Current Status of Nuclear Fusion Development Focusing on the Tokamak Concept

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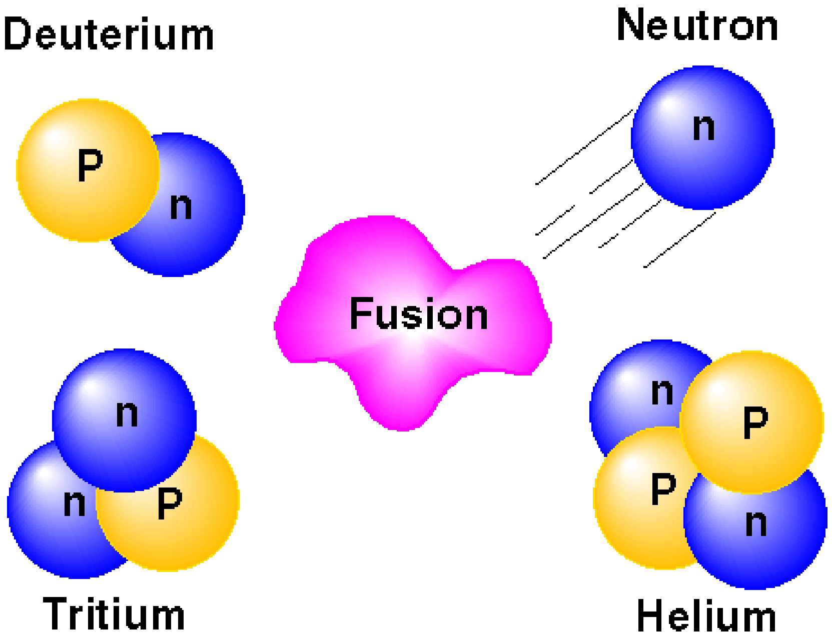
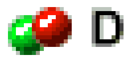
17 September, 2008

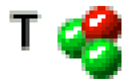
Contents

What is nuclear fusion?

