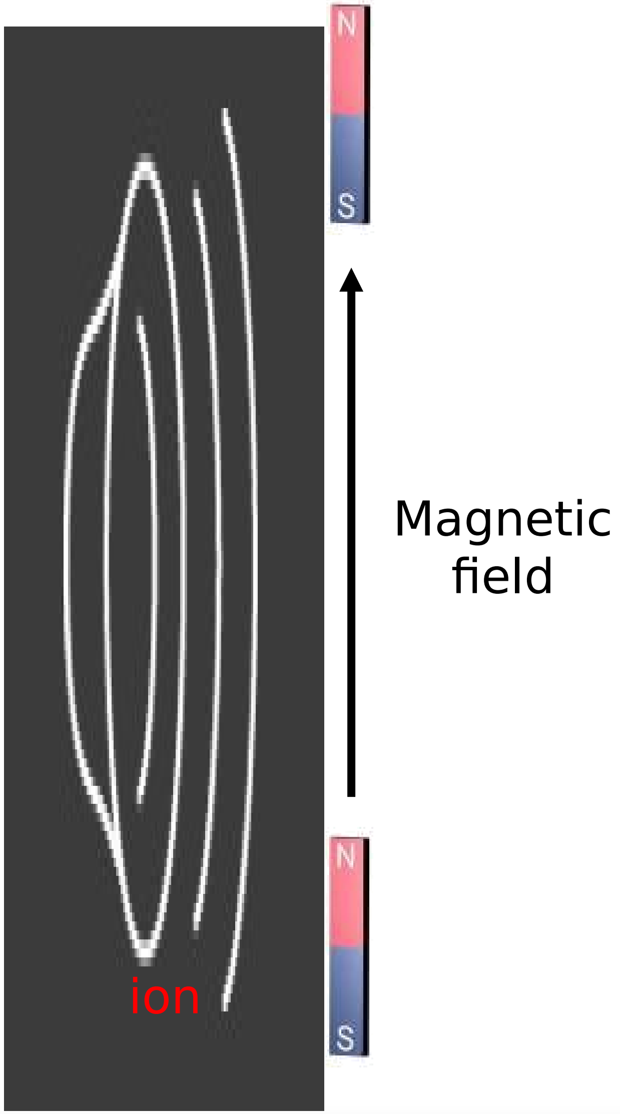


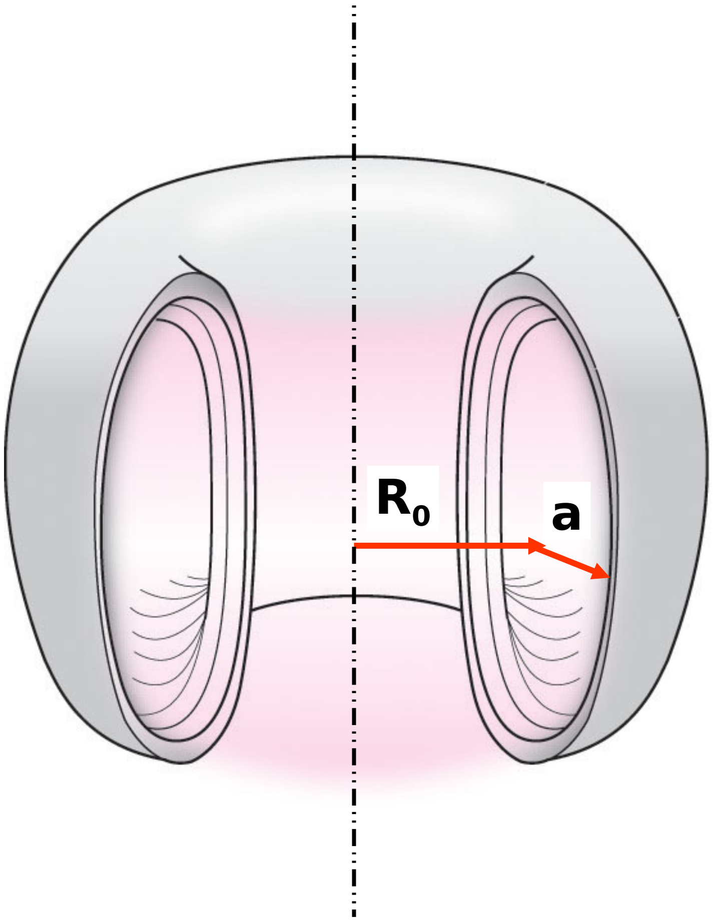




KSTAR HYUNDAI SAMHO HEAVY INDUSTRIES CO.,LTD.

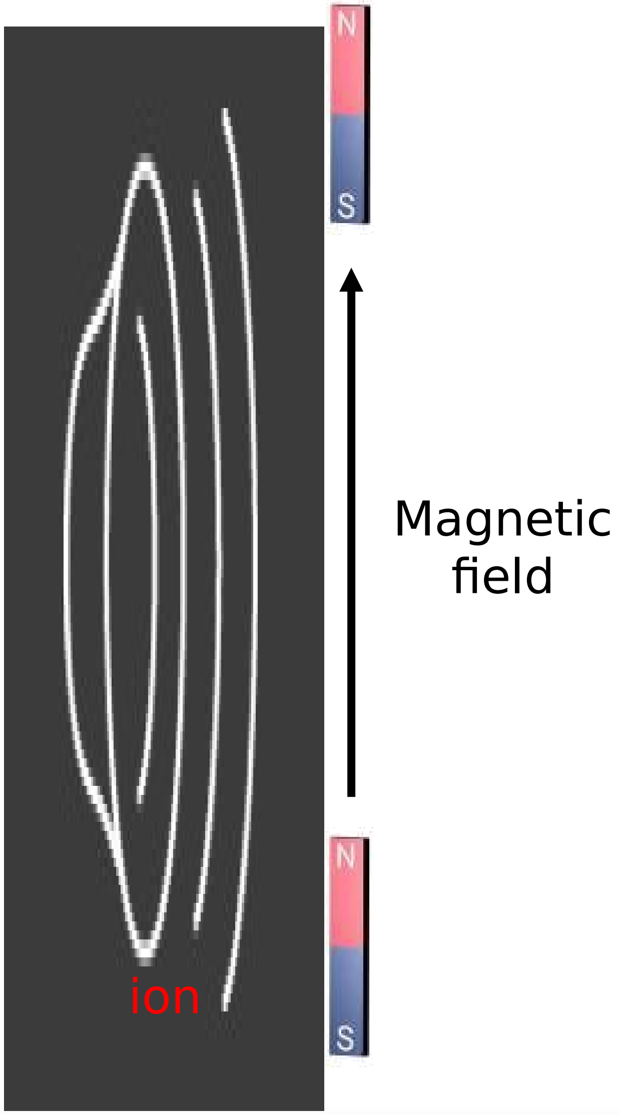
Closed Magnetic Systems

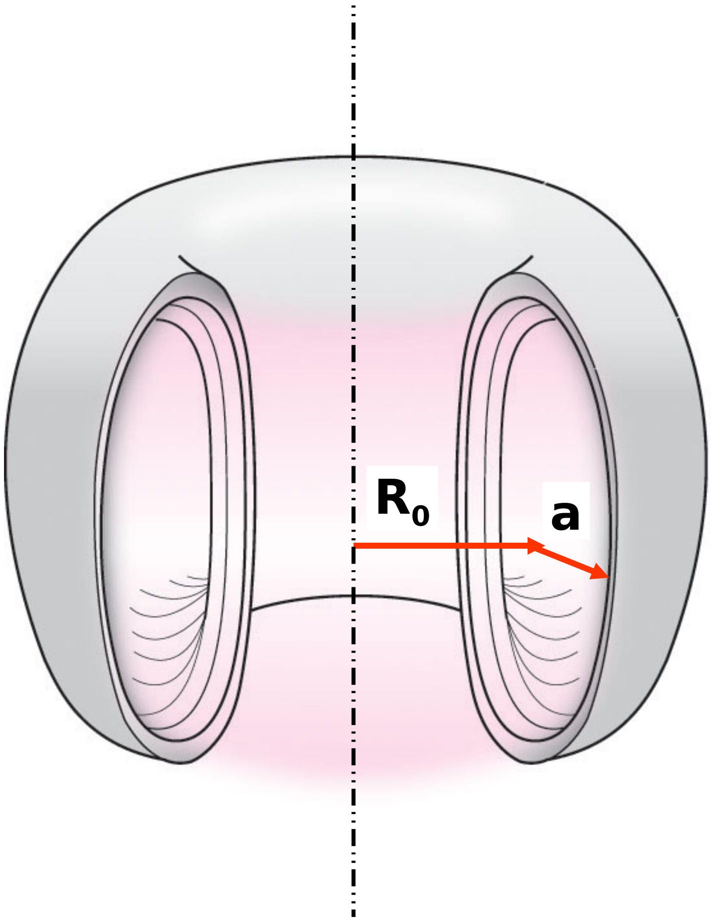




Plasma needs to be confined
R_0 = 1.8 m, a = 0.5 m in KSTAR

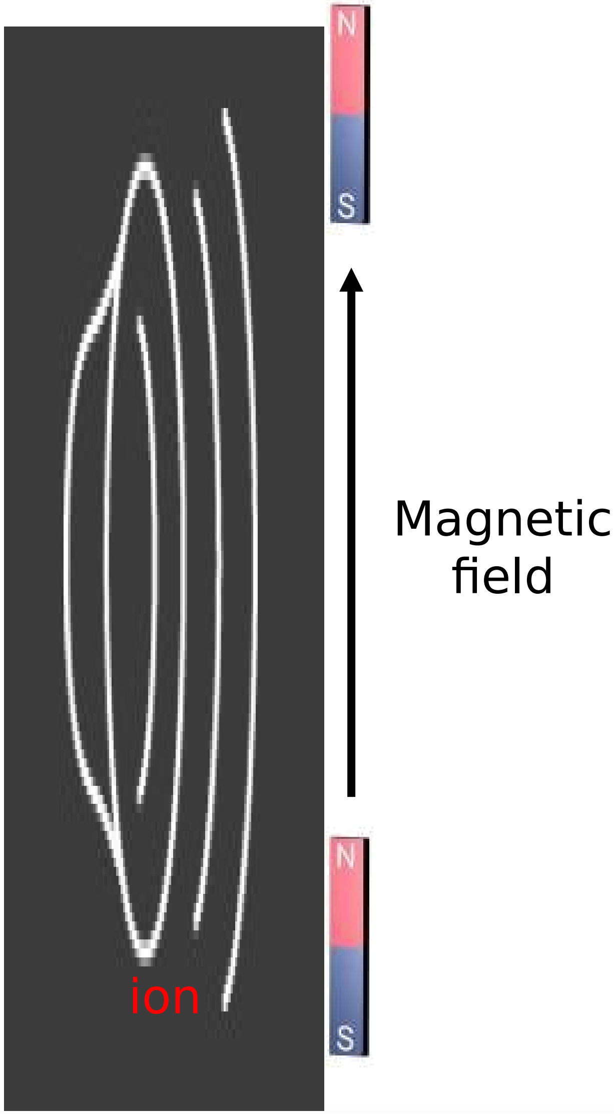
Closed Magnetic Systems

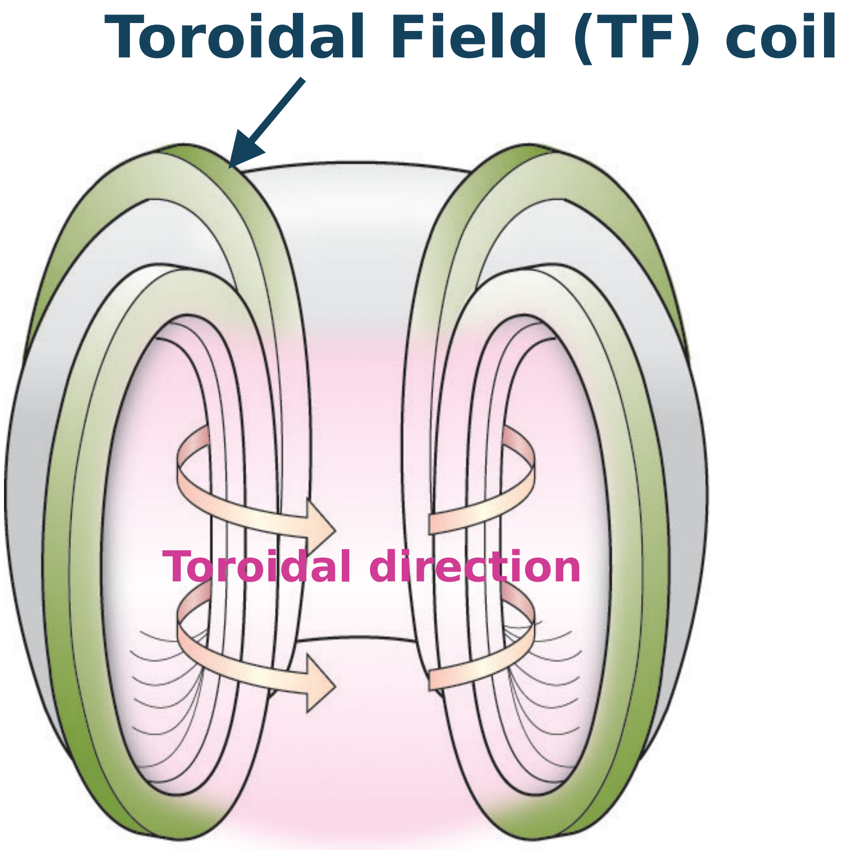




Plasma needs to be confined
R_0 = 6.2 m, a = 2.0 m in ITER

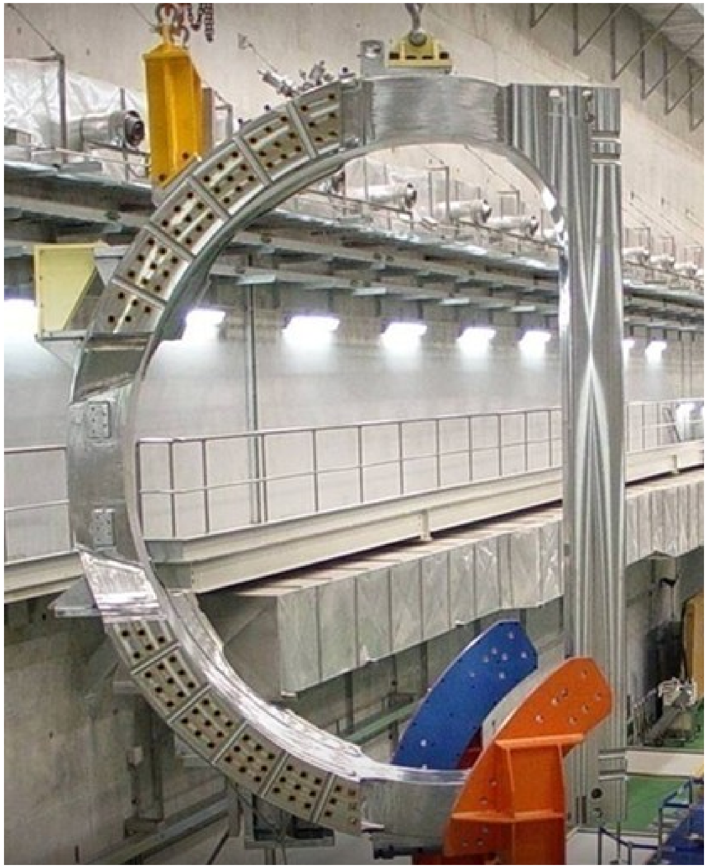
Closed Magnetic Systems





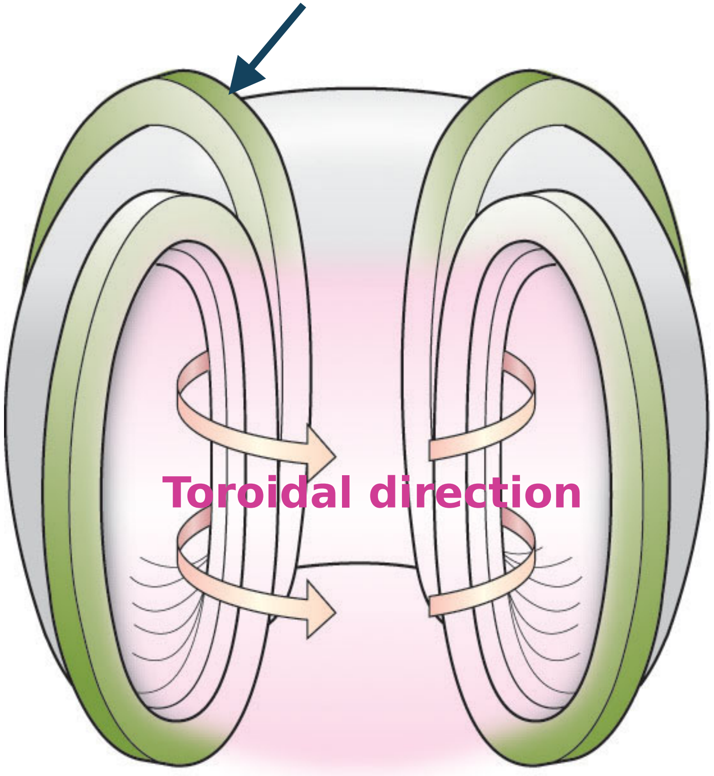
Applying toroidal magnetic field
3.5 T in KSTAR, 5.3 T in ITER