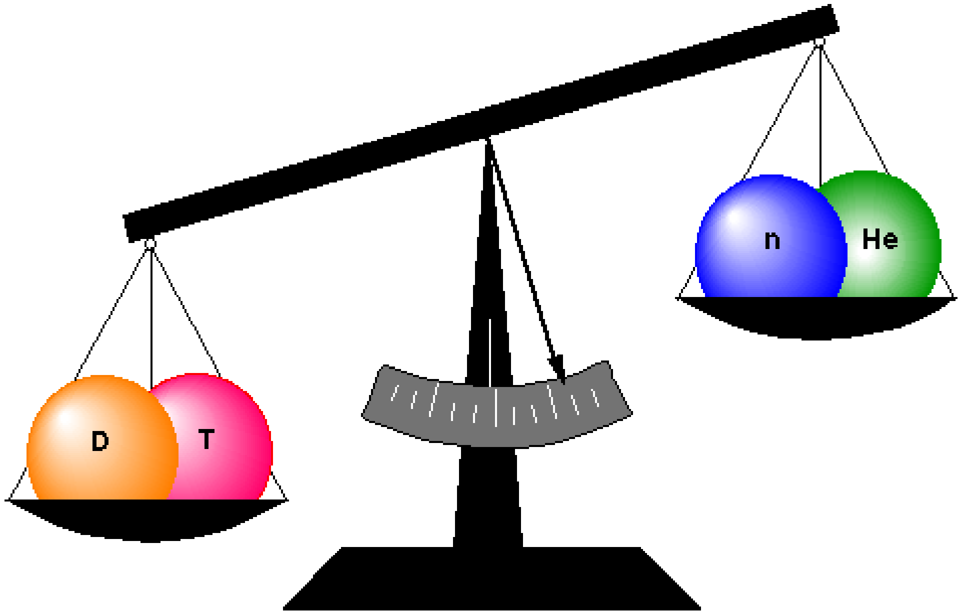
Nuclear Fusion Reaction

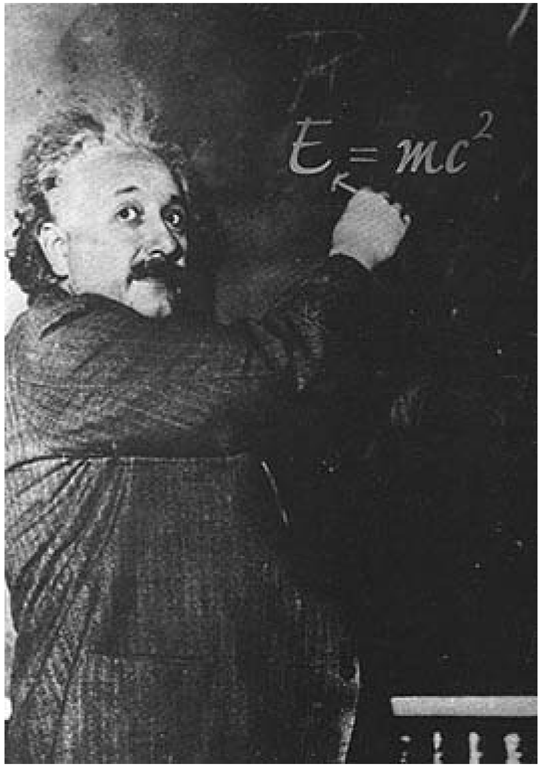




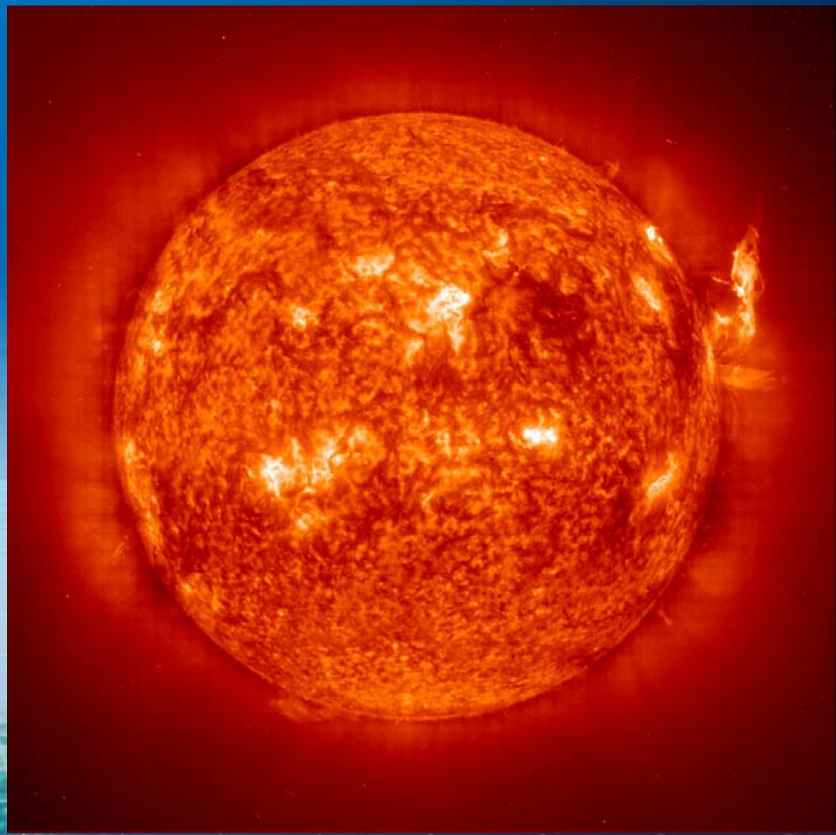


Nuclear Fusion Reaction



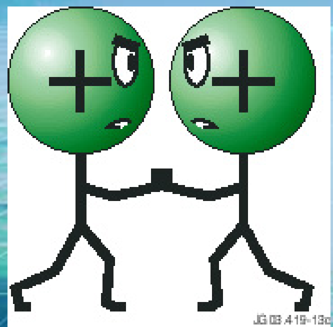


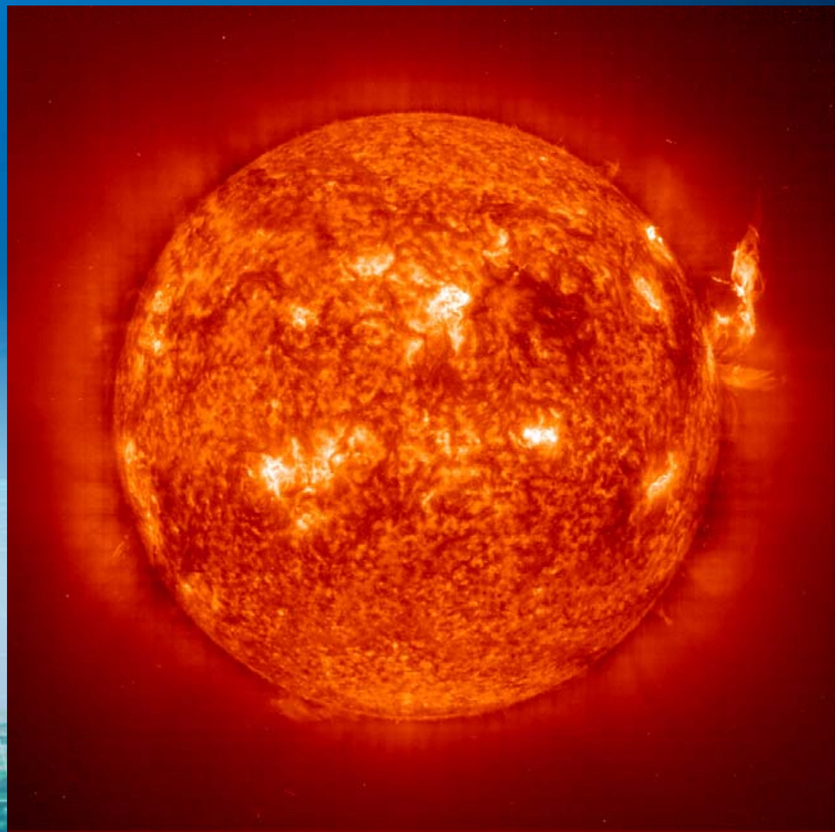
Origin of the Star Energy



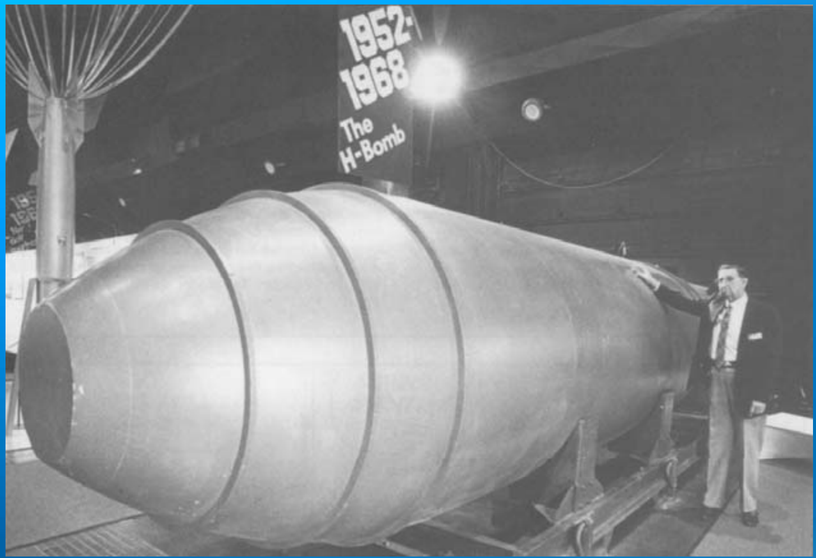
Origin of the Star Energy

Thermonuclear fusion





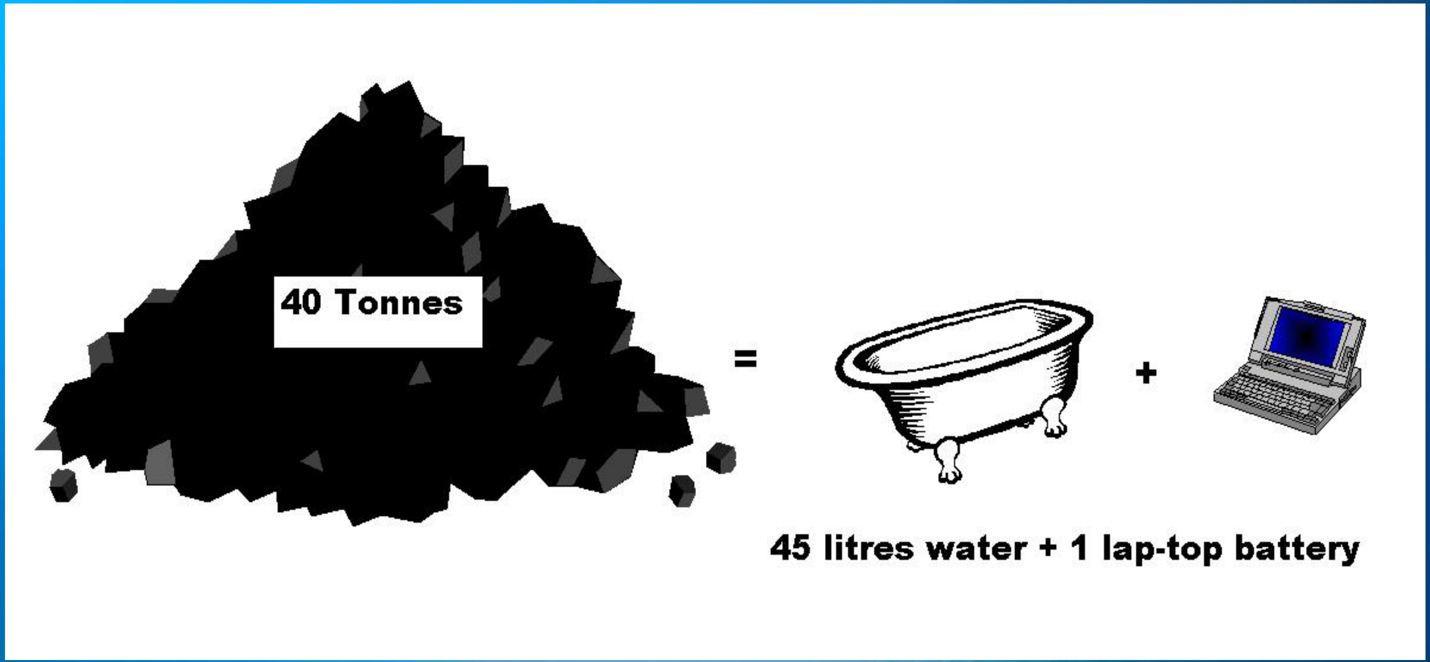
Utilisation of the Fusion Energy



A Mark-17 Hydrogen bomb at
the National Atomic Museum

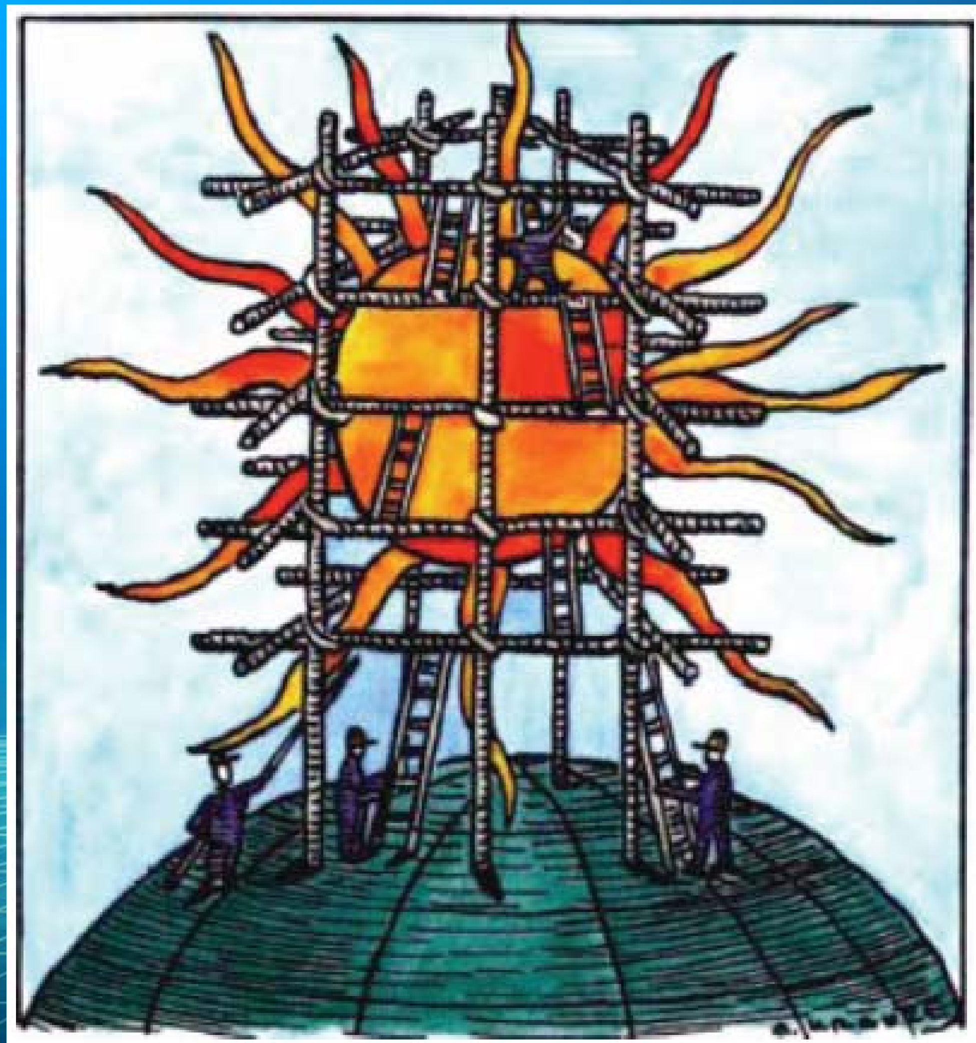
Peaceful use of the fusion energy?

Peaceful Use of the Fusion Energy

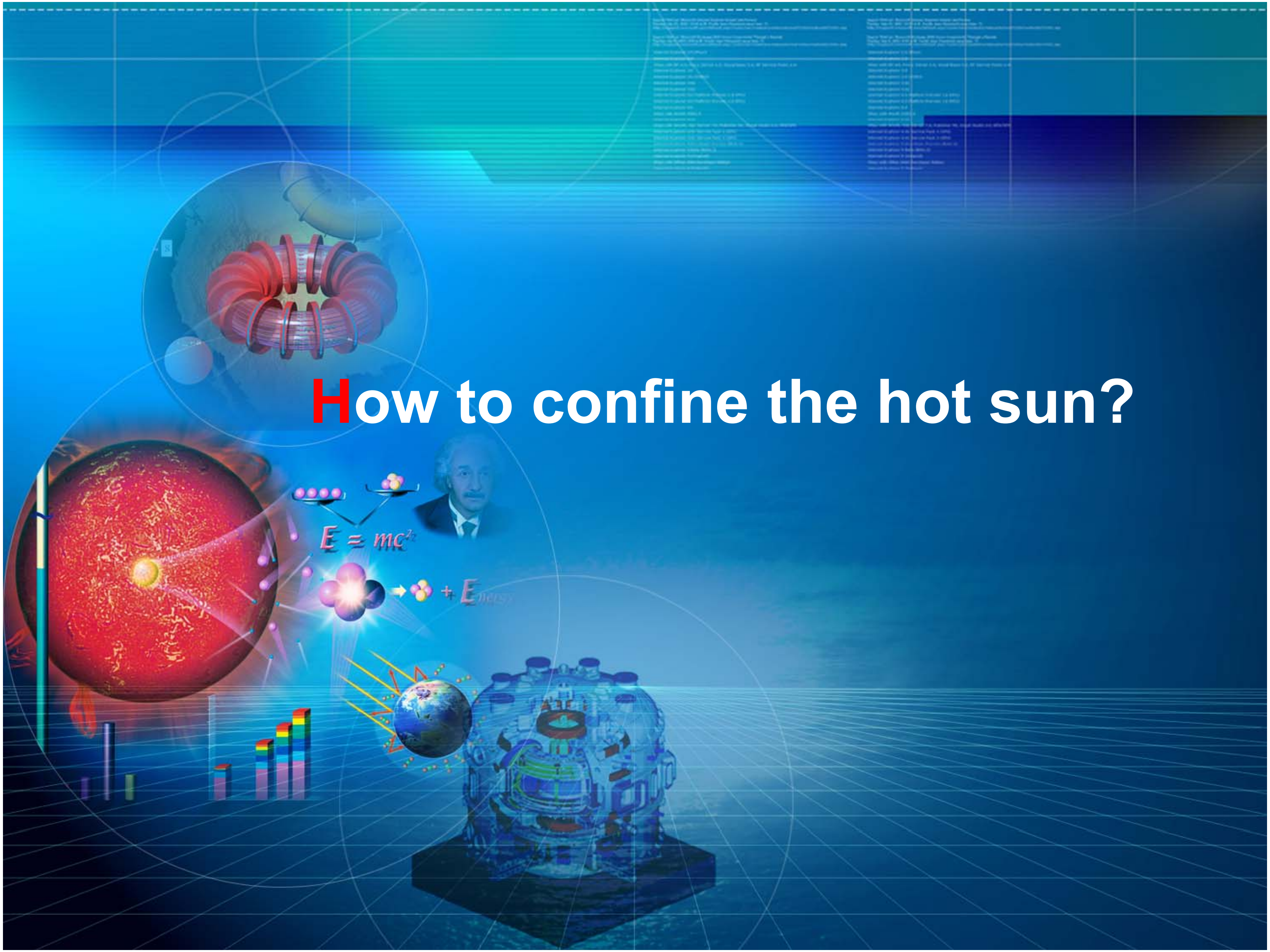


• Lithium in one laptop battery + half a bath-full of ordinary water ($\geq$ one egg cup full of heavy water) = 200 MW