Closed Magnetic Systems



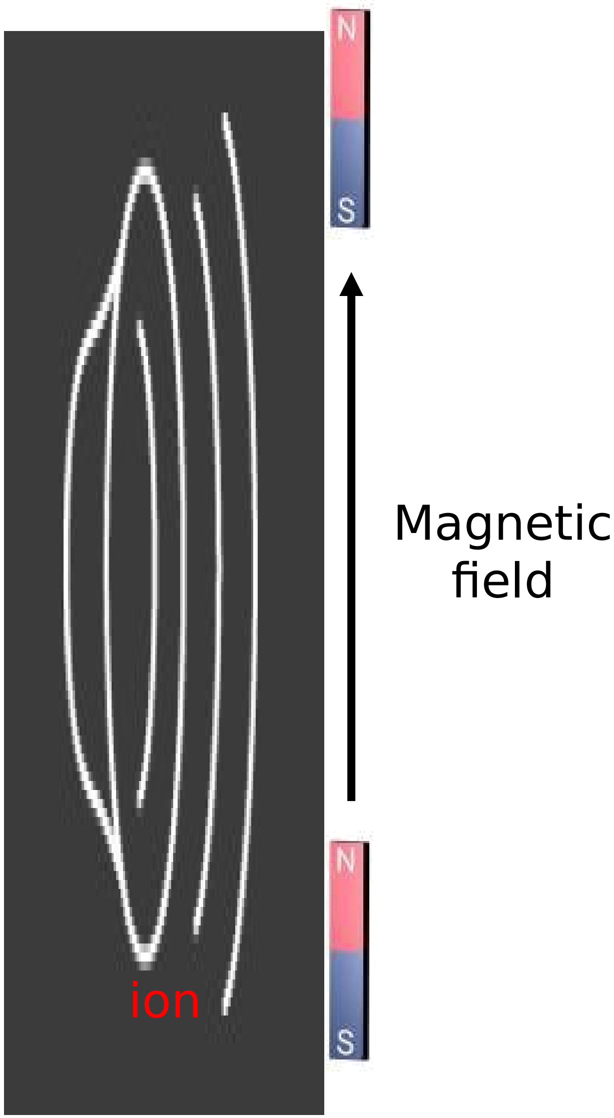
KSTAR

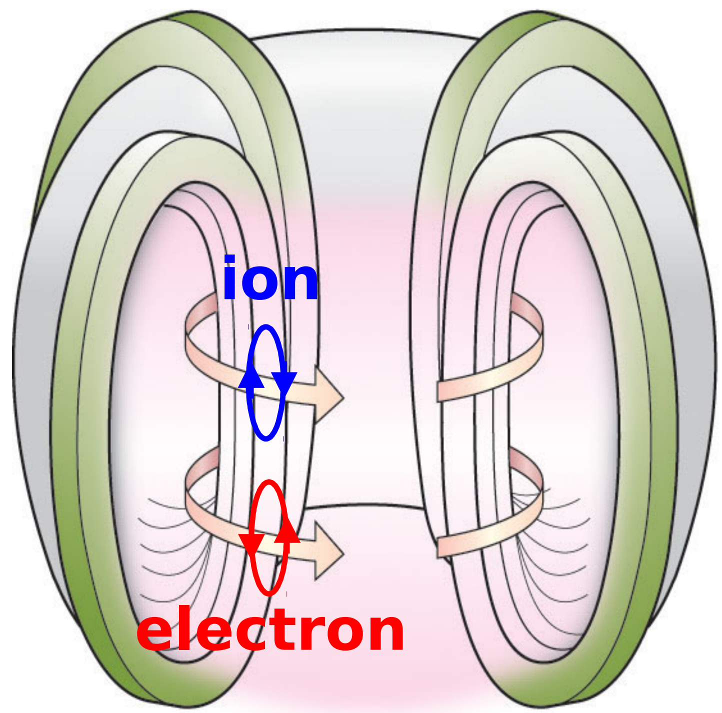
Toroidal Field (TF) coil



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

Closed Magnetic Systems

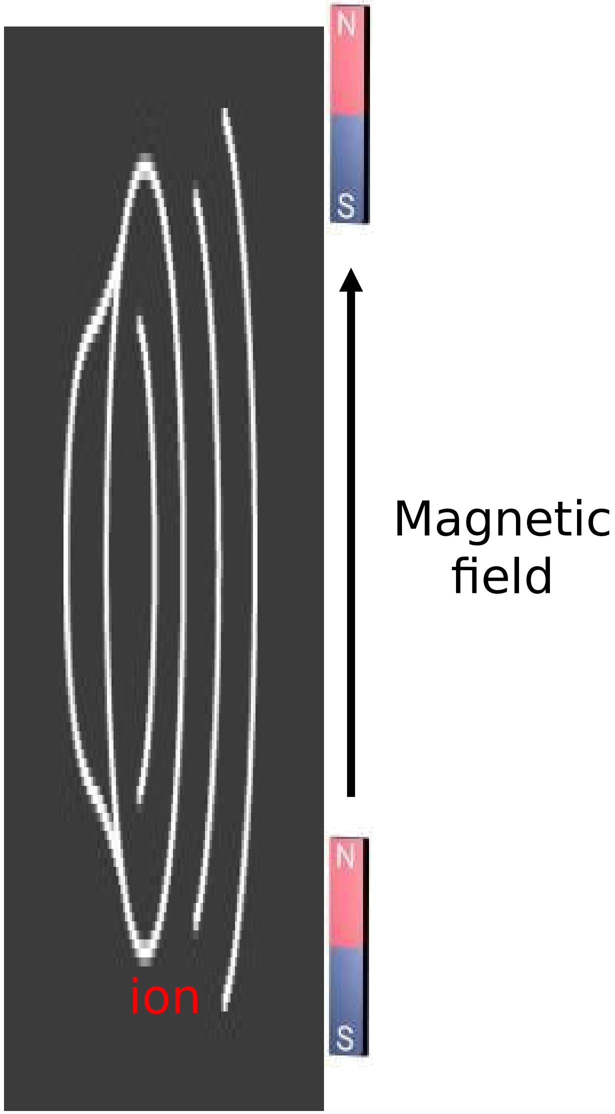


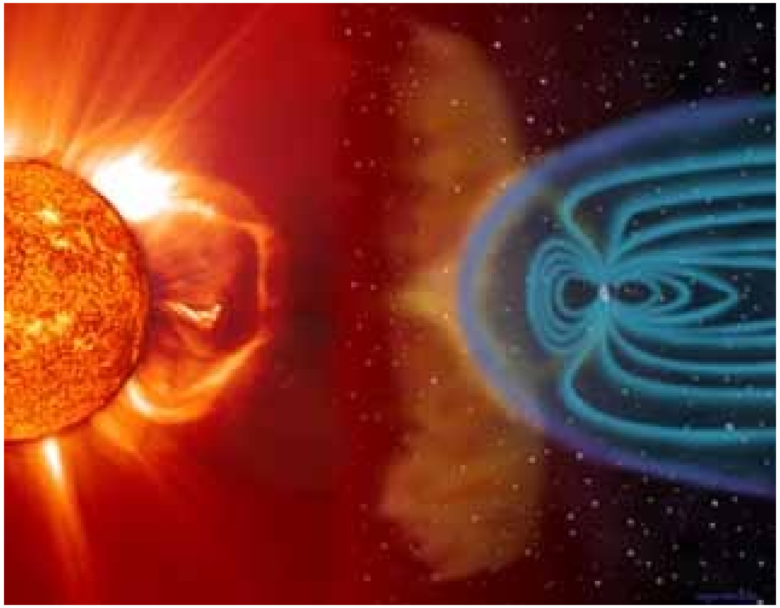


Magnetic field of earth?

0.5 Gauss = 0.00005 T

Closed Magnetic Systems

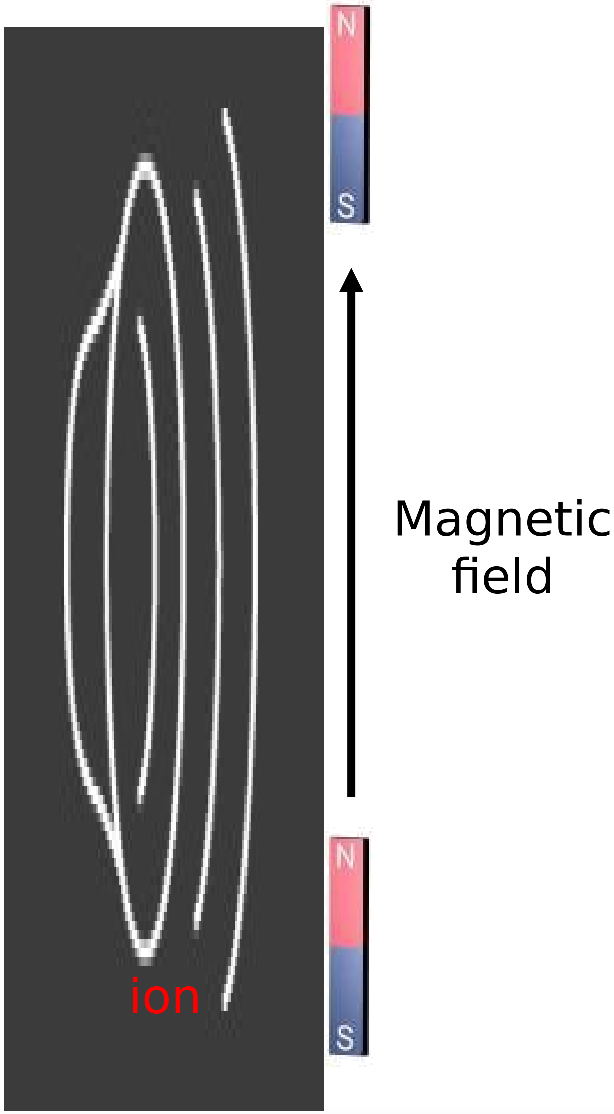


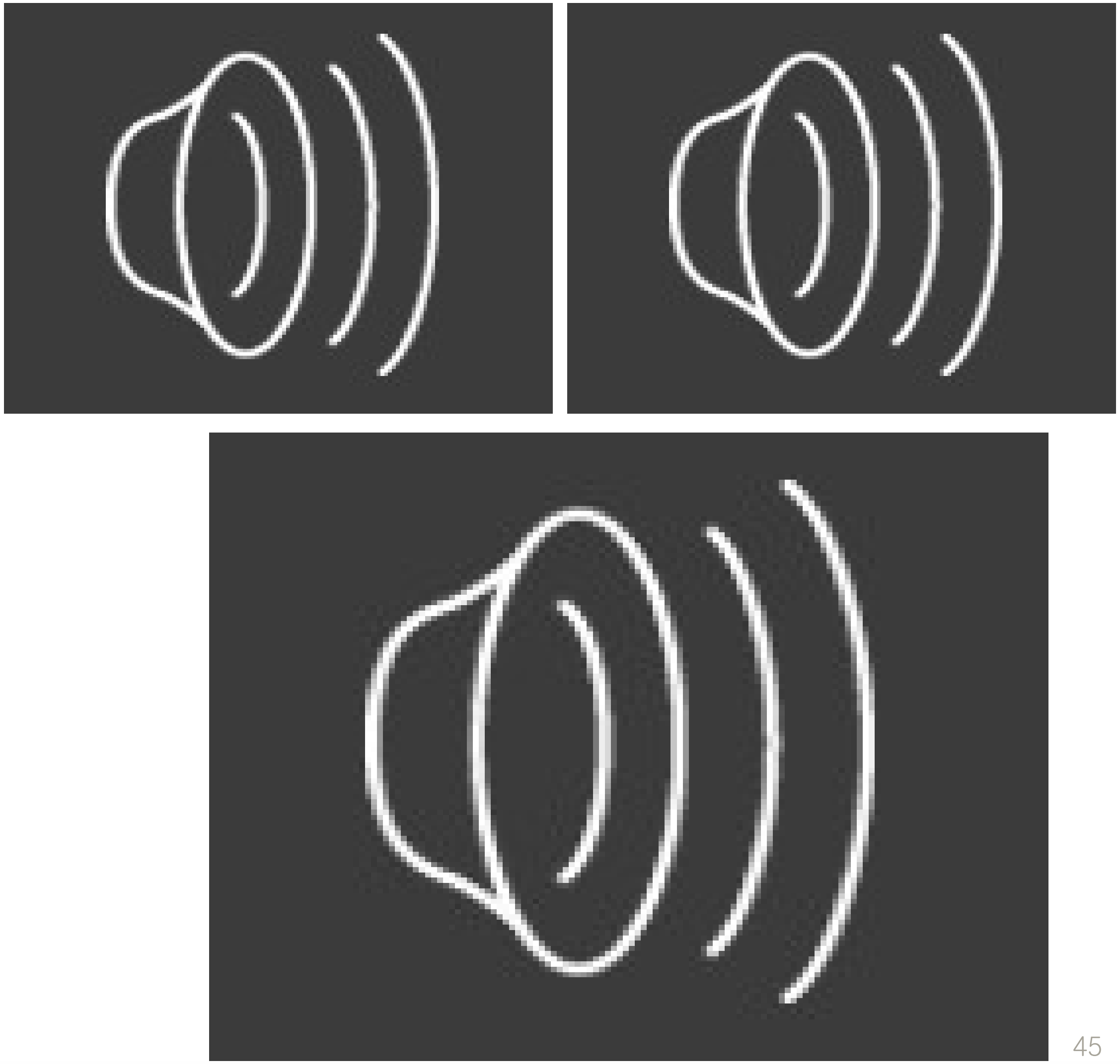


Magnetic field of earth?

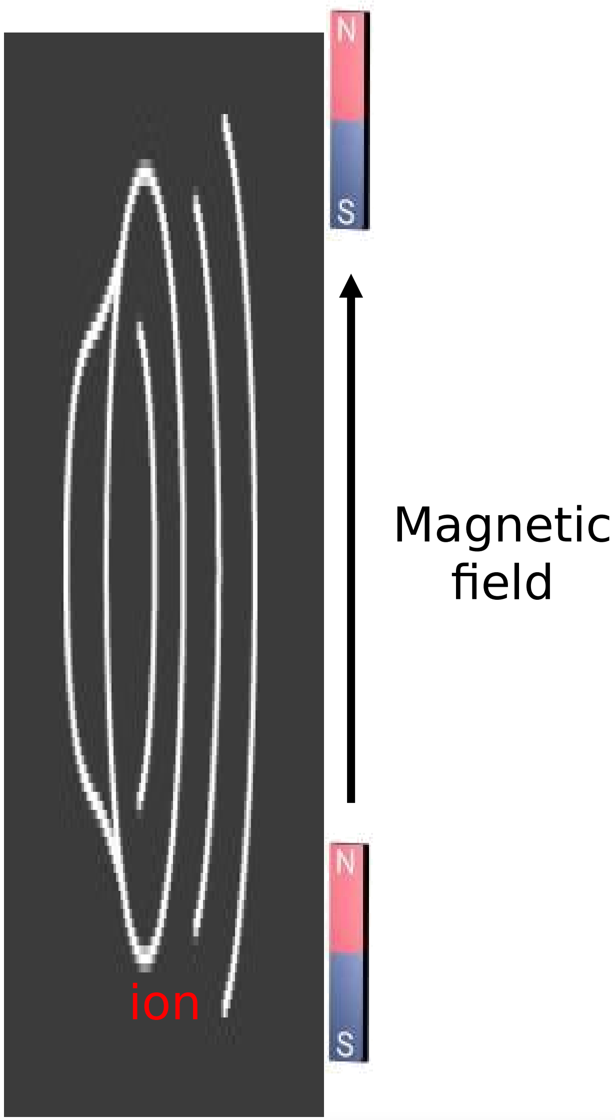
0.5 Gauss = 0.00005 T

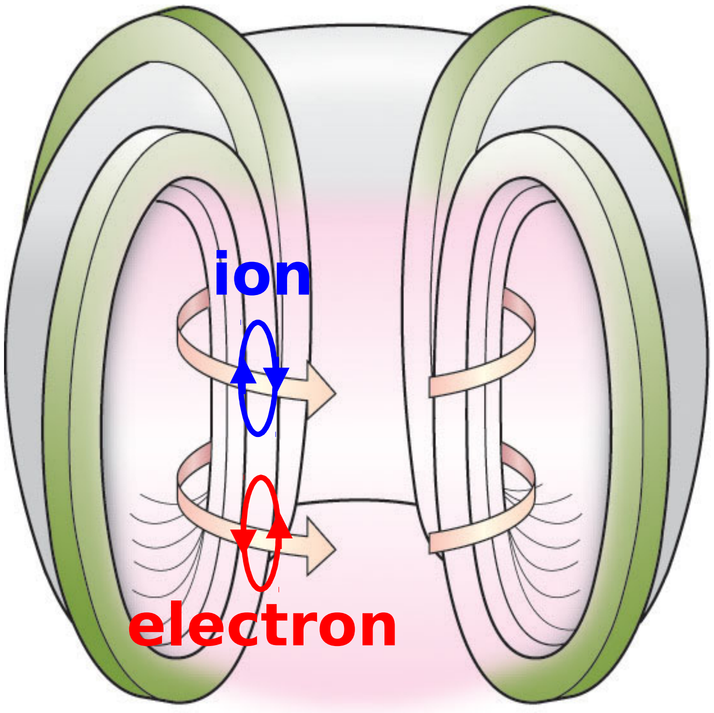
Closed Magnetic Systems





Closed Magnetic Systems





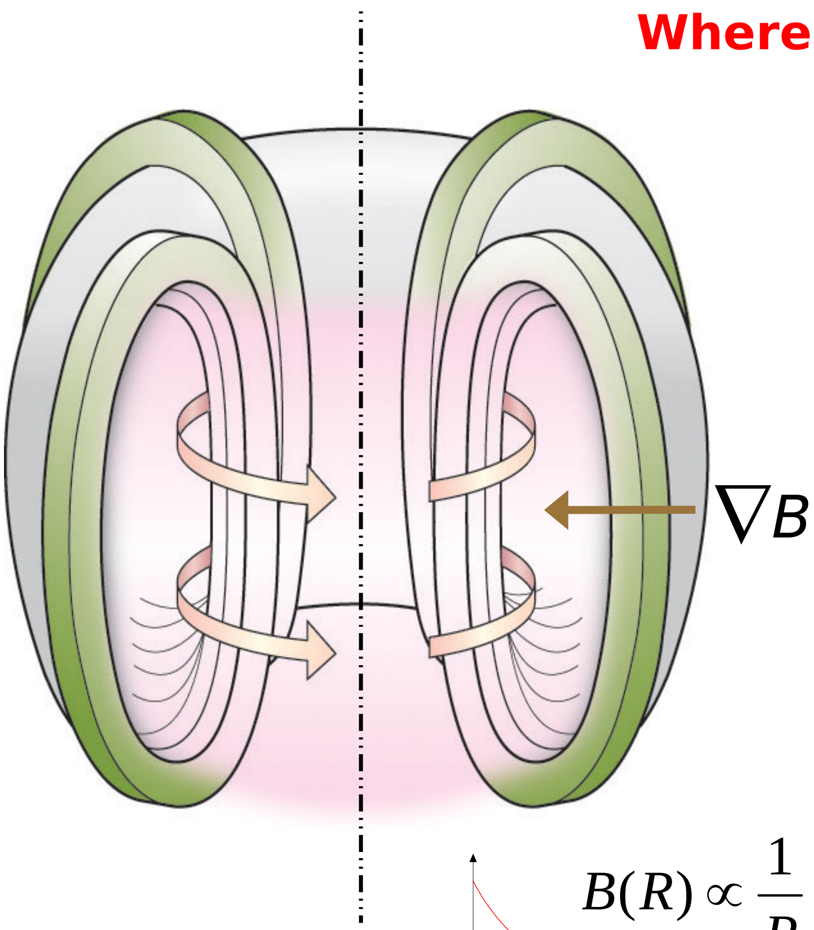
Magnetic field of earth?

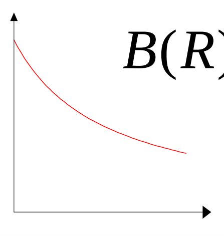
0.5 Gauss = 0.00005 T

What kind of drift motions?

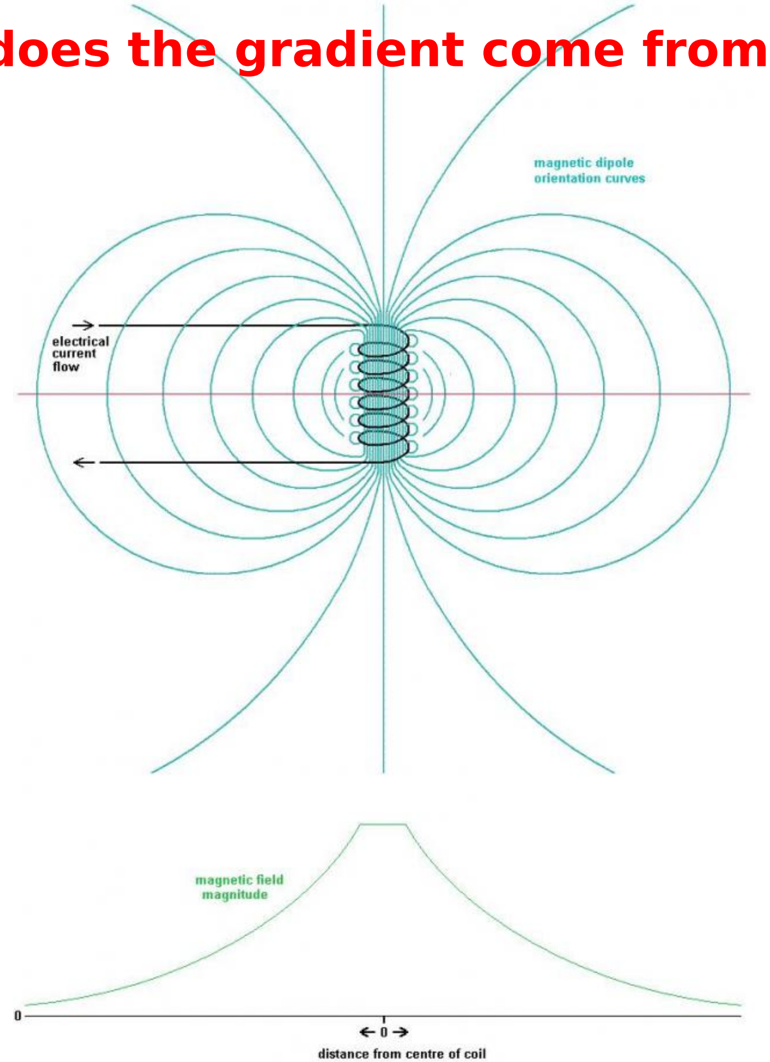
Closed Magnetic Systems

Where does the gradient come from?





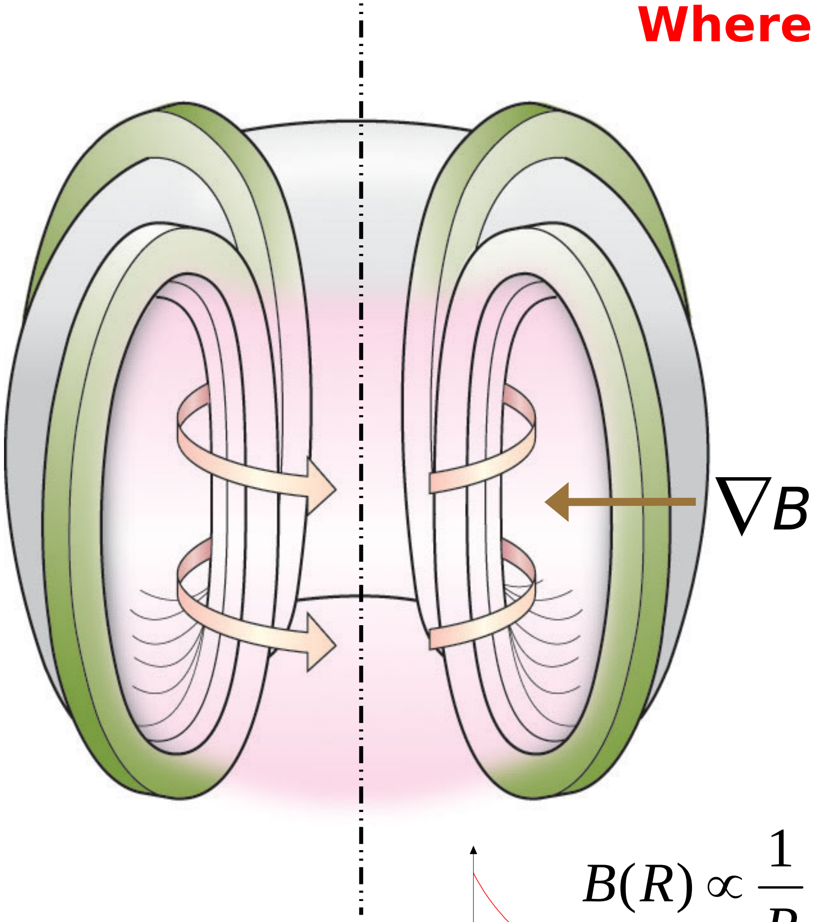
$$B(R) \propto \frac{1}{R}$$

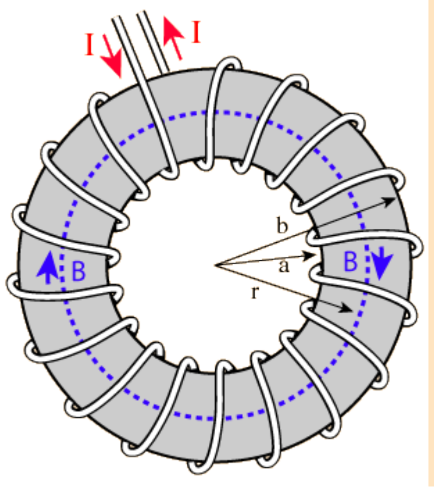


http://magnetoglide.wordpress.com/

Closed Magnetic Systems

Where does the gradient come from?

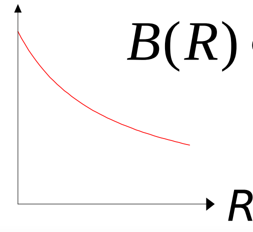




$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

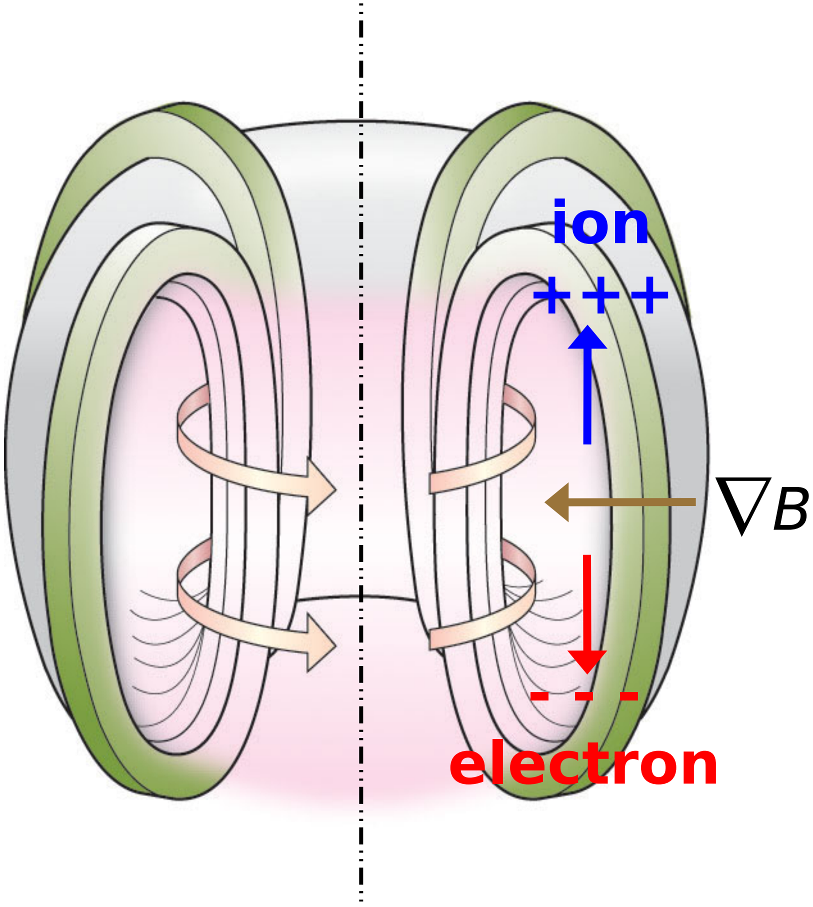
$$\oint \mathbf{B}_\phi \cdot d\mathbf{l} = \mu_0 N I_c$$

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



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

Closed Magnetic Systems



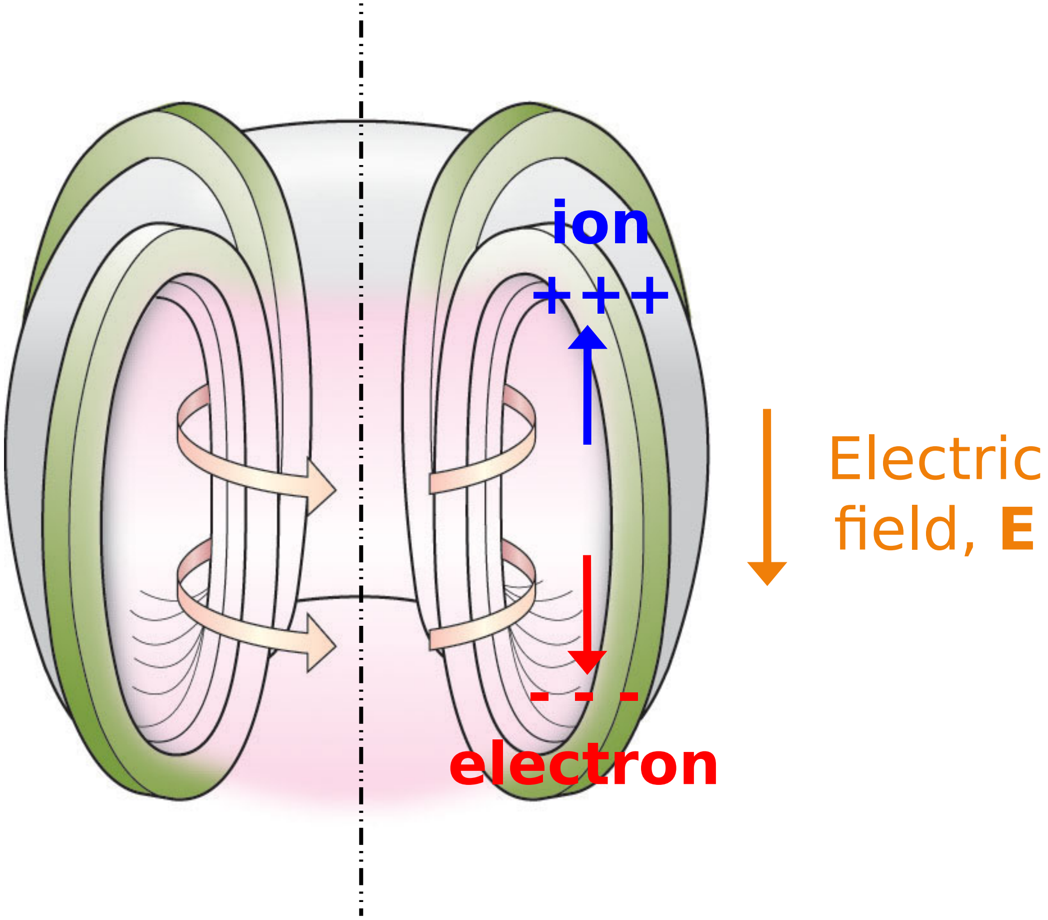
$$\mathbf{v}_{D,R} = \frac{mv_{\parallel}^2}{qB_0^2}\frac{\mathbf{R}_0 \times \mathbf{B}_0}{R^2}$$

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

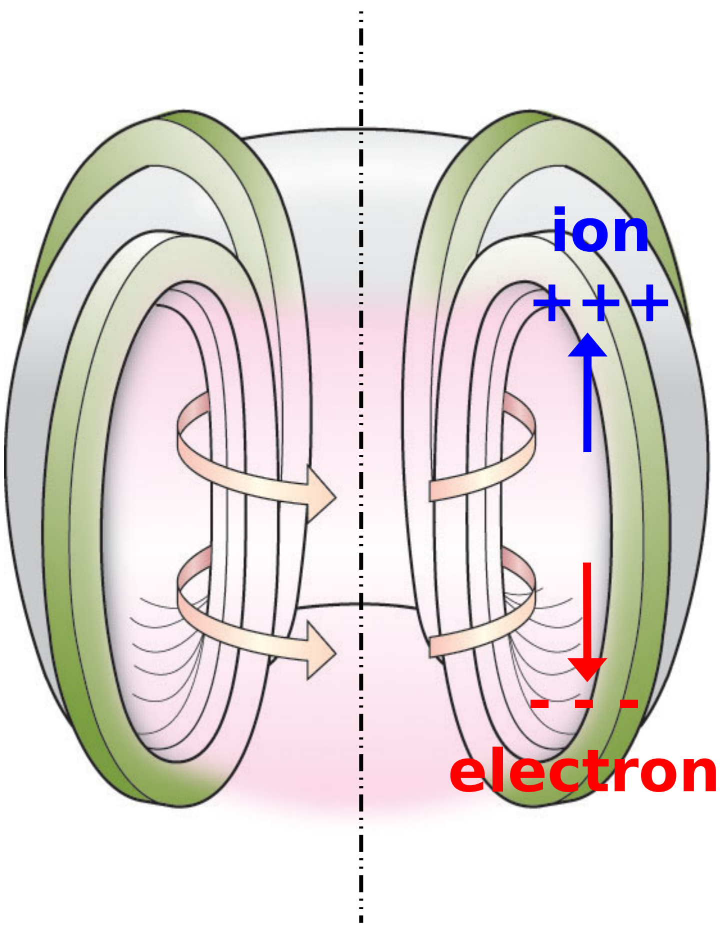
$$= \frac{mv_{\perp}^2}{2qB}\frac{\mathbf{B}\times\nabla B}{B^2}$$