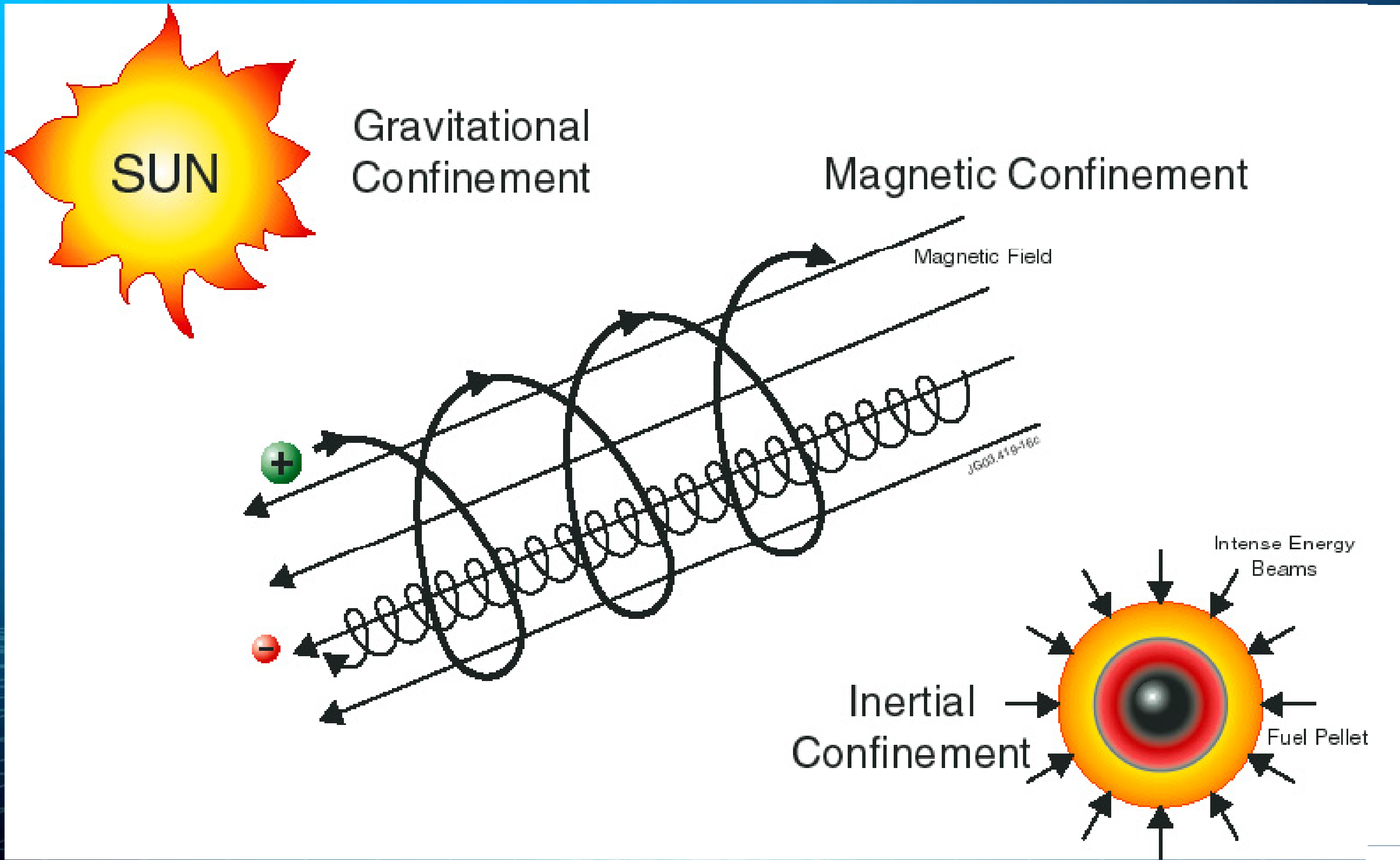
Build a Sun on the Earth



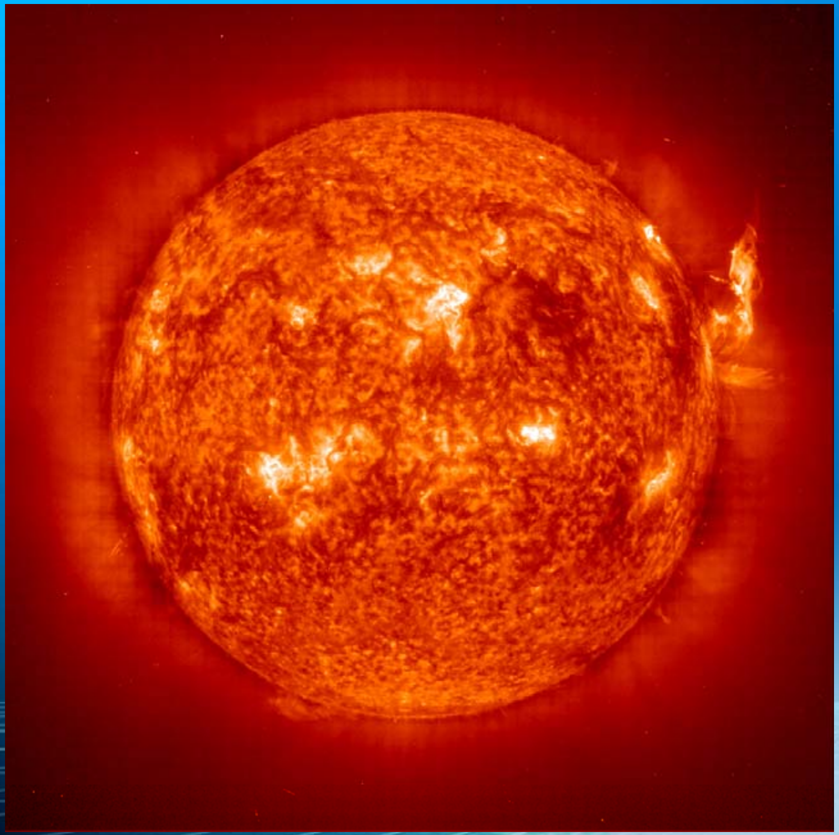
How to confine the hot sun?