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

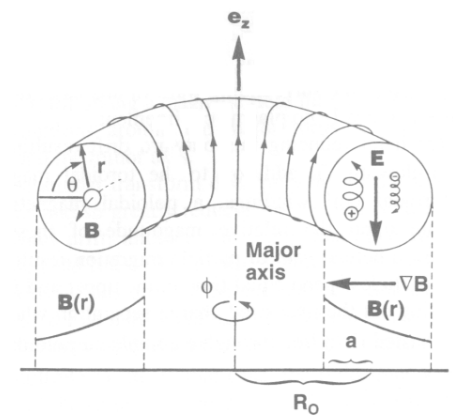
Closed Magnetic Systems



Closed Magnetic Systems



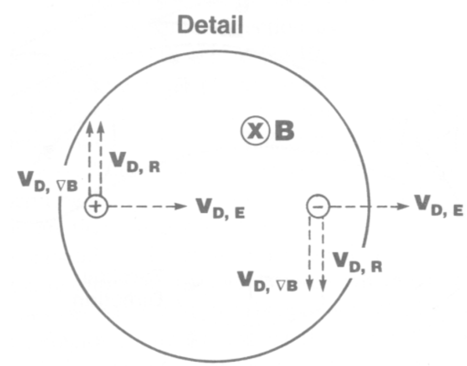
ExB drift



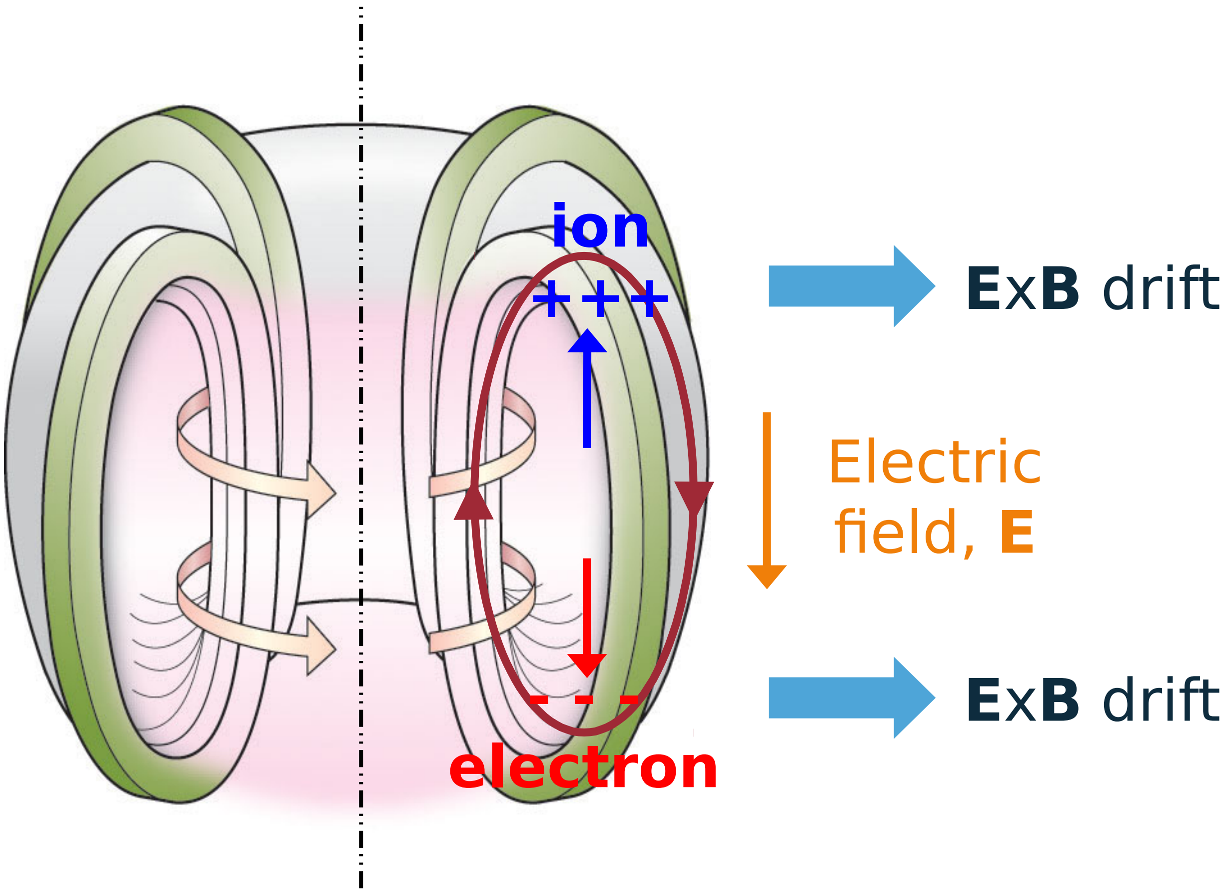
Electric field, **E**

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

ExB drift



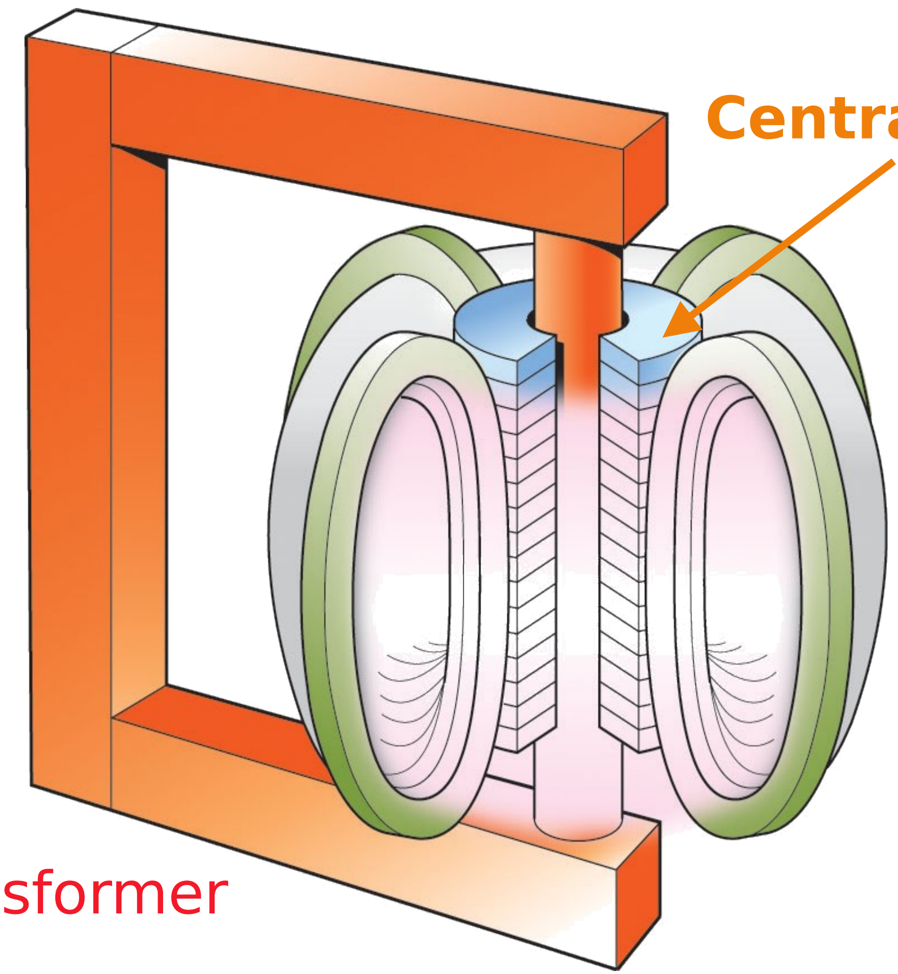
Closed Magnetic Systems

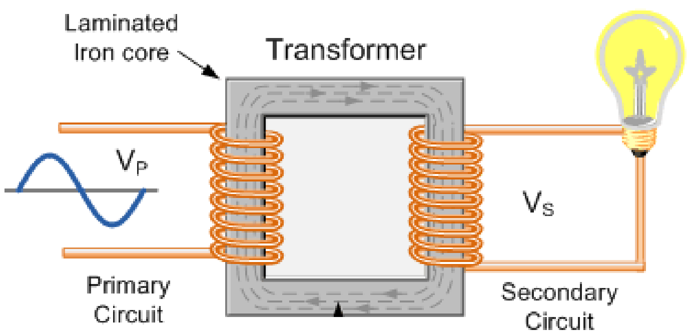


Poloidal magnetic field required

How to drive plasma current?

Tokamak

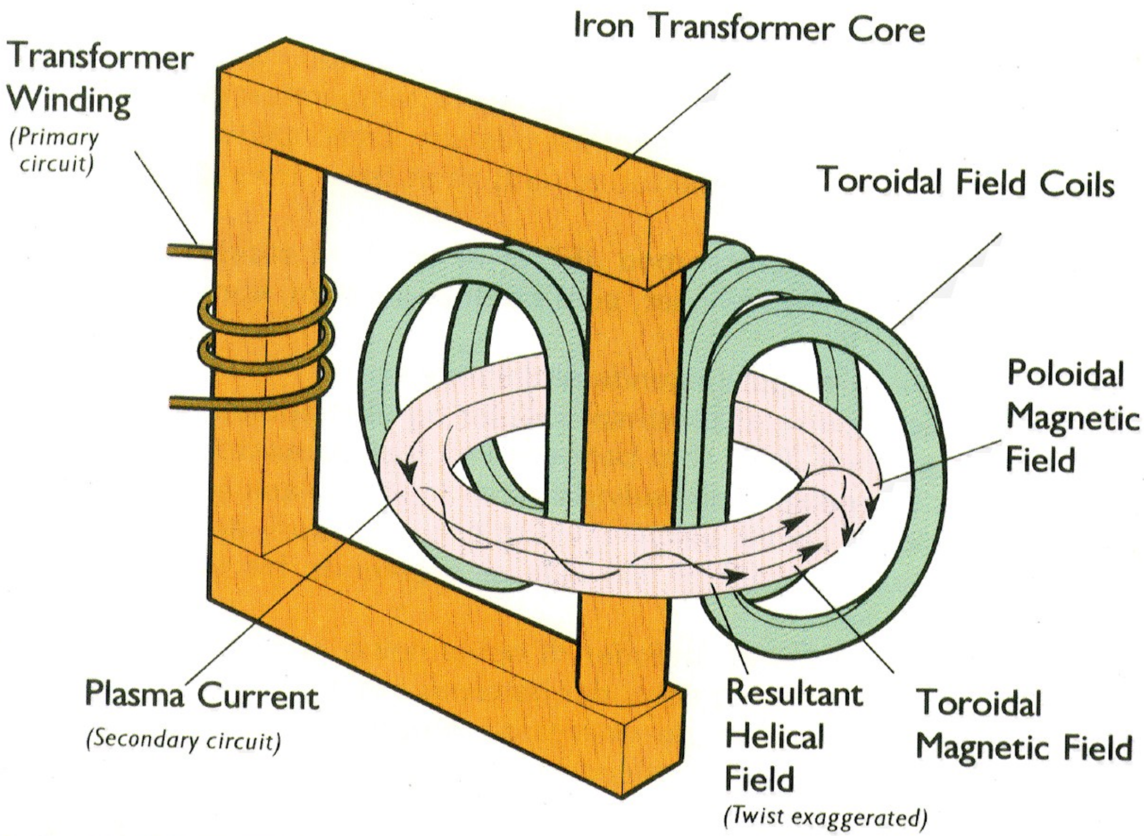


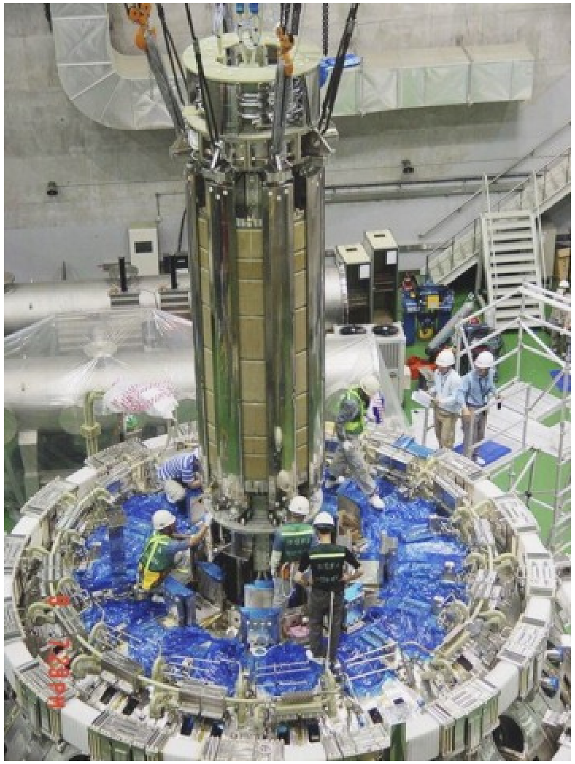


Faraday's law

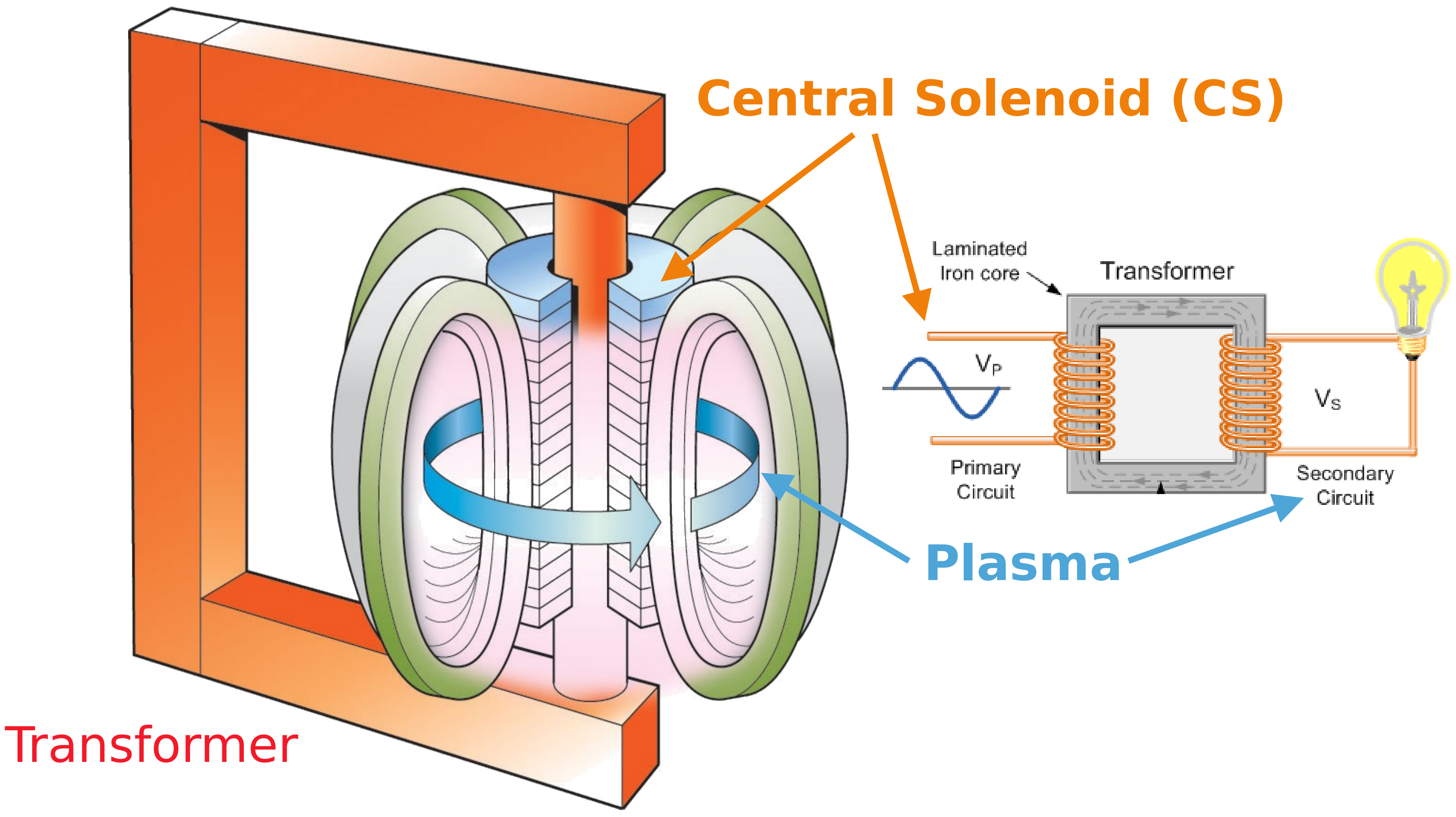
$$v = -\frac{d}{dt}\int_S \vec{B}\cdot d\vec{S}$$

Tokamak

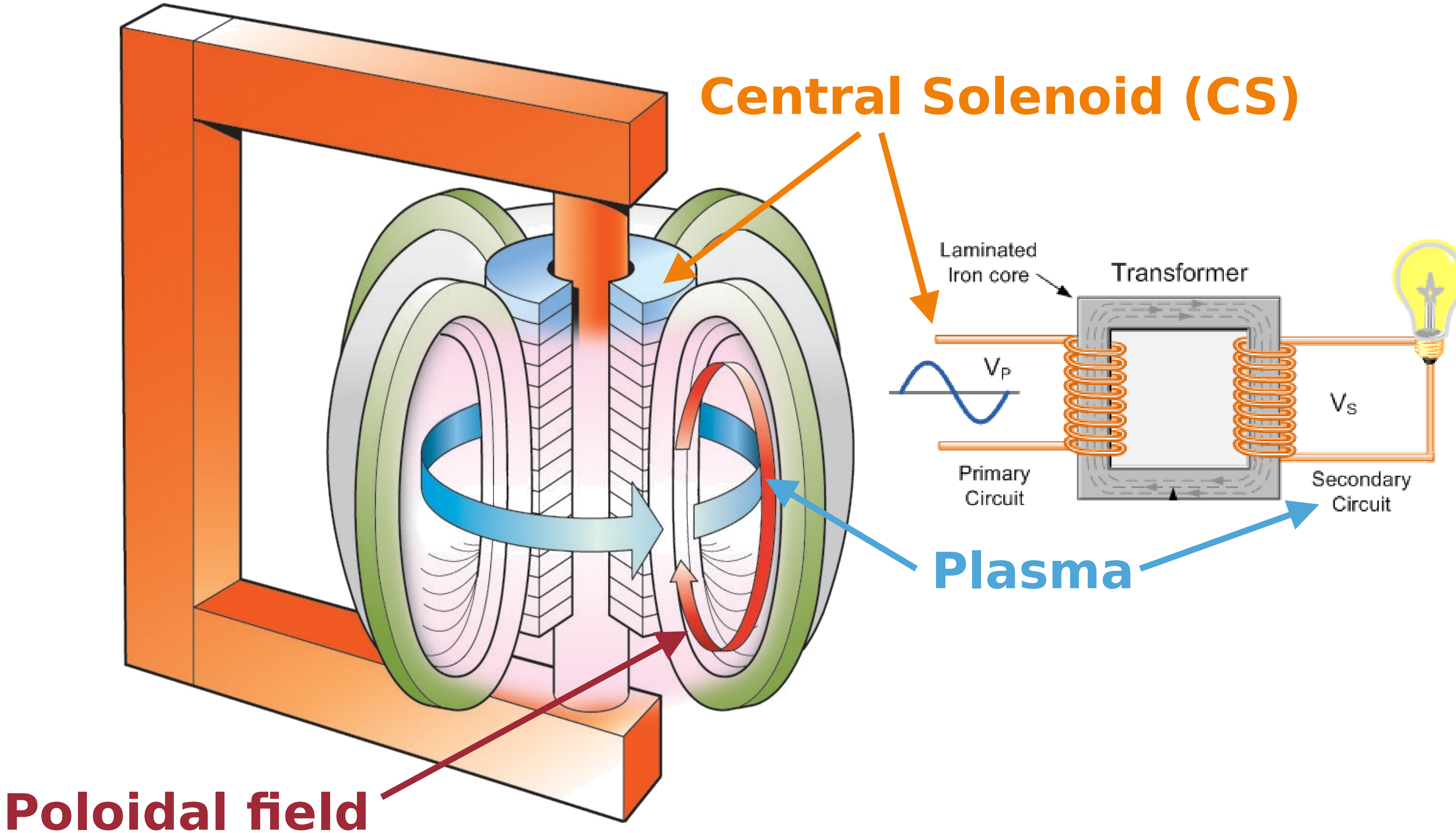

Iron Transformer Core
Transformer Winding
(Primary circuit)
Toroidal Field Coils
Poloidal Magnetic Field
Plasma Current
(Secondary circuit)
Resultant Helical Field
(Twist exaggerated)
Toroidal Magnetic Field



Tokamak

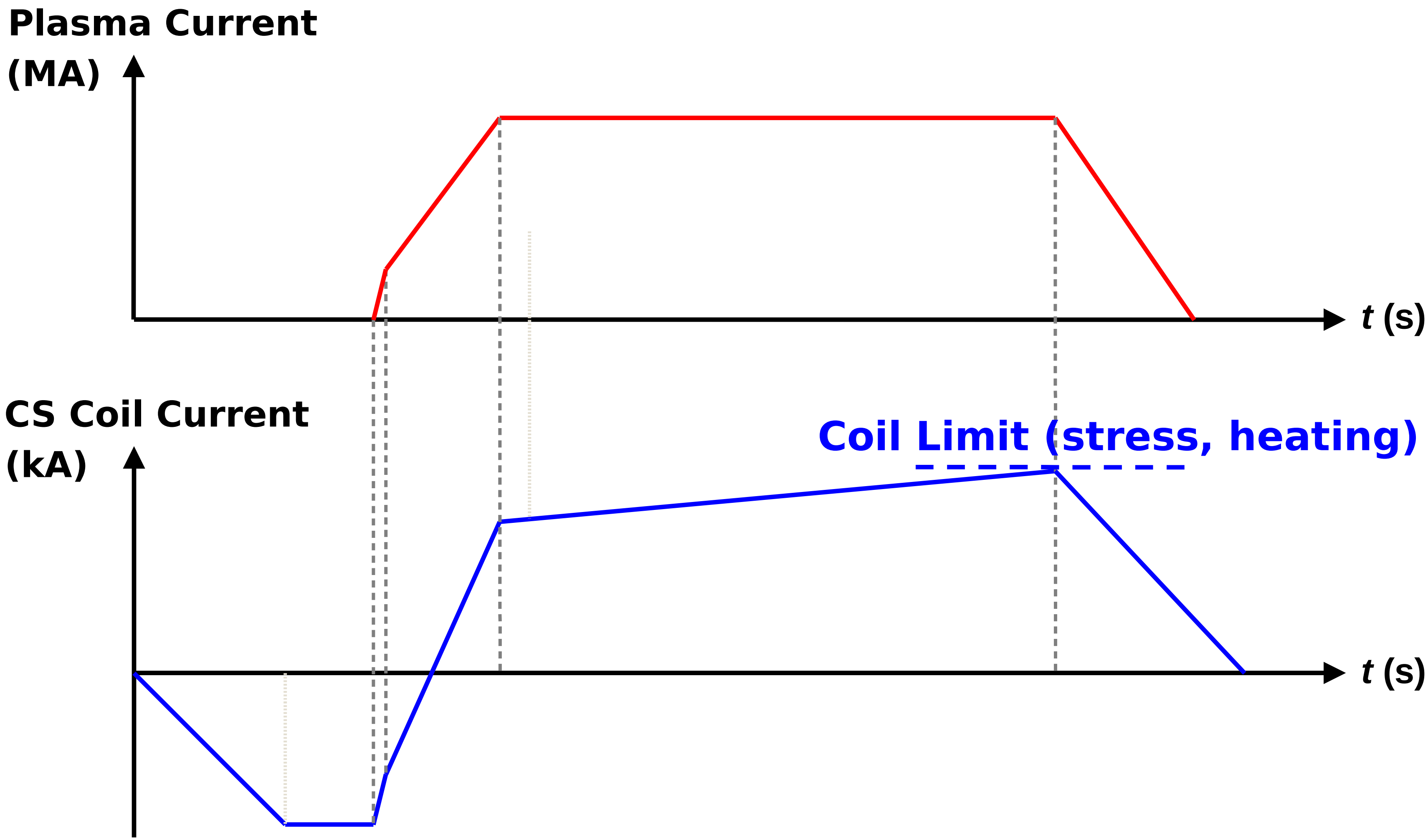

Central Solenoid (CS)
Laminated
Iron core
Transformer
V_P
V_S
Primary
Circuit
Secondary
Circuit
Plasma
Transformer

Tokamak

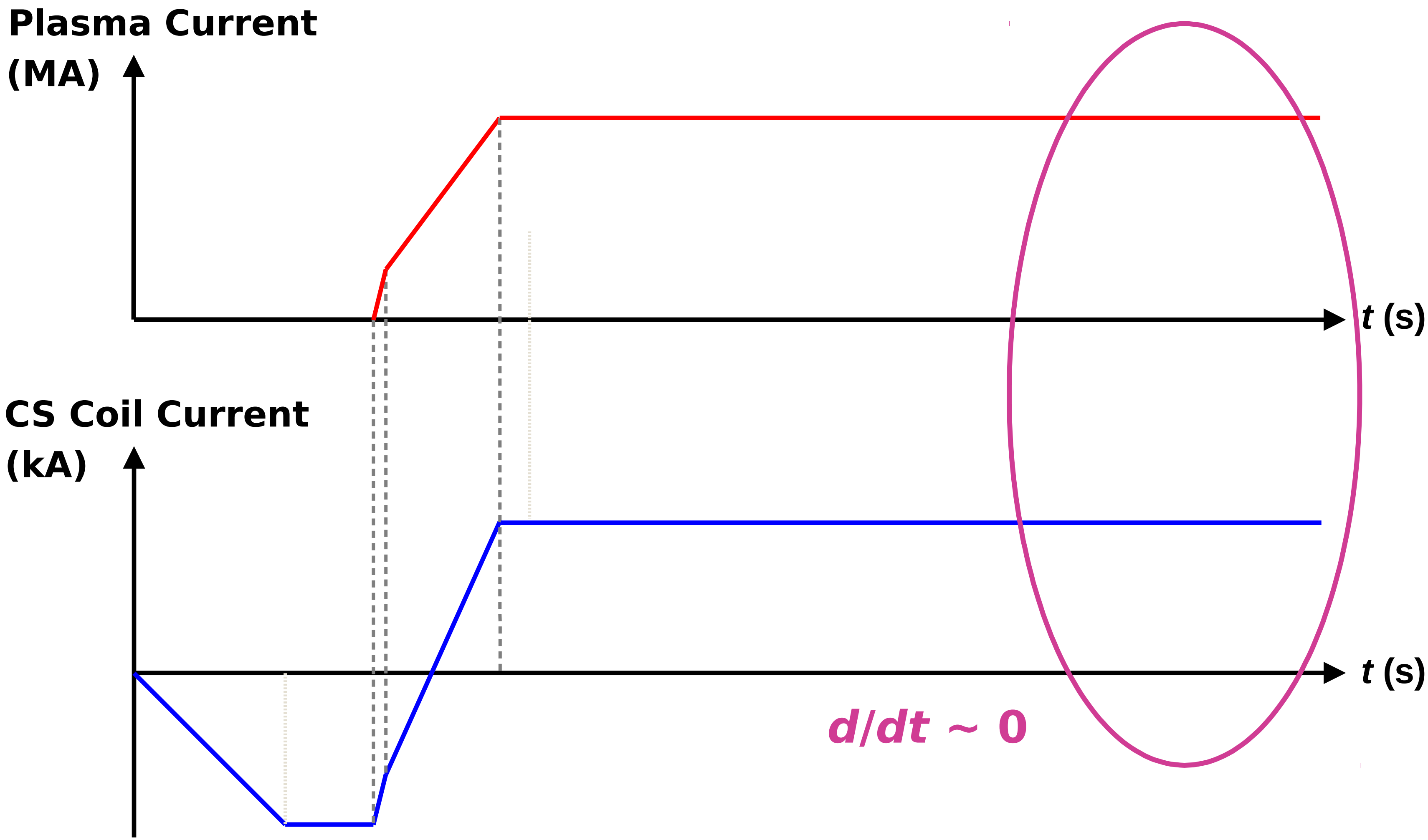


Pulsed Operation!