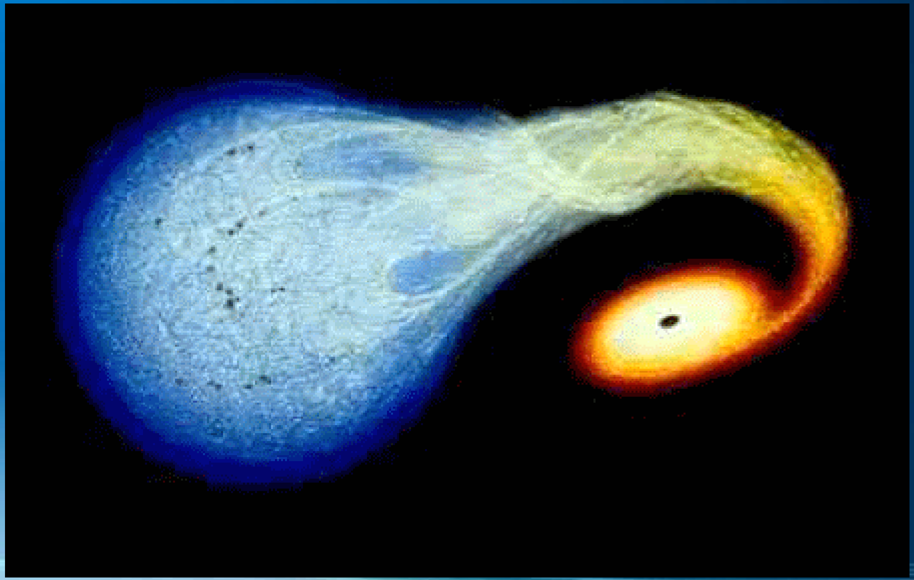
Confinement



Gravitational Confinement

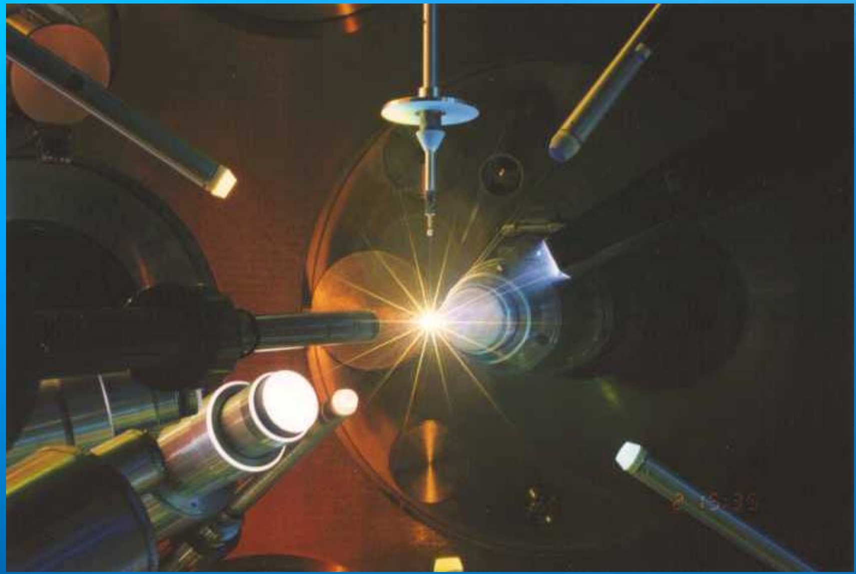


The sun

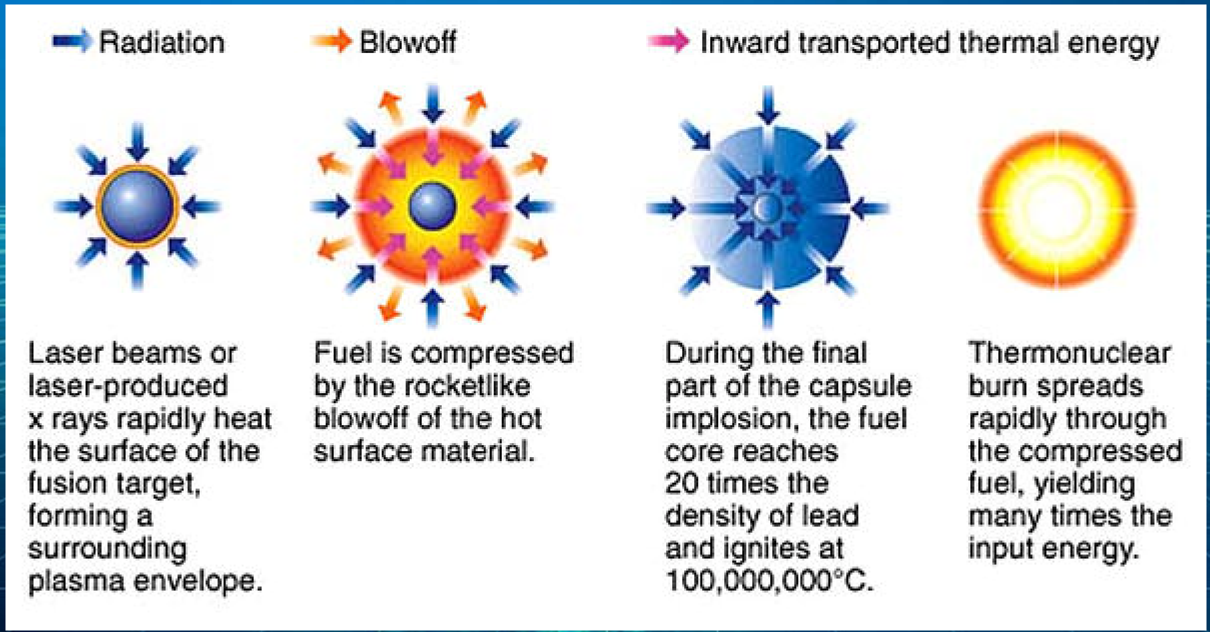


Black hole

Inertial Confinement



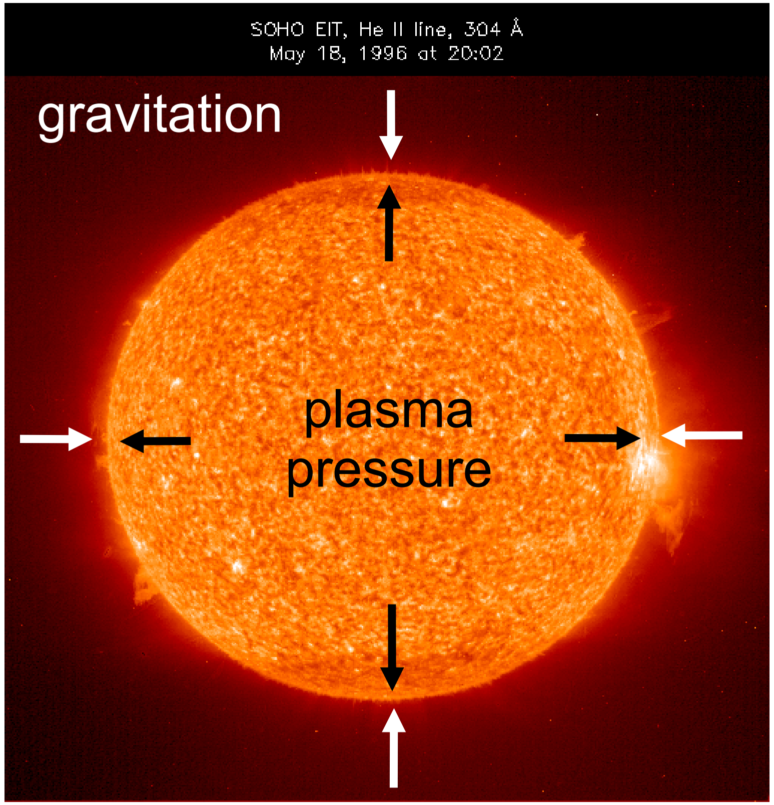
Fusion fuel microcapsule (microballoon)



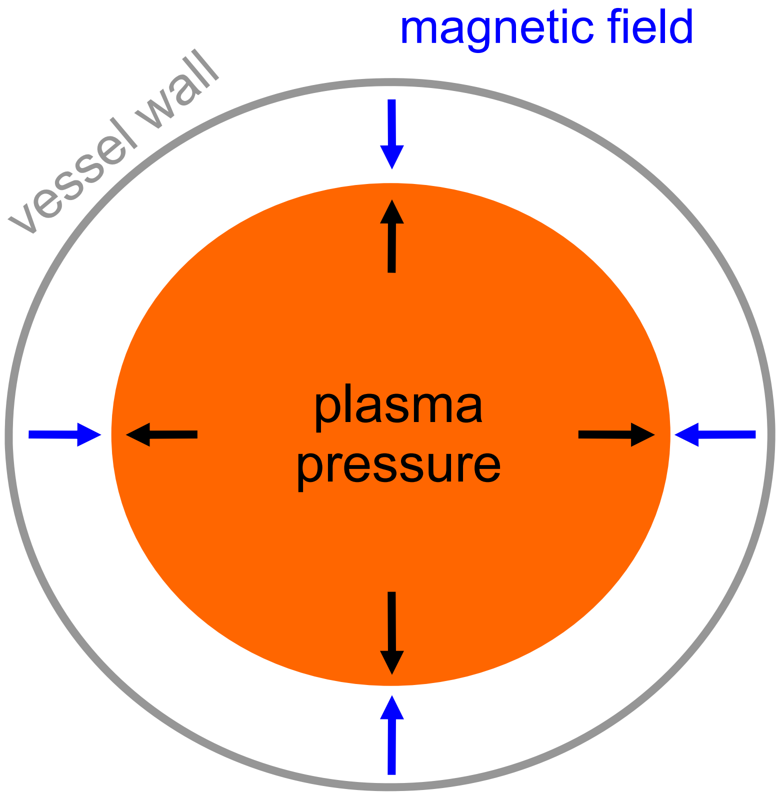
Spiderman II

Magnetic Confinement

- **Imitation of the Sun on Earth**



Equilibrium in the sun

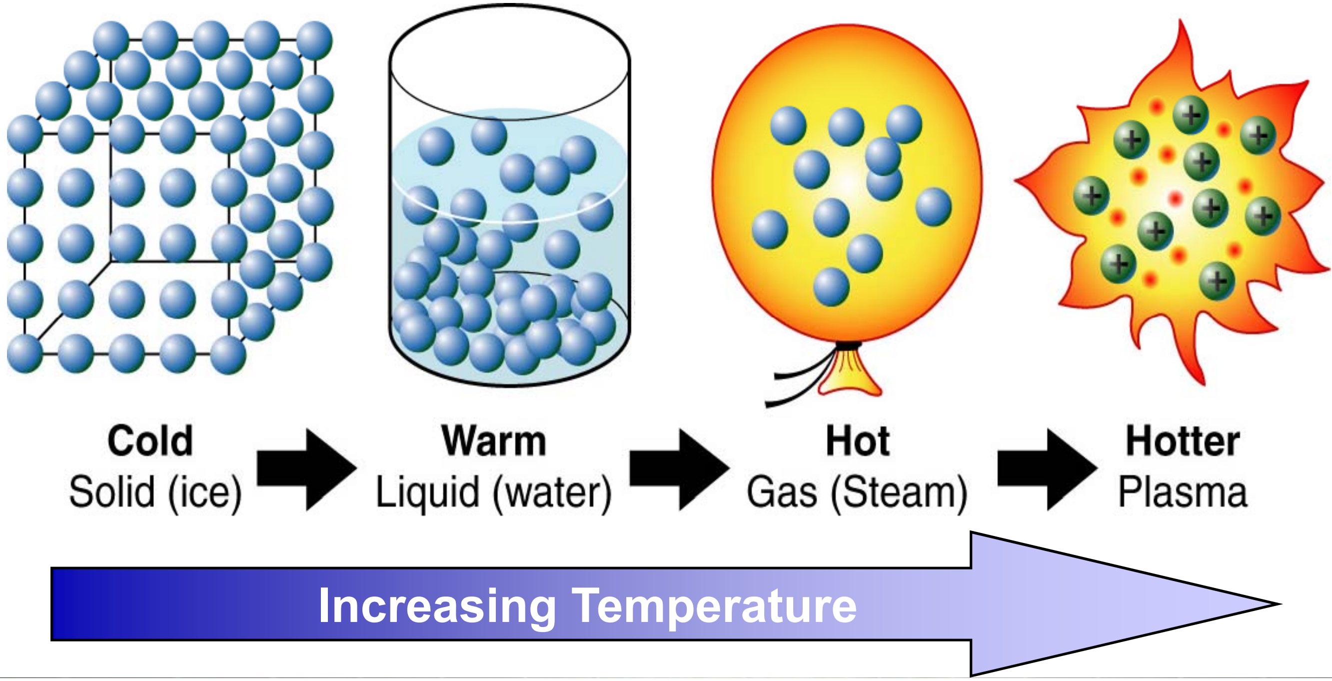


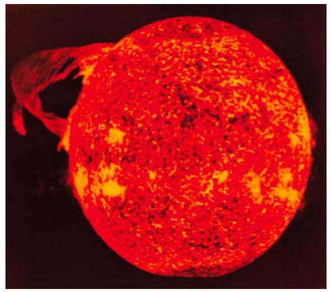
Plasma on earth

much, much smaller & tiny mass!