Pulsed Operation

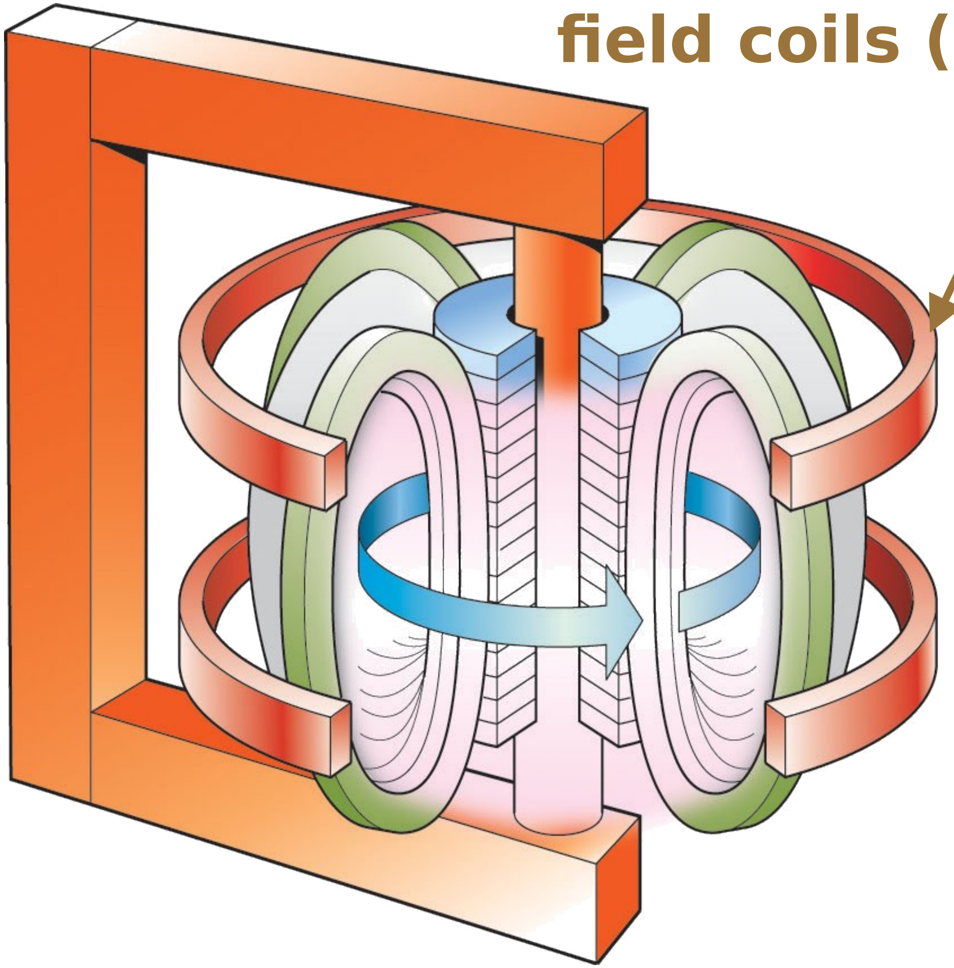


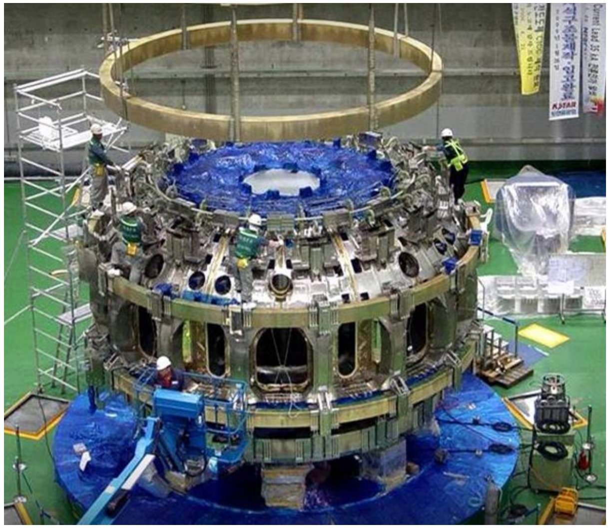
Steady-State Operation



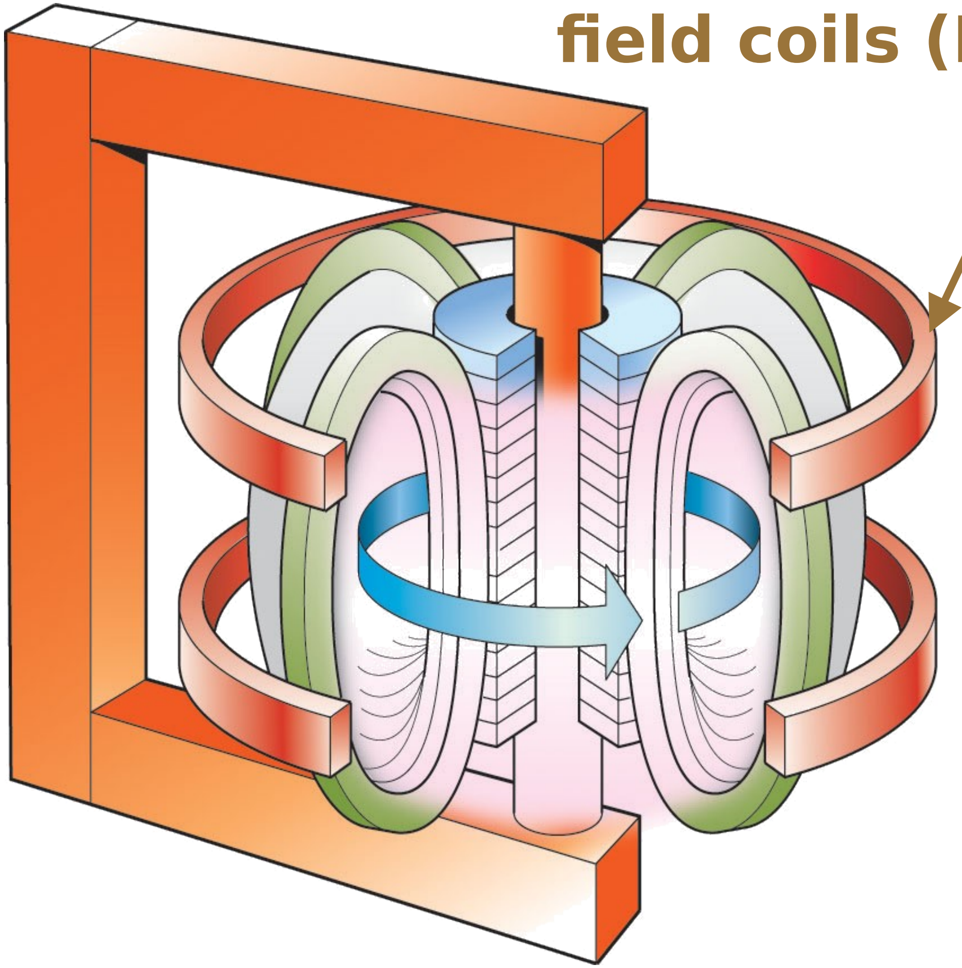
Tokamak

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

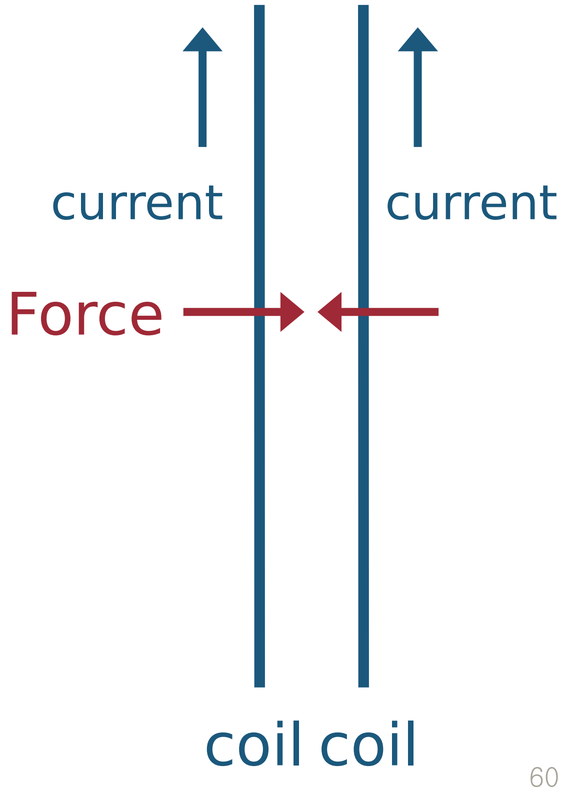




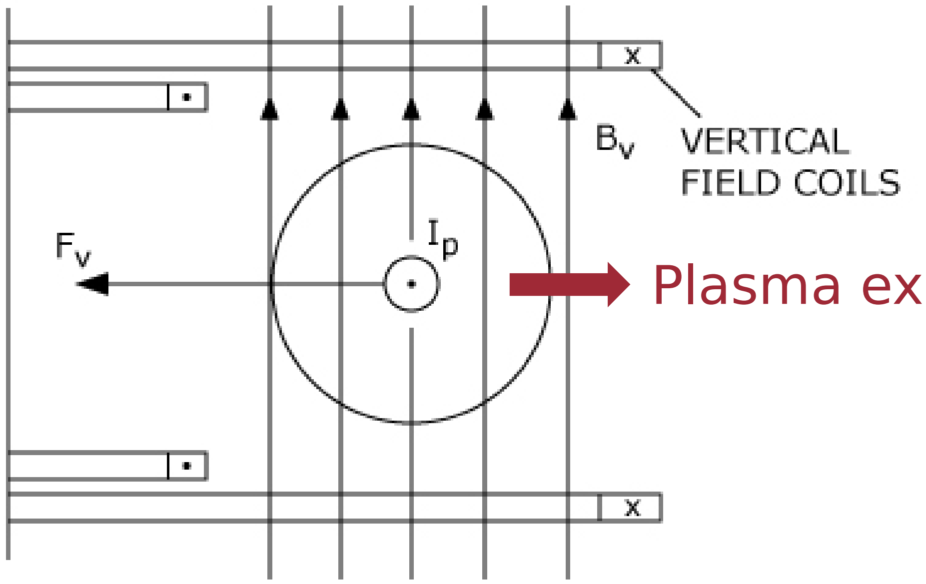
Tokamak



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



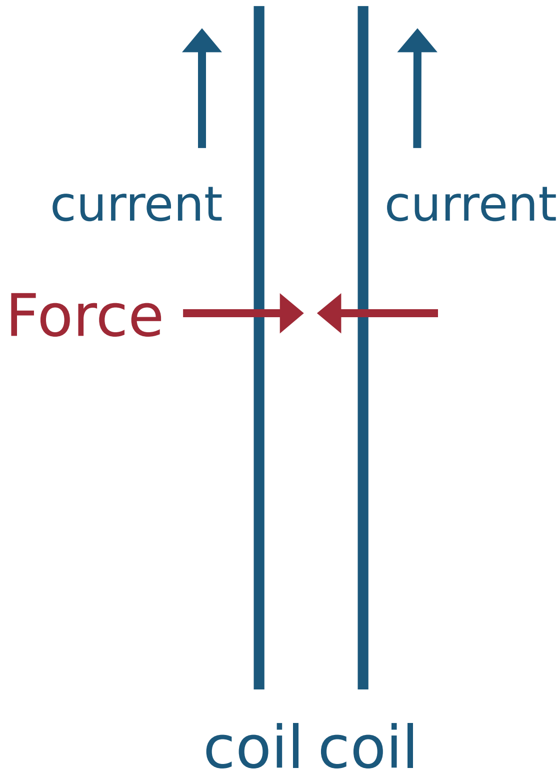
Tokamak

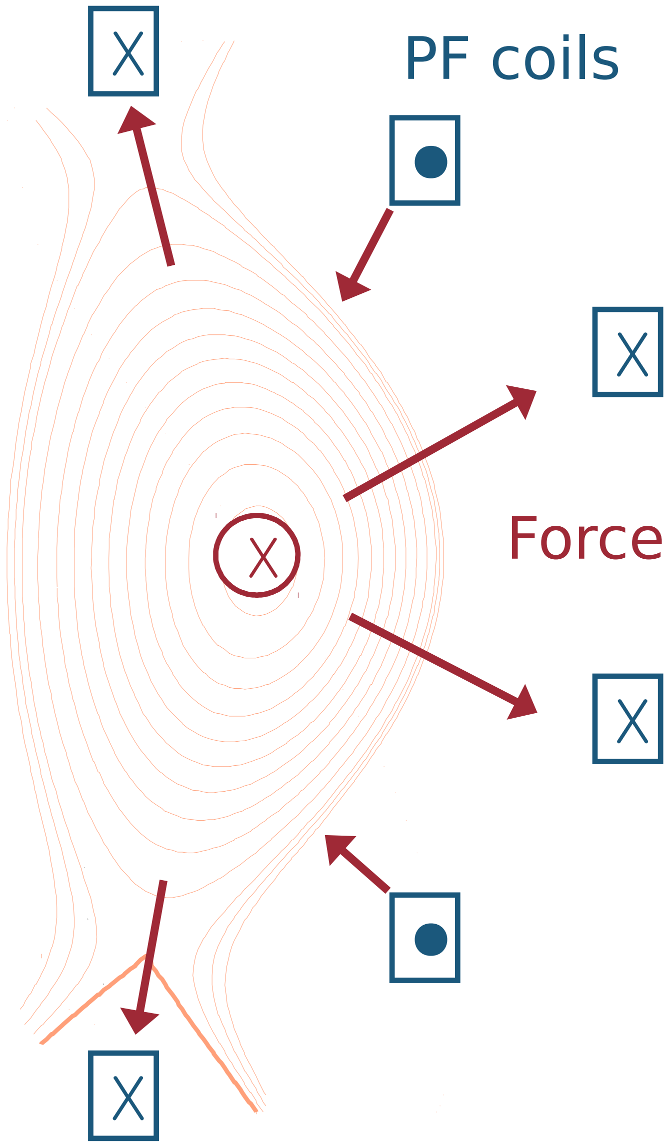


Plasma expansion force

Force balance by vertical field coils: Plasma positioning

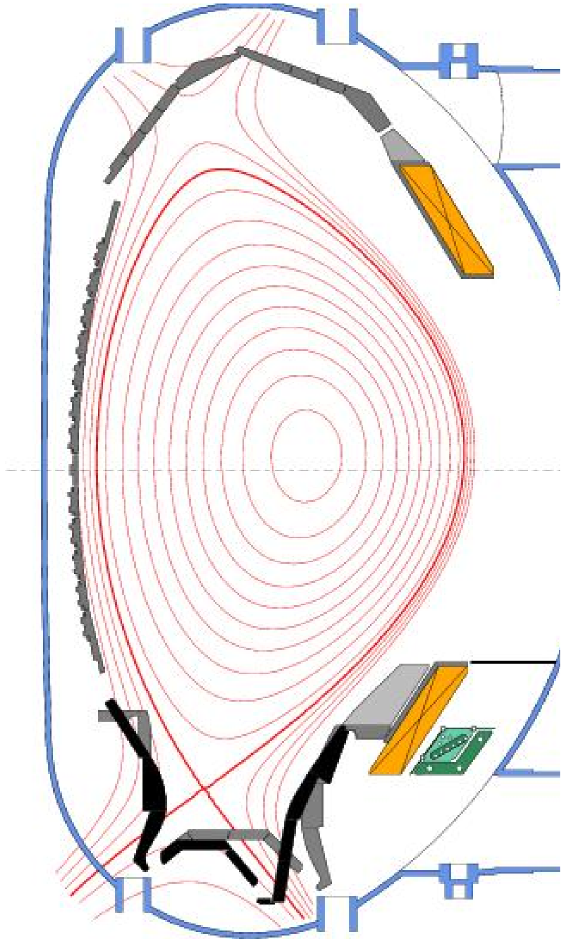
Tokamak

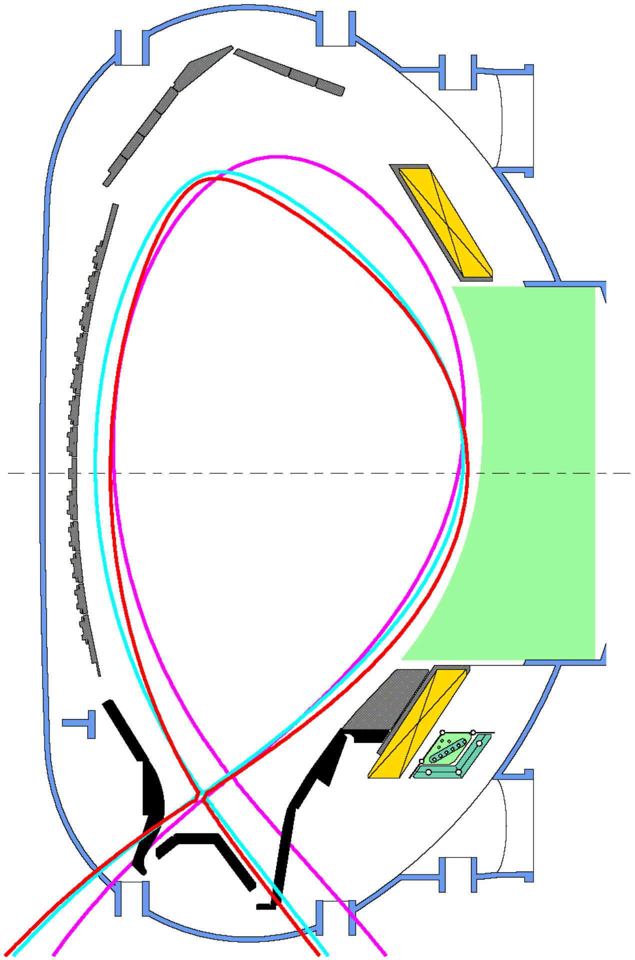




Plasma shaping by PF coils

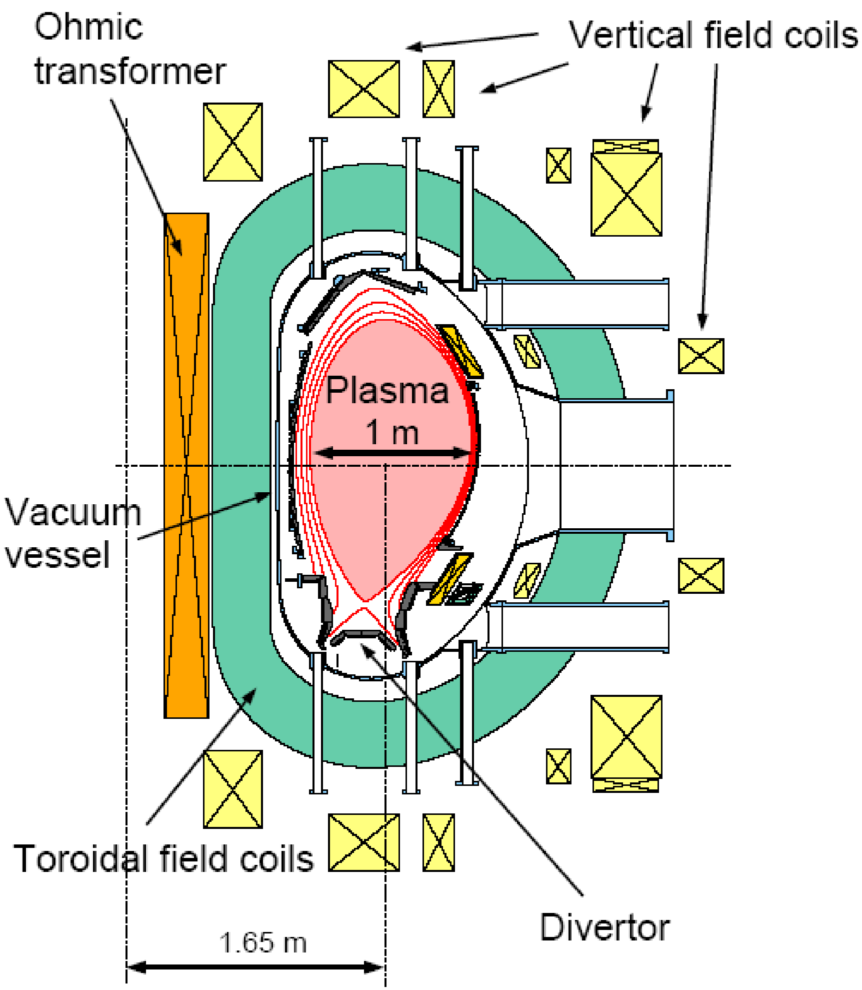
Tokamak



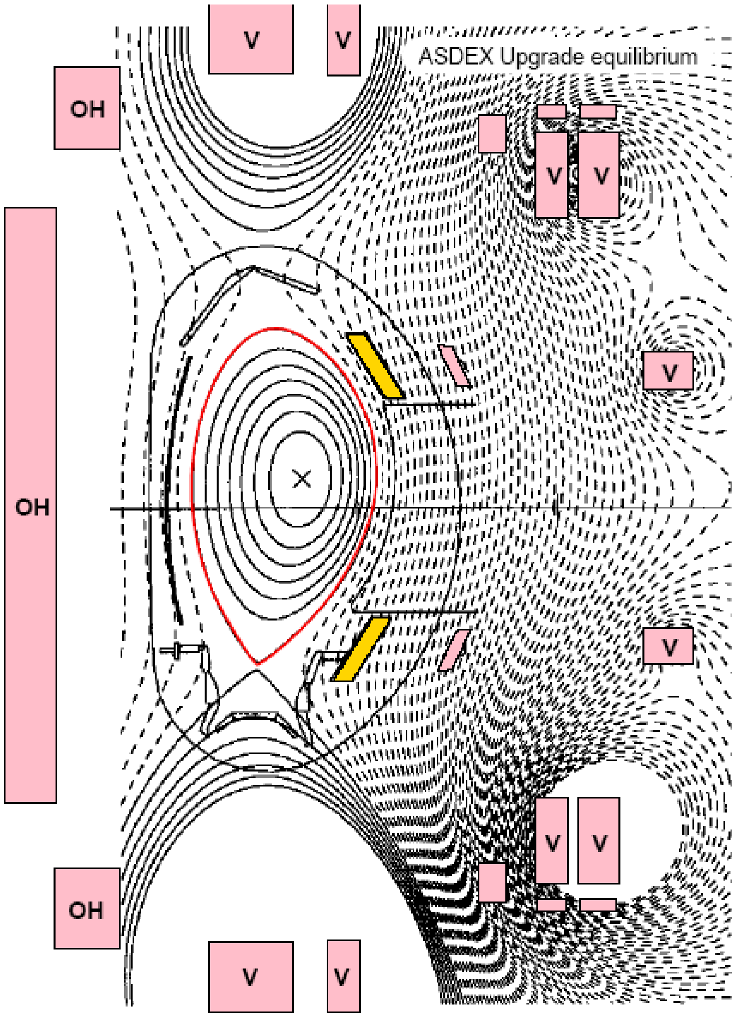


- The plasma shape can be modified by PF coil currents.

Tokamak



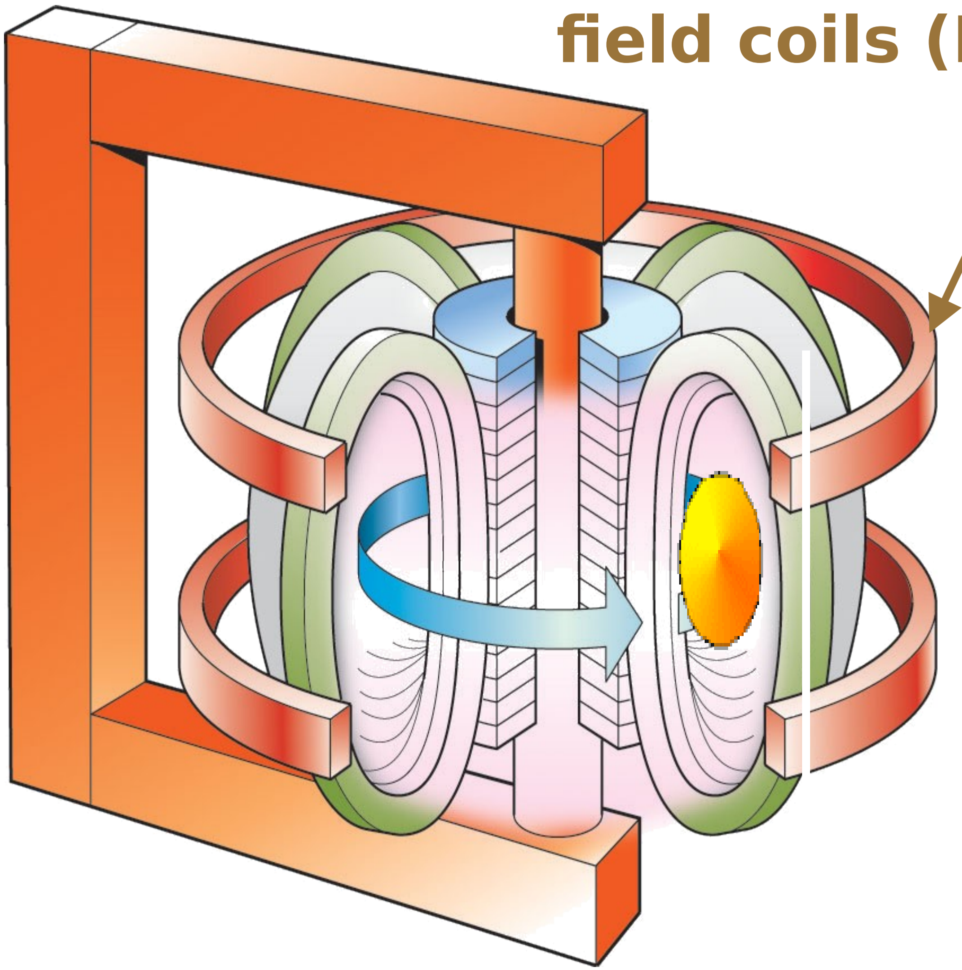
Ohmic transformer
Vertical field coils
Plasma
1 m
Vacuum vessel
Toroidal field coils
1.65 m
Divertor