Plasma – The 4th State of Matter

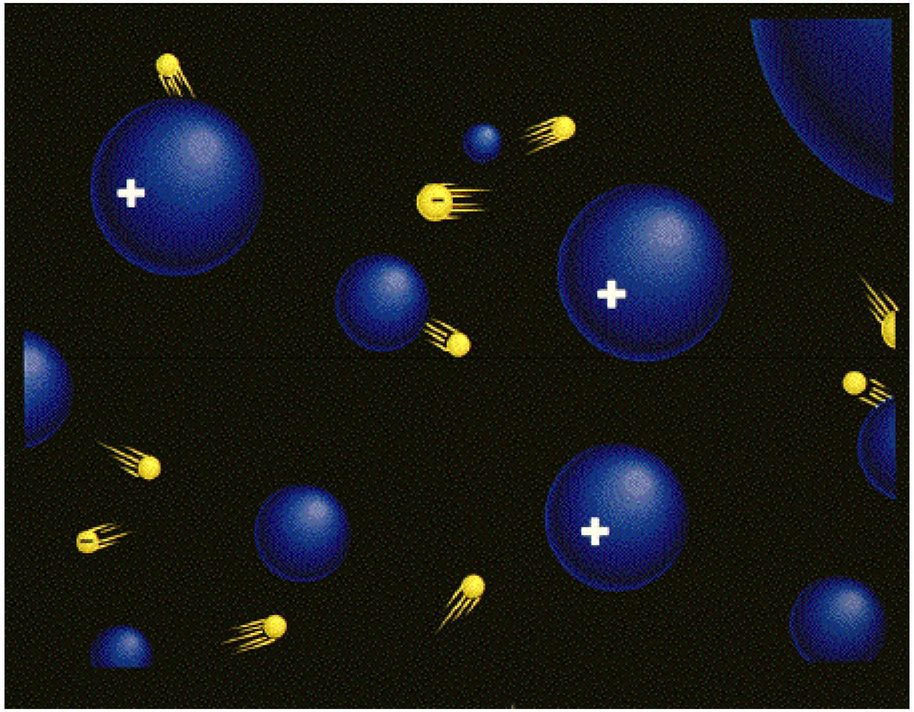


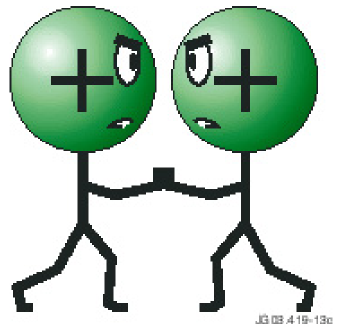


The 4th state of matter

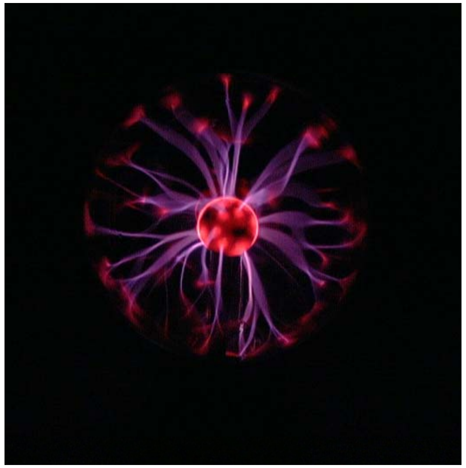
Plasma – The 4th State of Matter

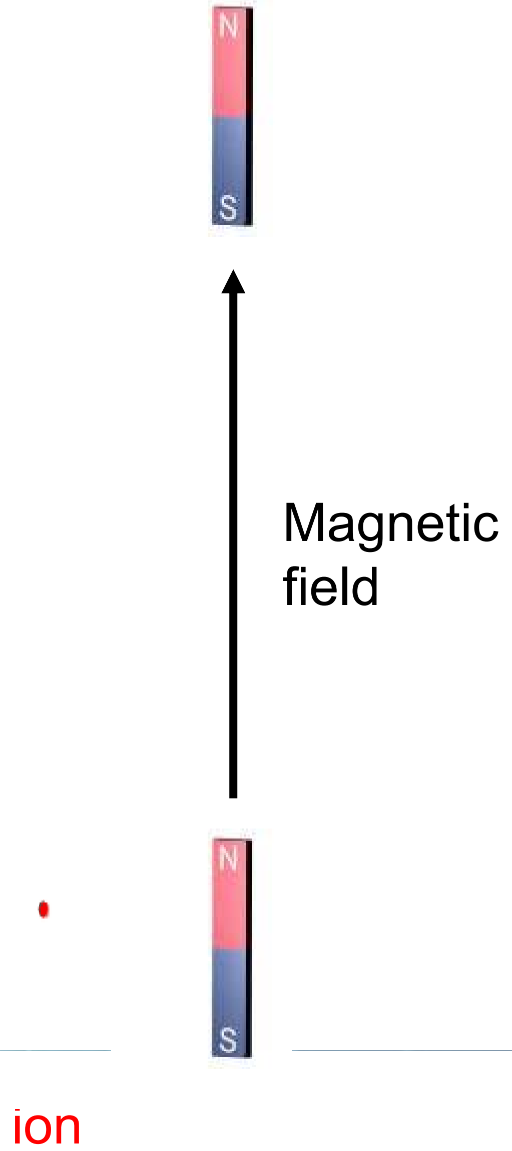




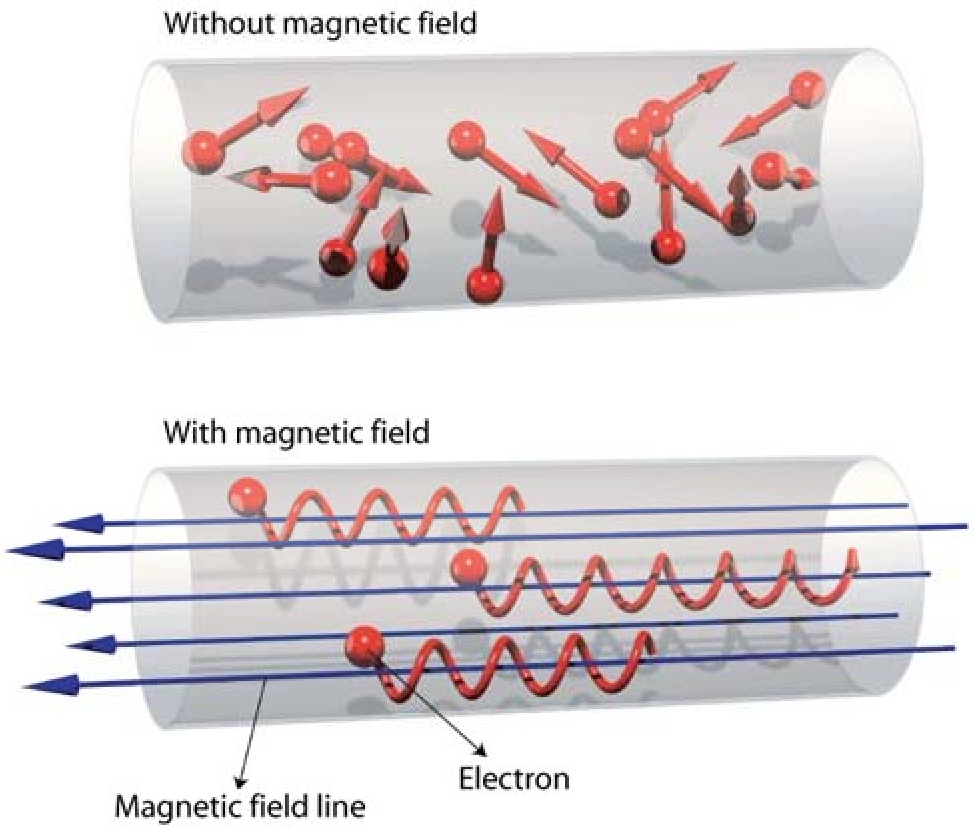
Ions and electrons are separated.

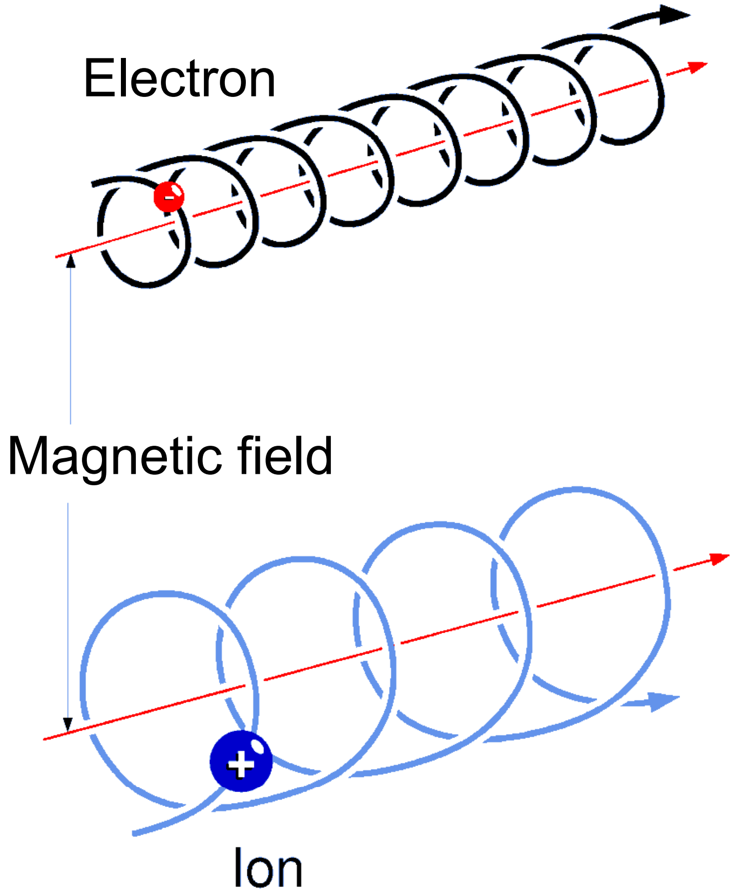
Magnetic Confinement



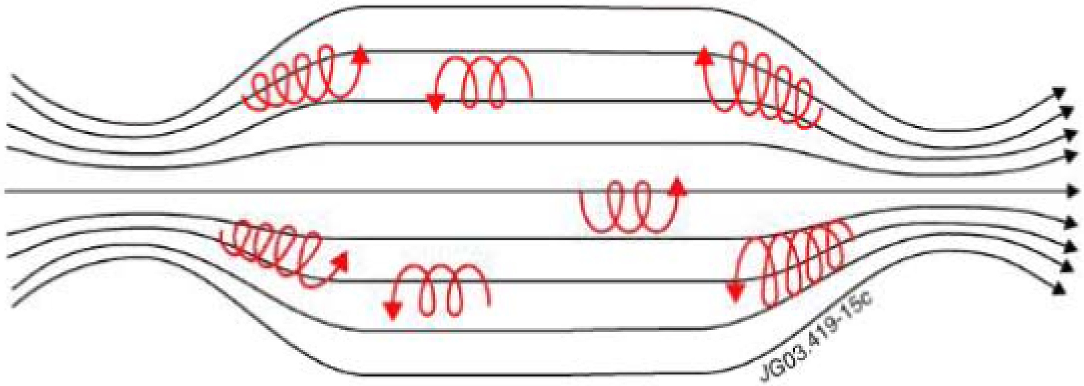


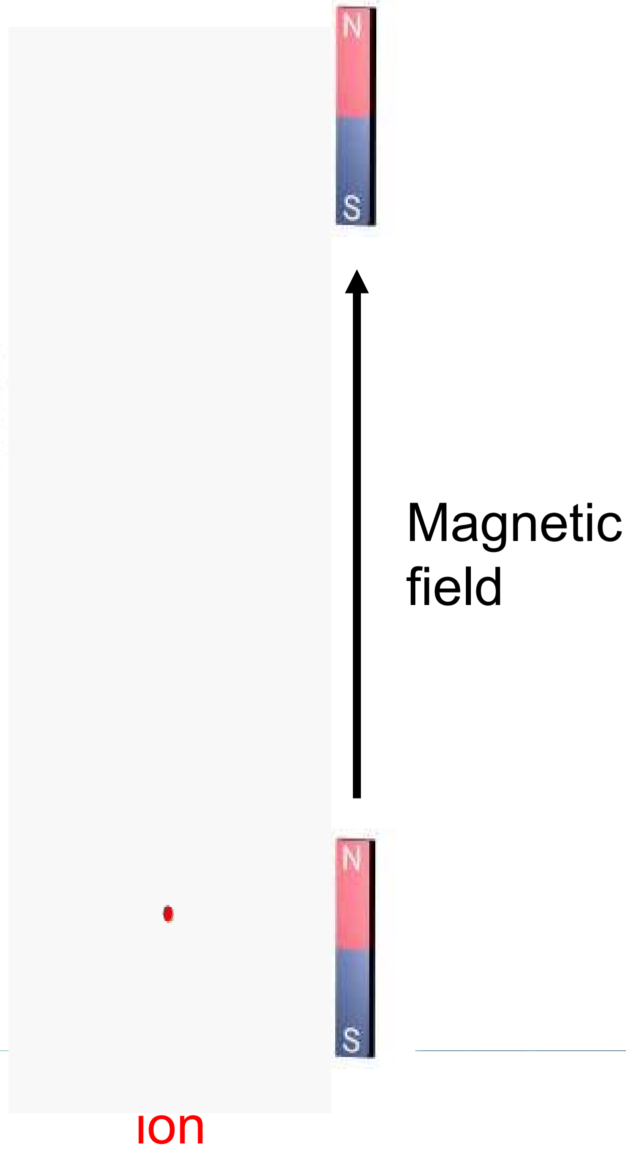
Magnetic Confinement



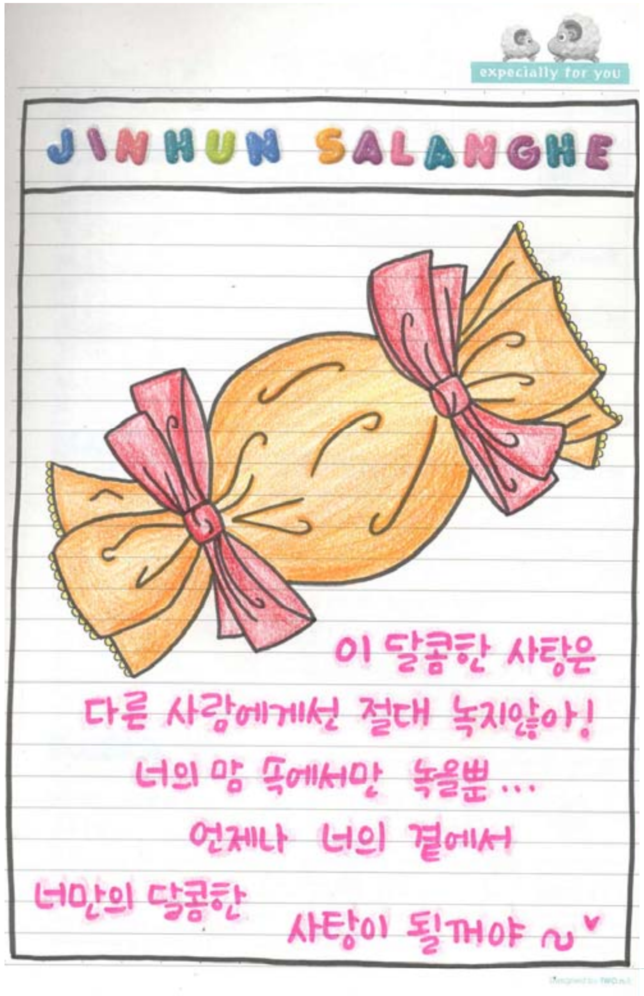


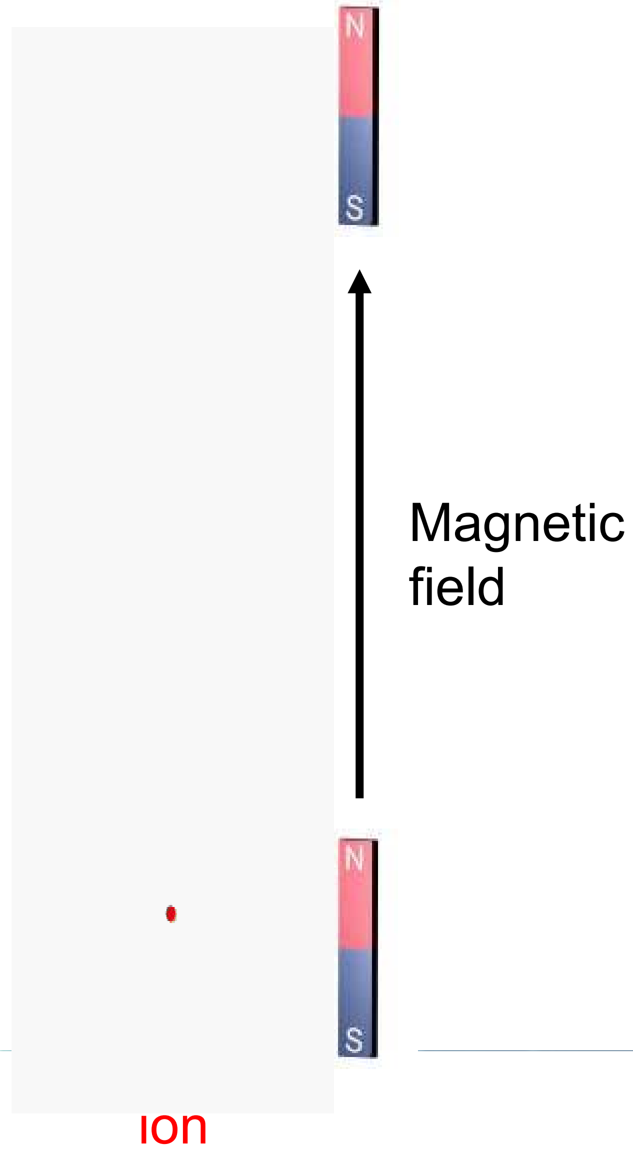
Magnetic Confinement



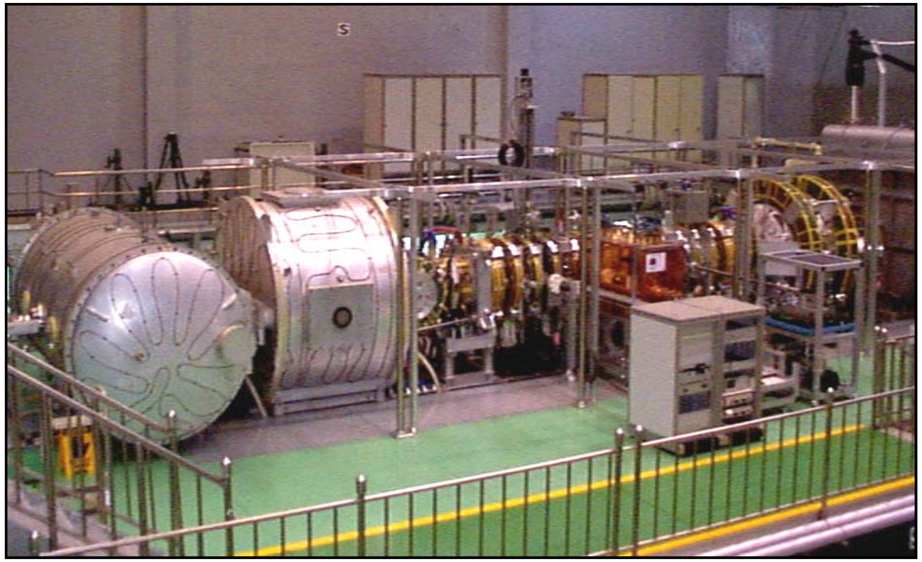


Magnetic Confinement



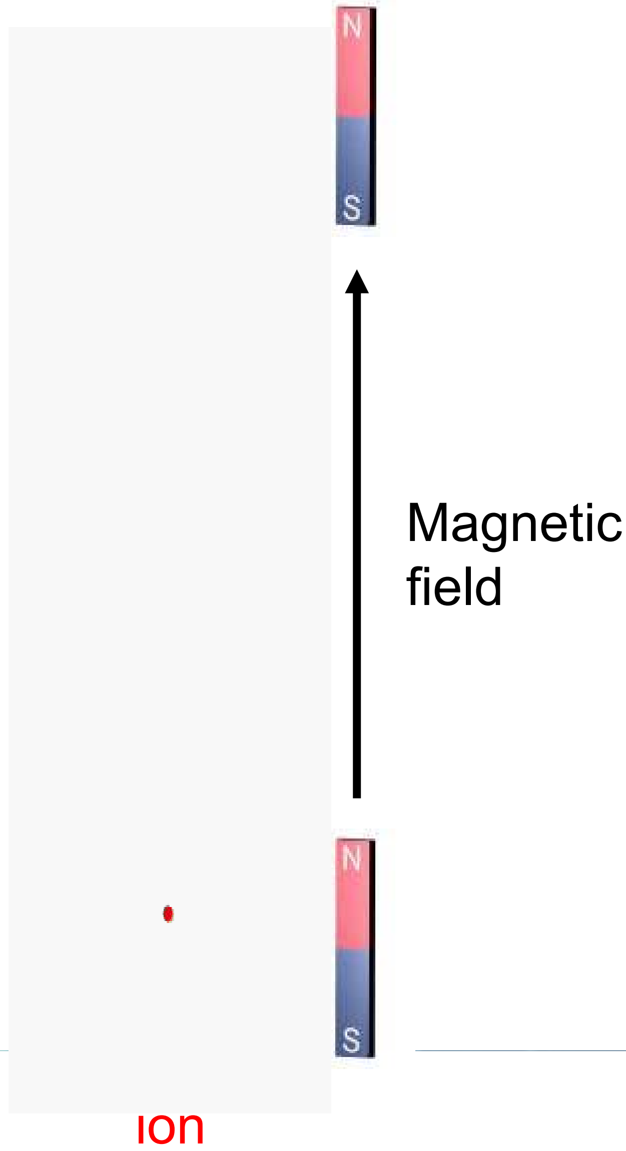


Magnetic Confinement

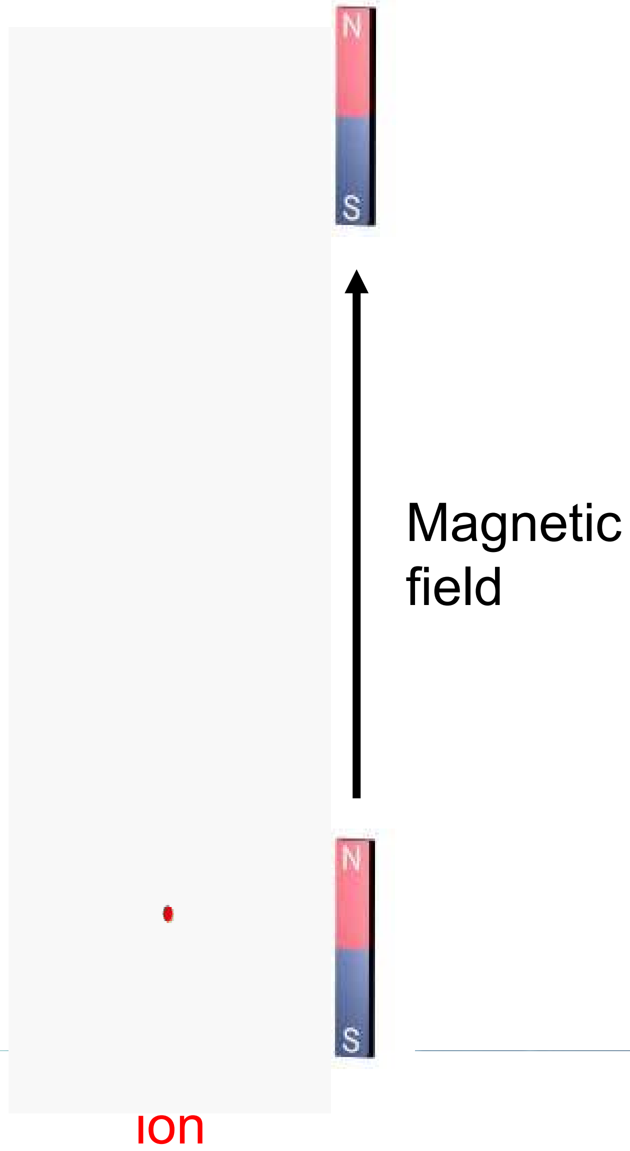


Mirror Machine

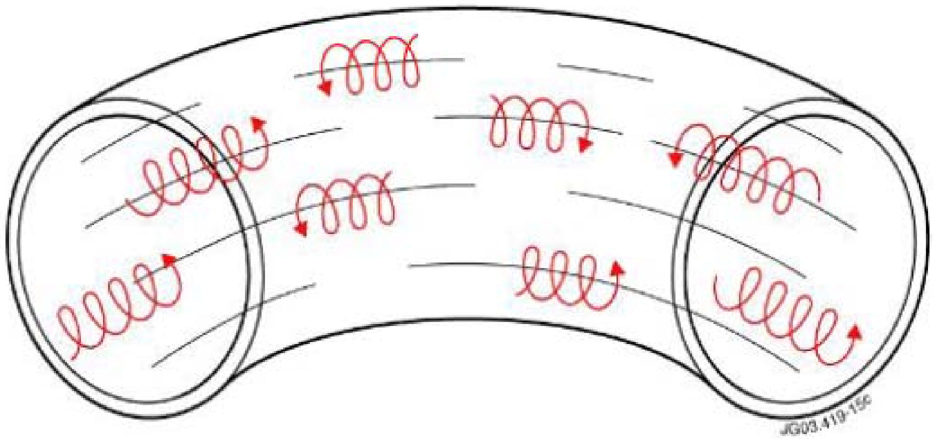