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

Tokamak

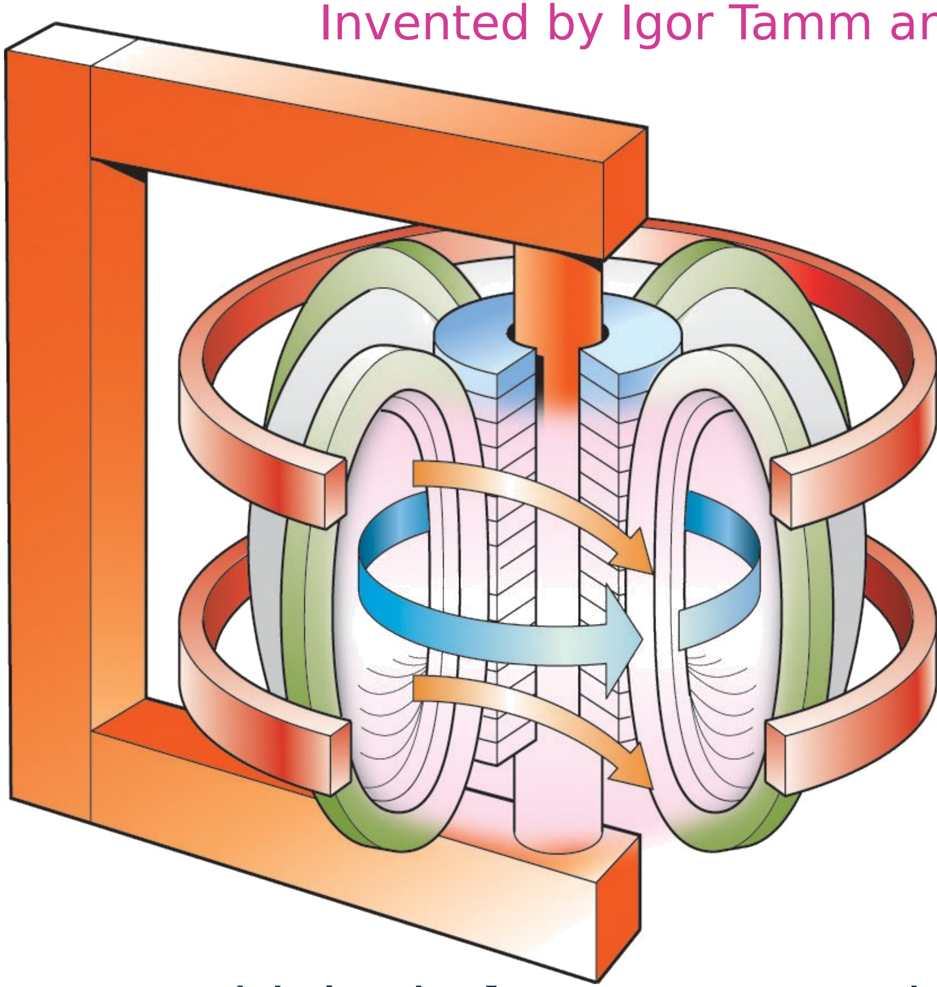
Adding vertical (equilibrium) field coils (PF: Poloidal Field)

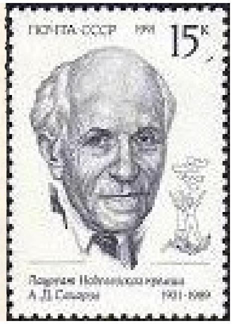


Plasma positioning & shaping by PF coils

Tokamak

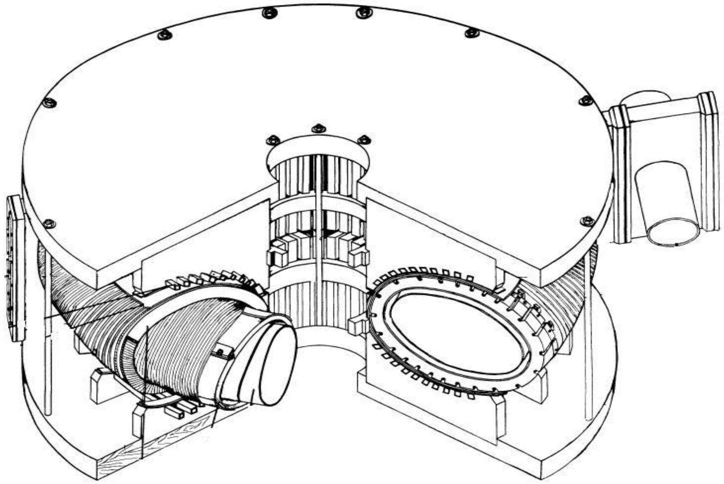
Invented by Igor Tamm and Andrei Sakharov in 1952





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

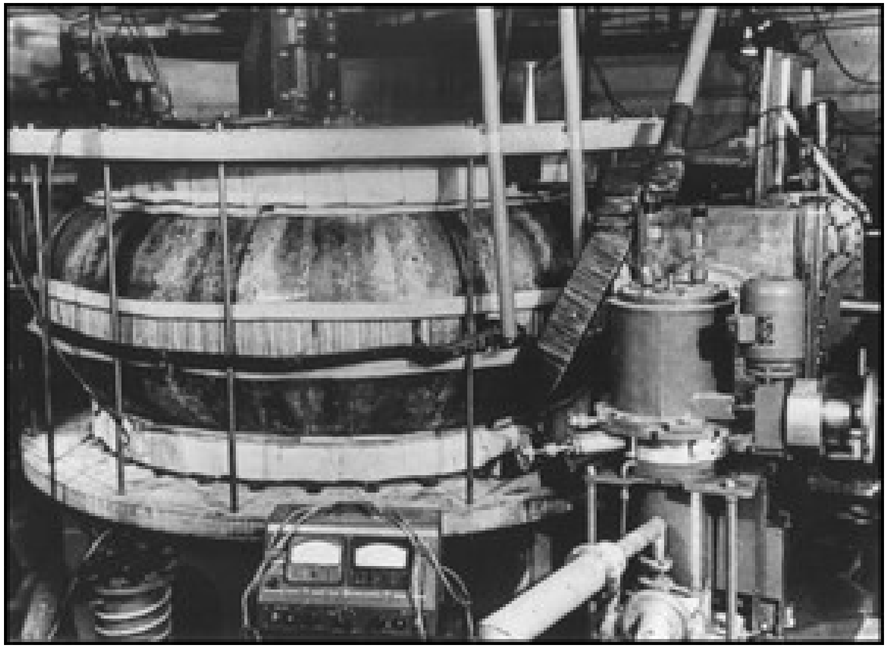
Tokamak



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

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

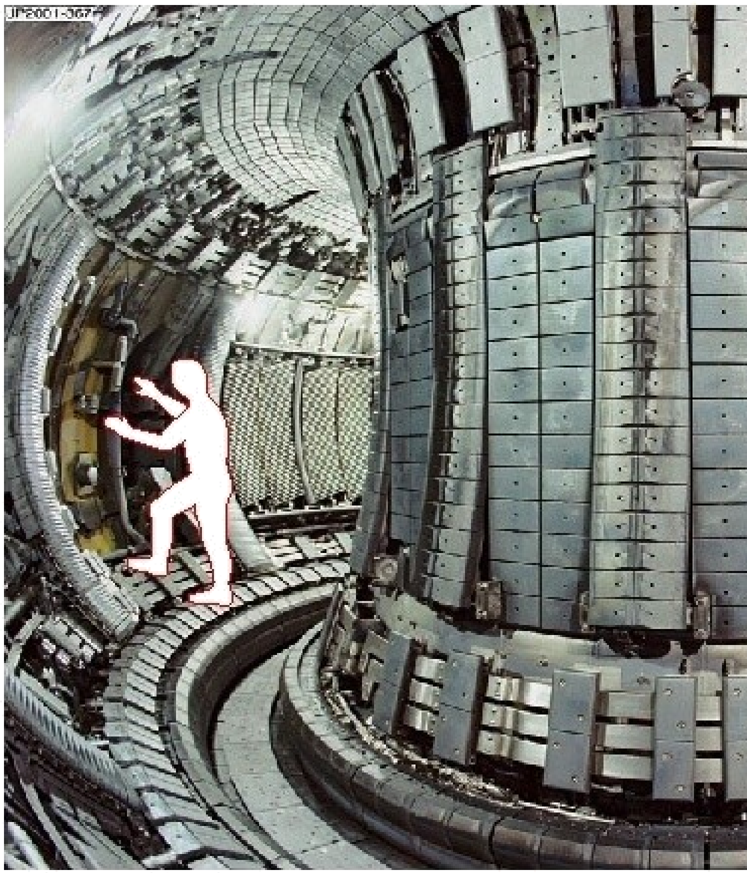
It was the first device to use a stainless steel liner within a copper vacuum chamber.

Tokamak

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

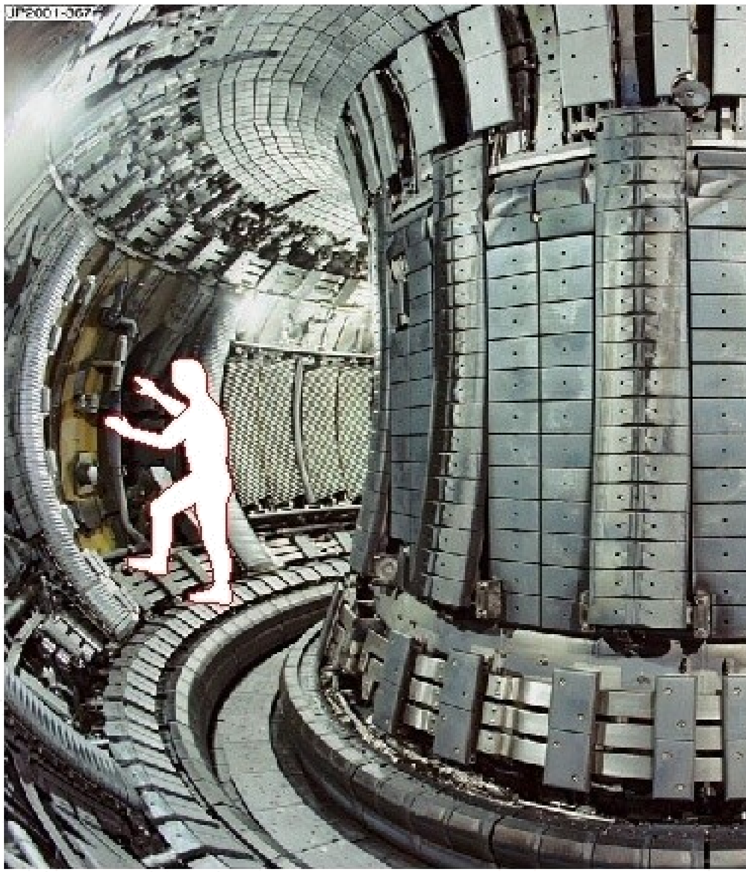
Tokamak

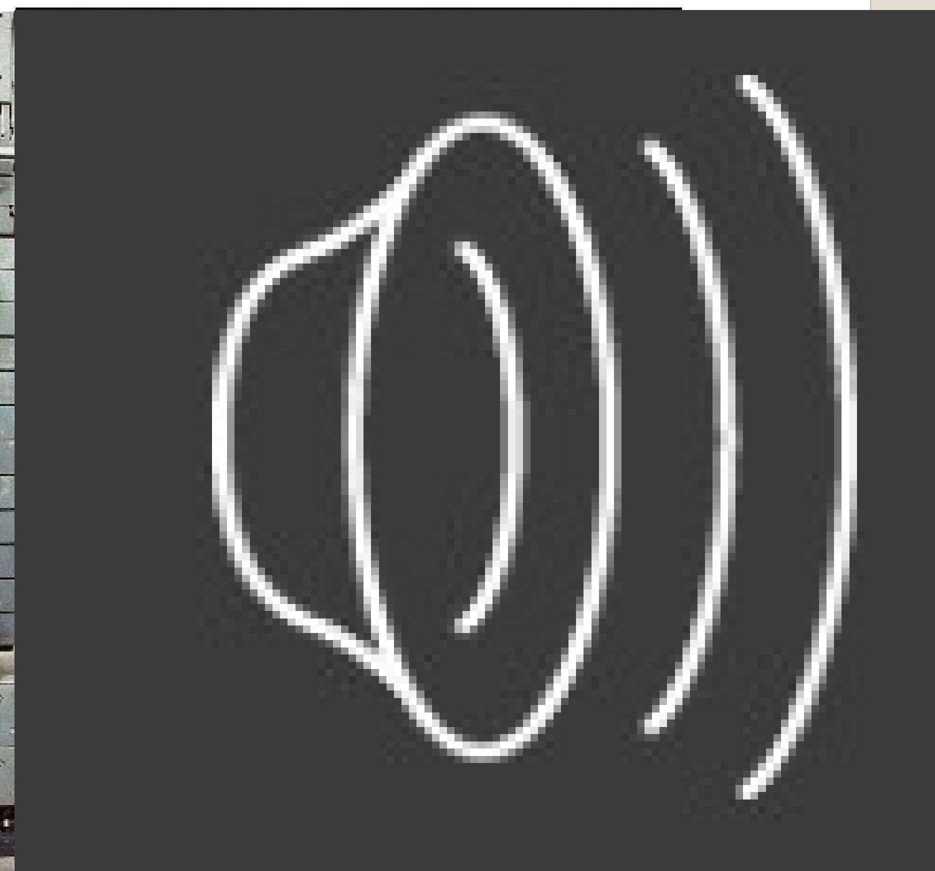
JET (Joint European Torus): R_0 = 3 m, a = 0.9 m, 1983-today