old Hanbit Device in NFRI

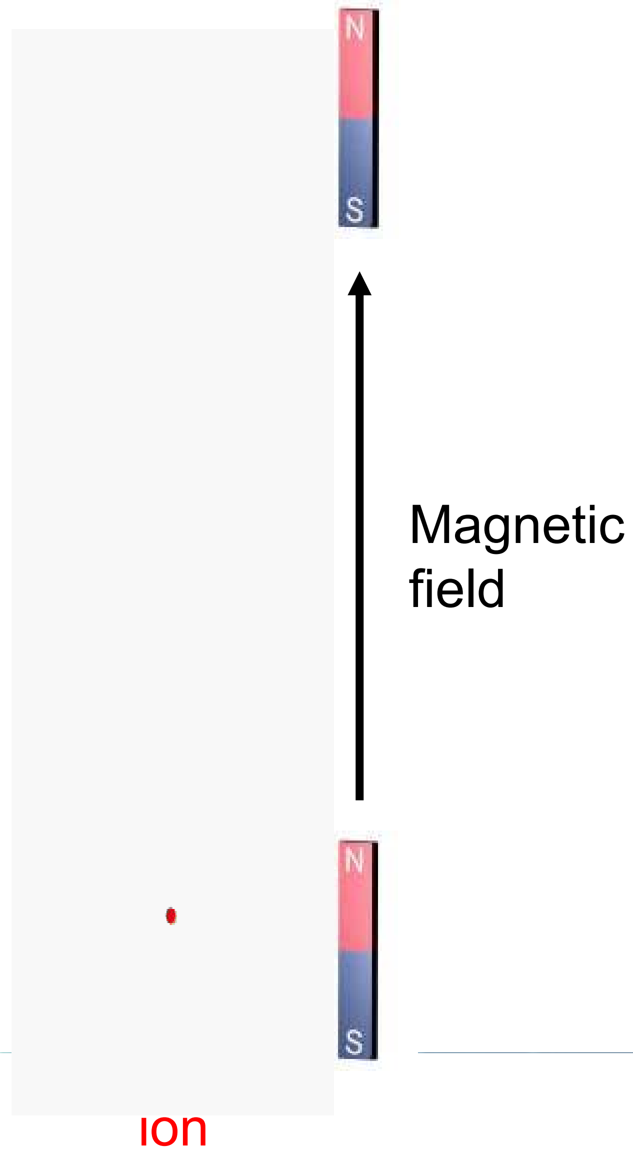


Magnetic Confinement

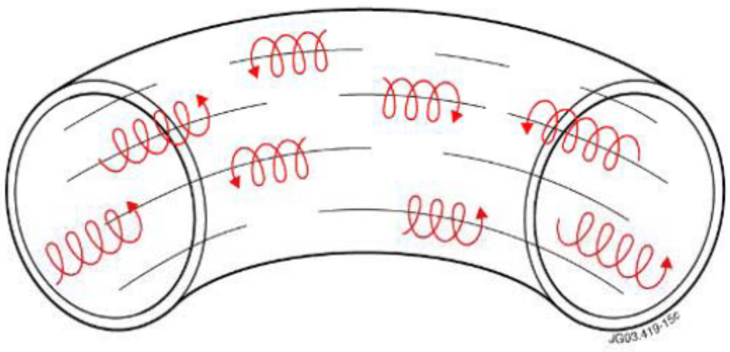


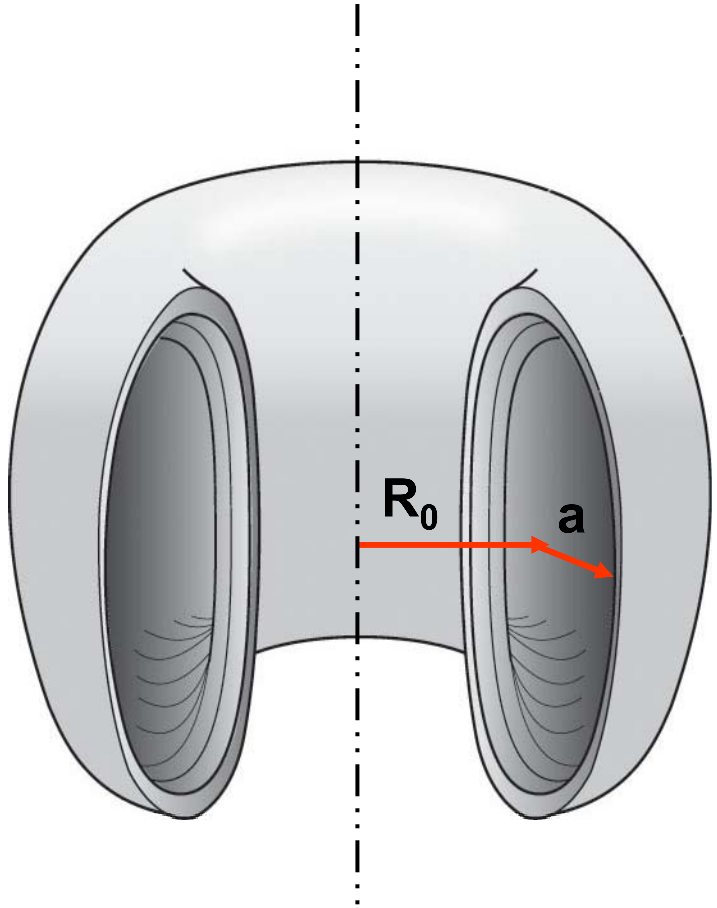
Magnetic Confinement





Confinement of the Plasma

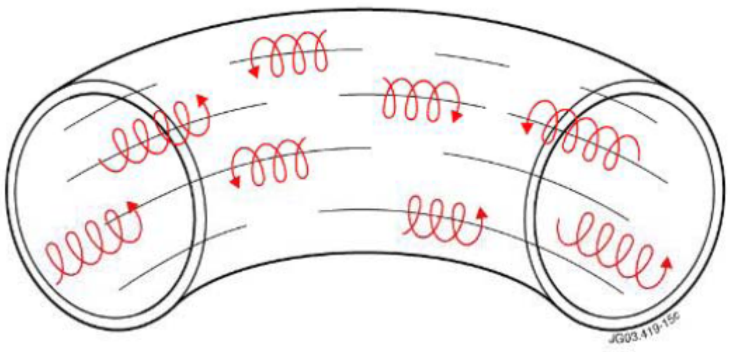


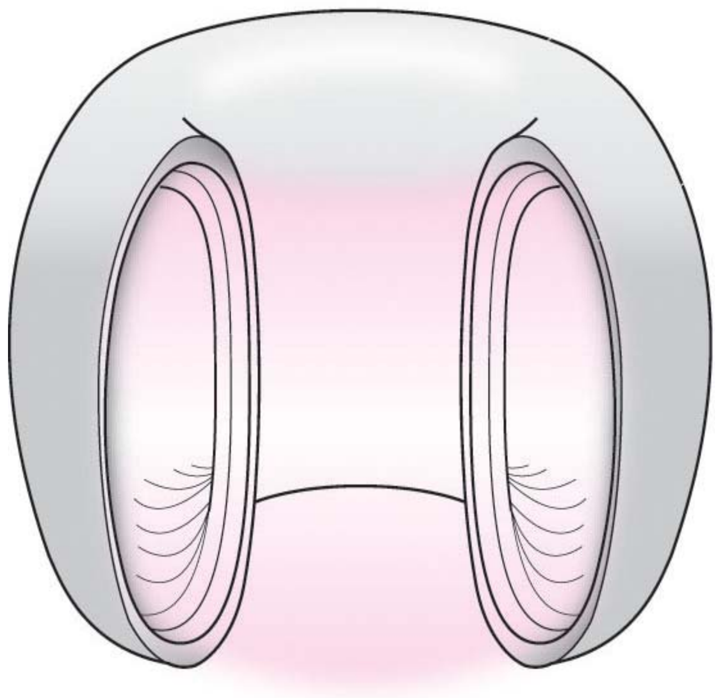


Donut-shaped vacuum vessel

R_0 = 1.8 m, a = 0.5 m in KSTAR

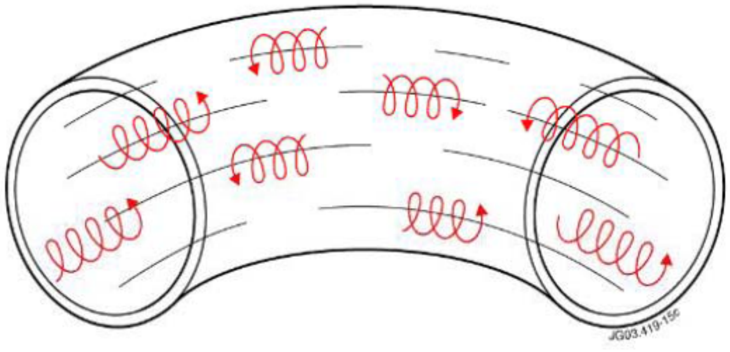
Confinement of the Plasma



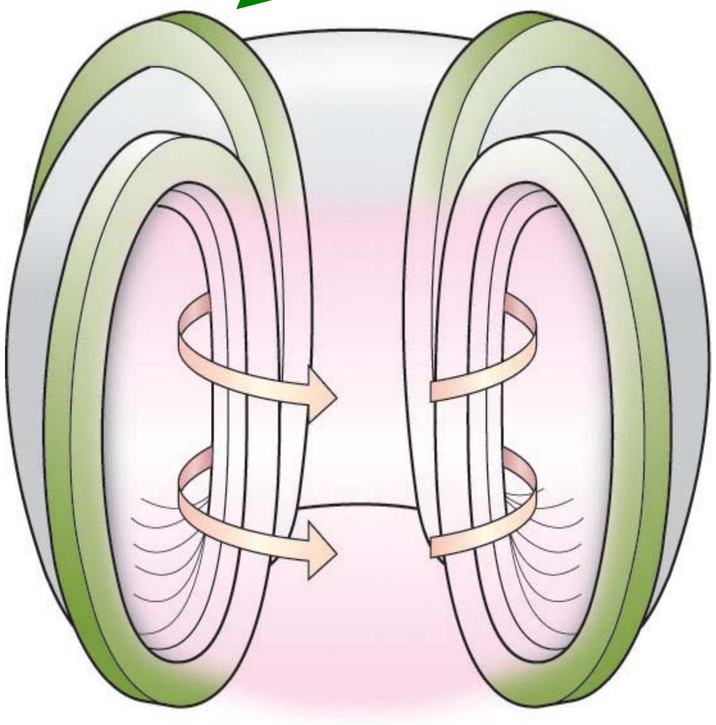