Tokamak

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

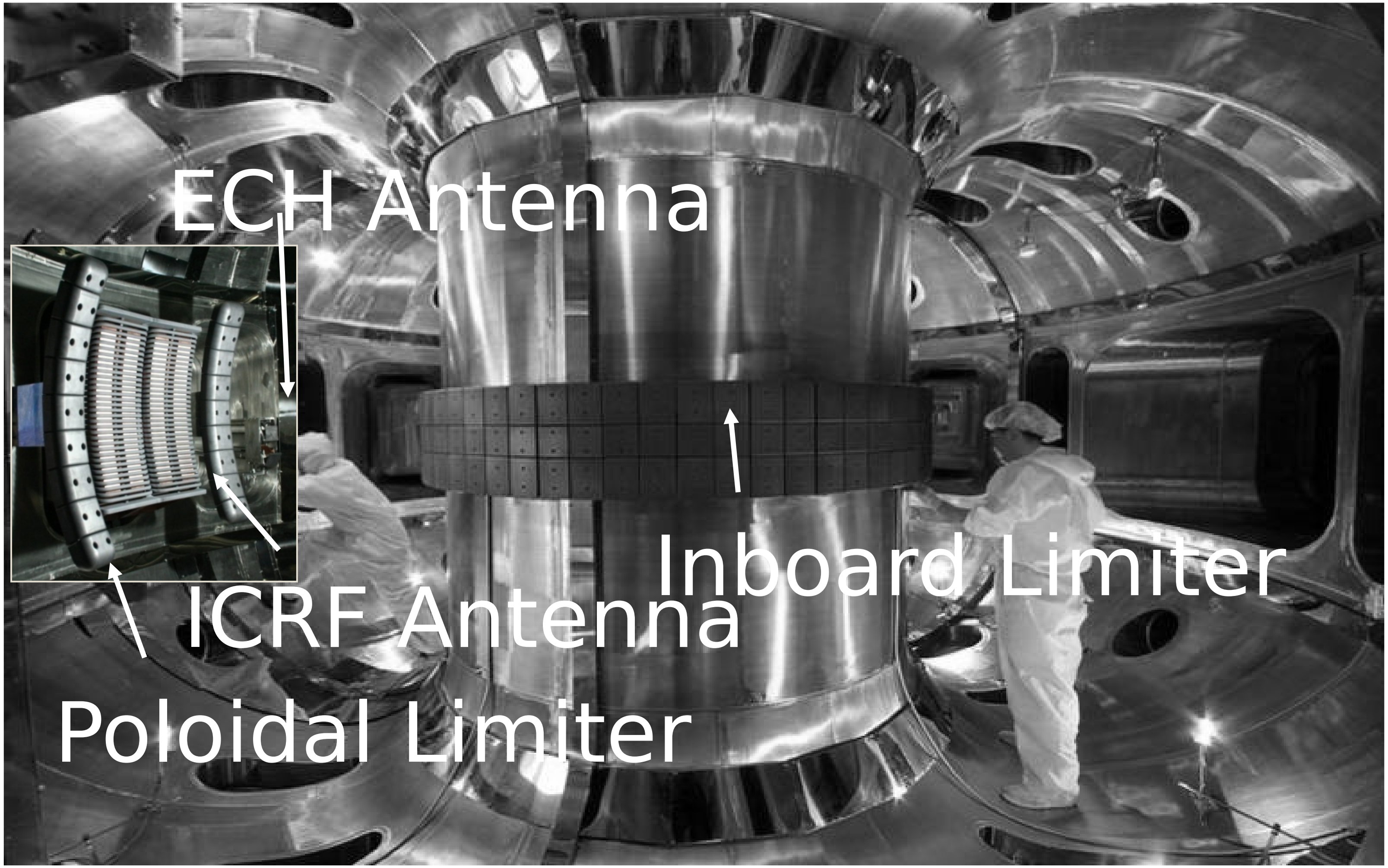




Tokamak

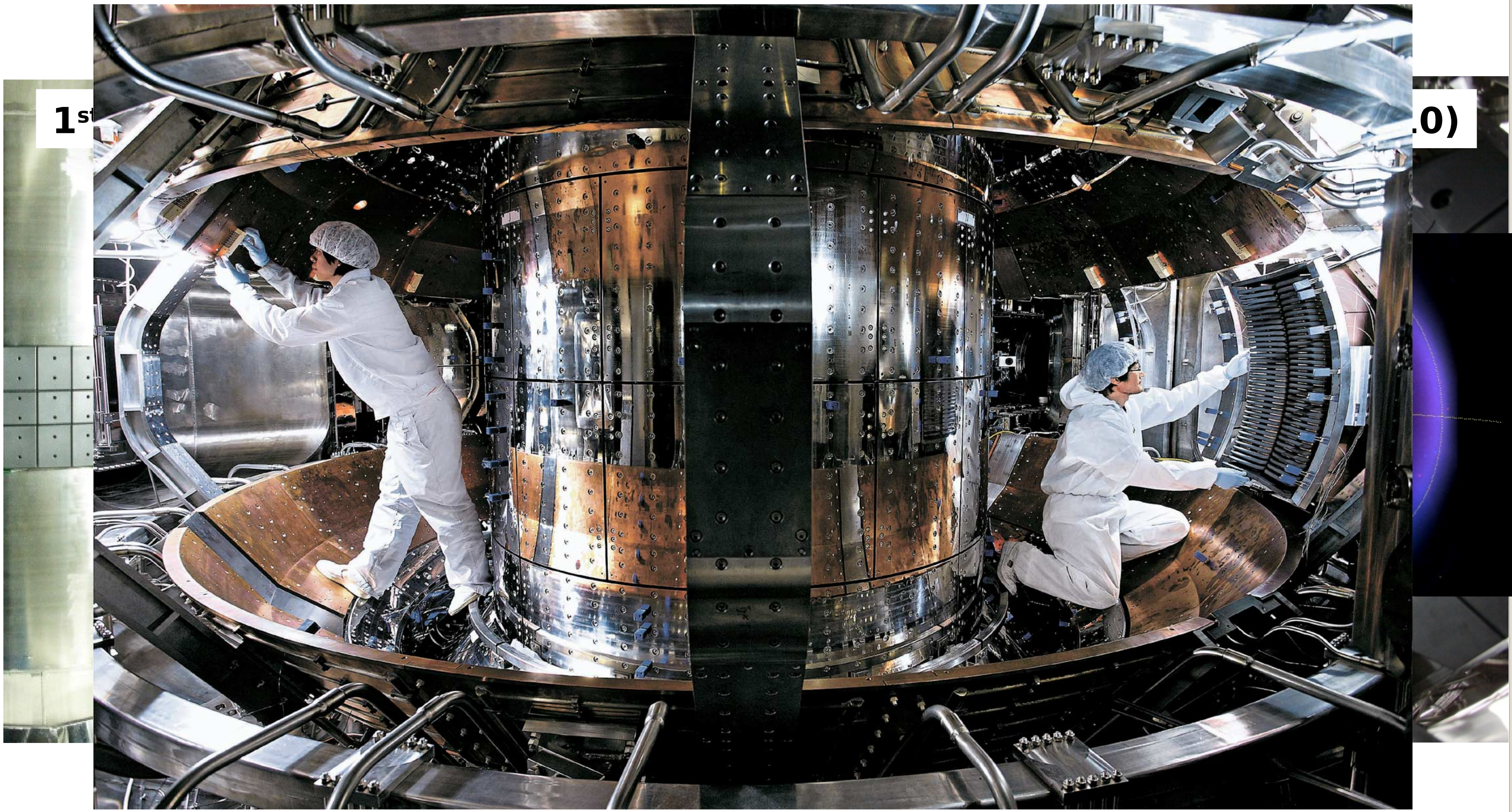
Tokamak

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



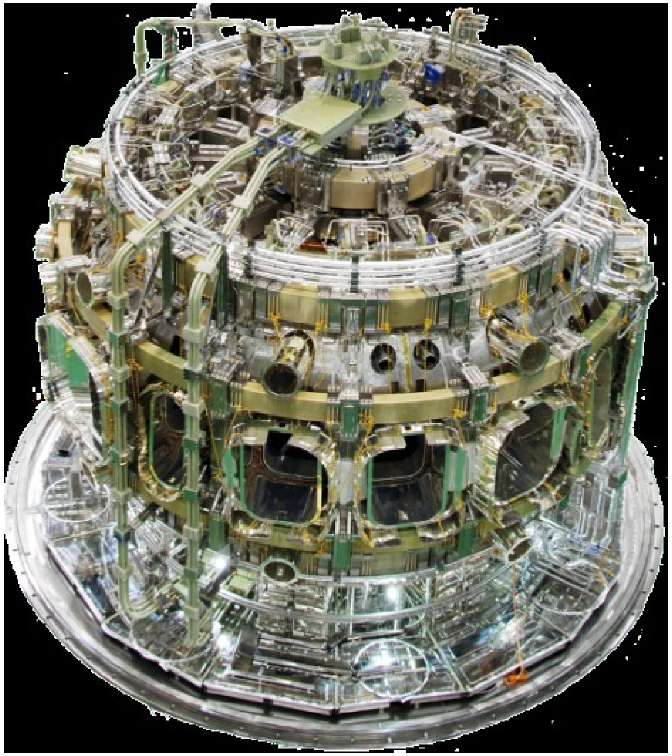
Tokamak

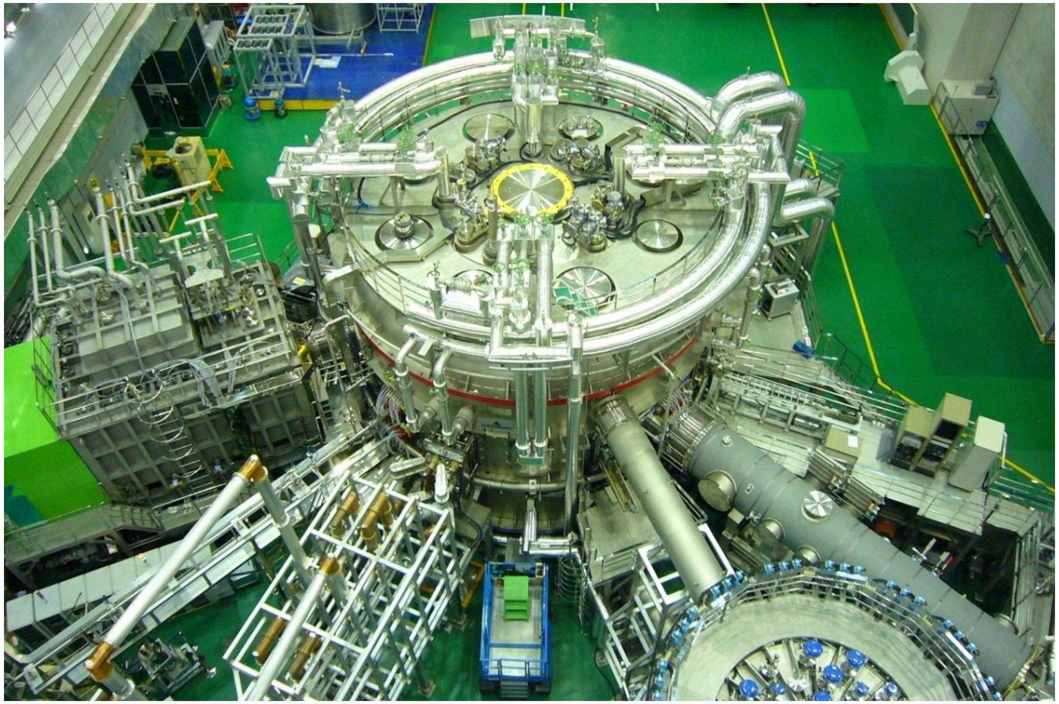
KSTAR (Korea Superconducting Tokamak Advanced Research):
R_0 = 1.8 m, a = 0.5 m, 2008-today



Tokamak

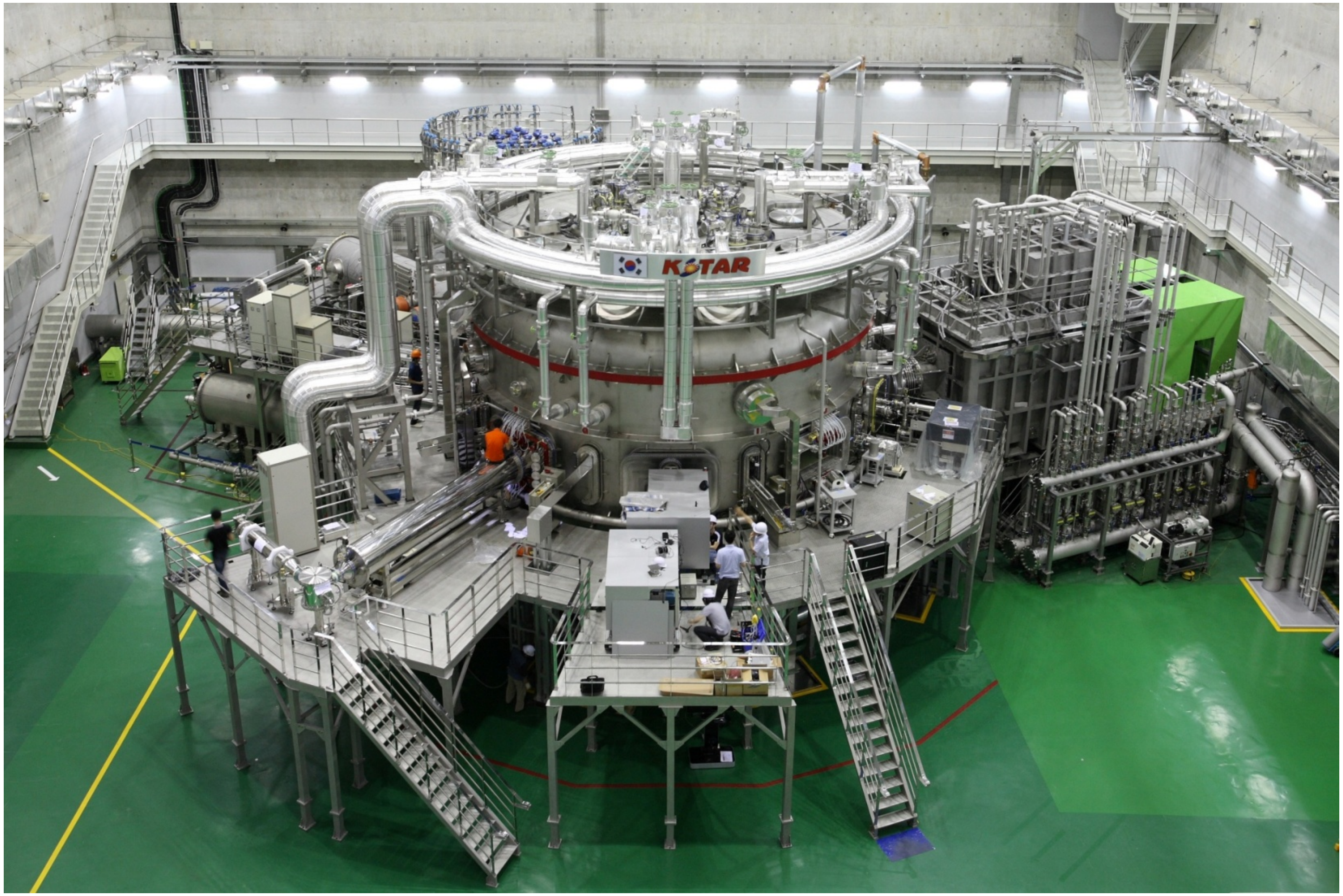
KSTAR (Korea Superconducting Tokamak Advanced Research):
R_0 = 1.8 m, *a* = 0.5 m, 2008-today





Tokamak

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



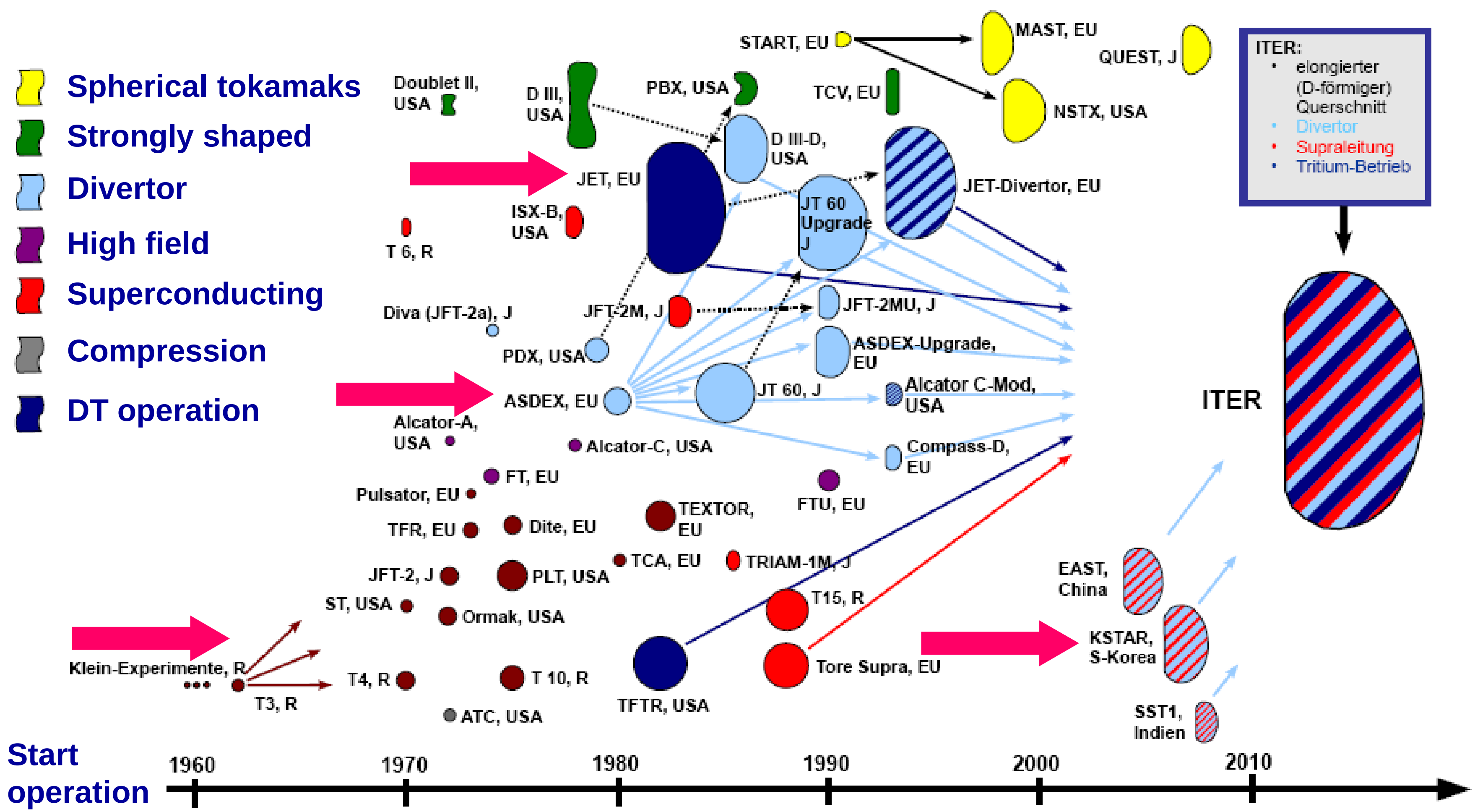
Tokamak

KSTAR (Korea Superconducting Tokamak Advanced Research):

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

KSTAR 1st plasma

Tokamak



Spherical tokamaks
Strongly shaped
Divertor
High field
Superconducting
Compression
DT operation
ITER:
elongierter (D-förmiger) Querschnitt
Divertor
Supraleitung
Tritium-Betrieb
ITER
START, EU
MAST, EU
QUEST, J
NSTX, USA
TCV, EU
PBX, USA
Doublet II, USA
D III, USA
D III-D, USA
JET, EU
JET-Divertor, EU
JT 60 Upgrade J
ISX-B, USA
T 6, R
Diva (JFT-2a), J
JFT-2M, J
JFT-2MU, J
PDX, USA
ASDEX-Upgrade, EU
ASDEX, EU
JT 60, J
Alcator C-Mod, USA
Alcator-A, USA
Alcator-C, USA
Compass-D, EU
FT, EU
FTU, EU
Pulsator, EU
TFR, EU
Dite, EU
TEXTOR, EU
TCA, EU
TRIAM-1M, J
JFT-2, J
PLT, USA
ST, USA
Ormak, USA
T15, R
EAST, China
KSTAR, S-Korea
Klein-Experimente, R
T3, R
T4, R
T 10, R
ATC, USA
TFTR, USA
Tore Supra, EU
SST1, Indien
Start operation
1960
1970
1980
1990
2000
2010

References

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- [*http://blog.naver.com/PostView.nhn?blogId=vvi82fe04&logNo=94516497&parentCategoryNo=45&viewDate=&currentPage=1&listtype=0&from=postList*](http://blog.naver.com/PostView.nhn?blogId=vvi82fe04&logNo=94516497&parentCategoryNo=45&viewDate=&currentPage=1&listtype=0&from=postList)
- *26th JET Anniversay 20 May 2004*
- *D. Palumbo, "Setting JET on track" Prof. D.Palumbo*
- *P.H. Rebut, "JET : A step in fusion Concept and Objectives"*
- *François Waelbroeck, "Scientific Raison d'Etre for JET"*