Plasma needs to be confined

Confinement of the Plasma



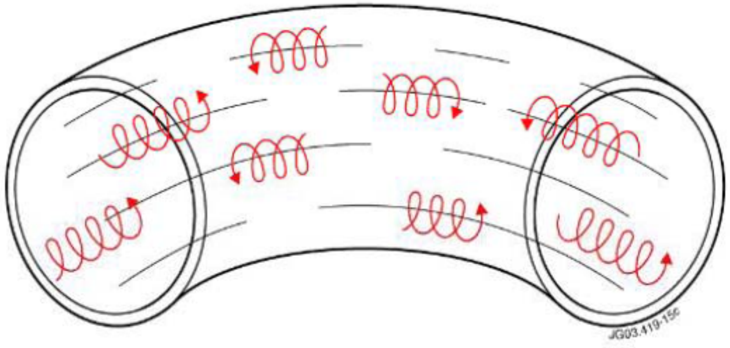
Toroidal Field (TF) coil

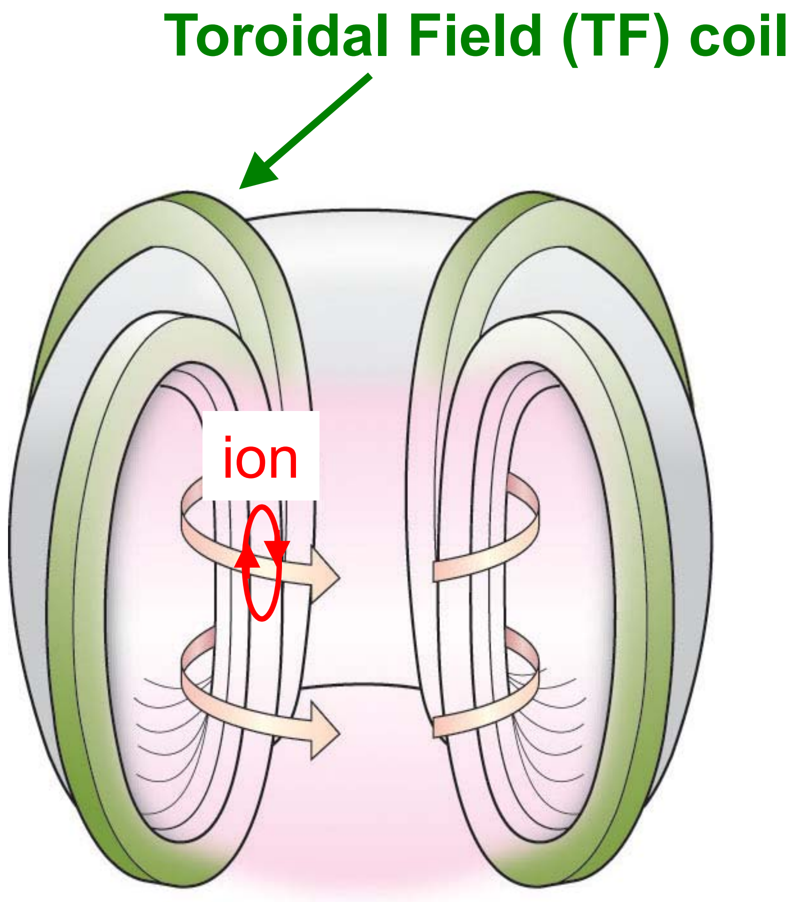


Applying toroidal magnetic field

3.5T in KSTAR

Confinement of the Plasma





Applying toroidal magnetic field

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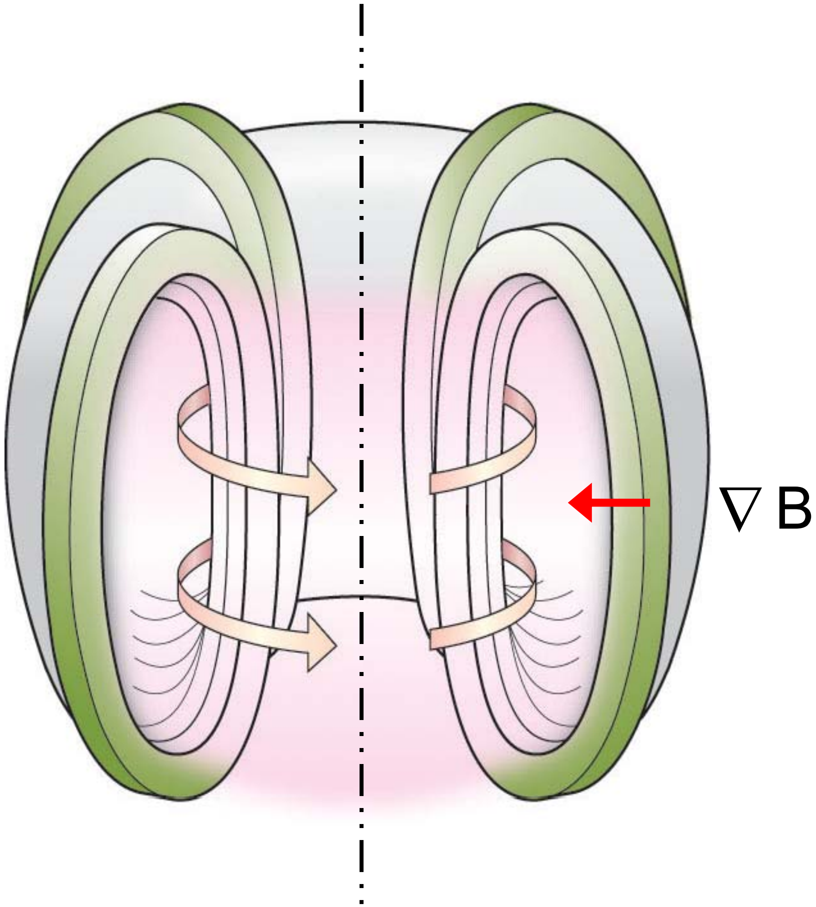
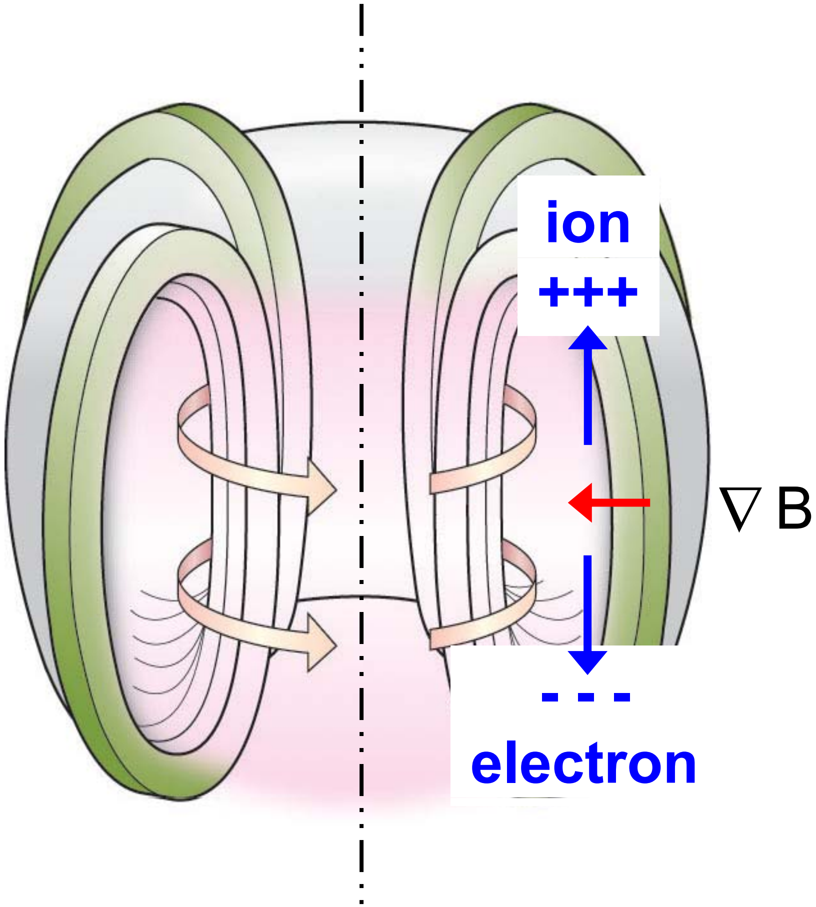
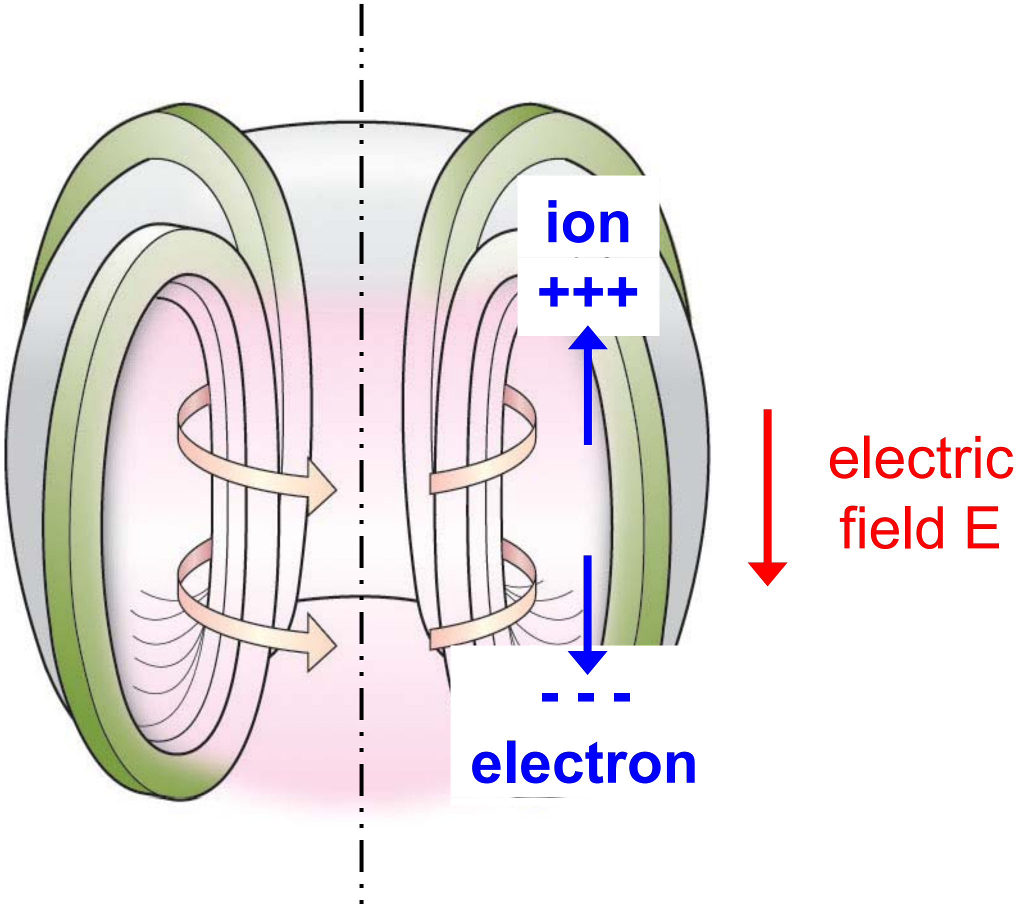
Confinement of the Plasma



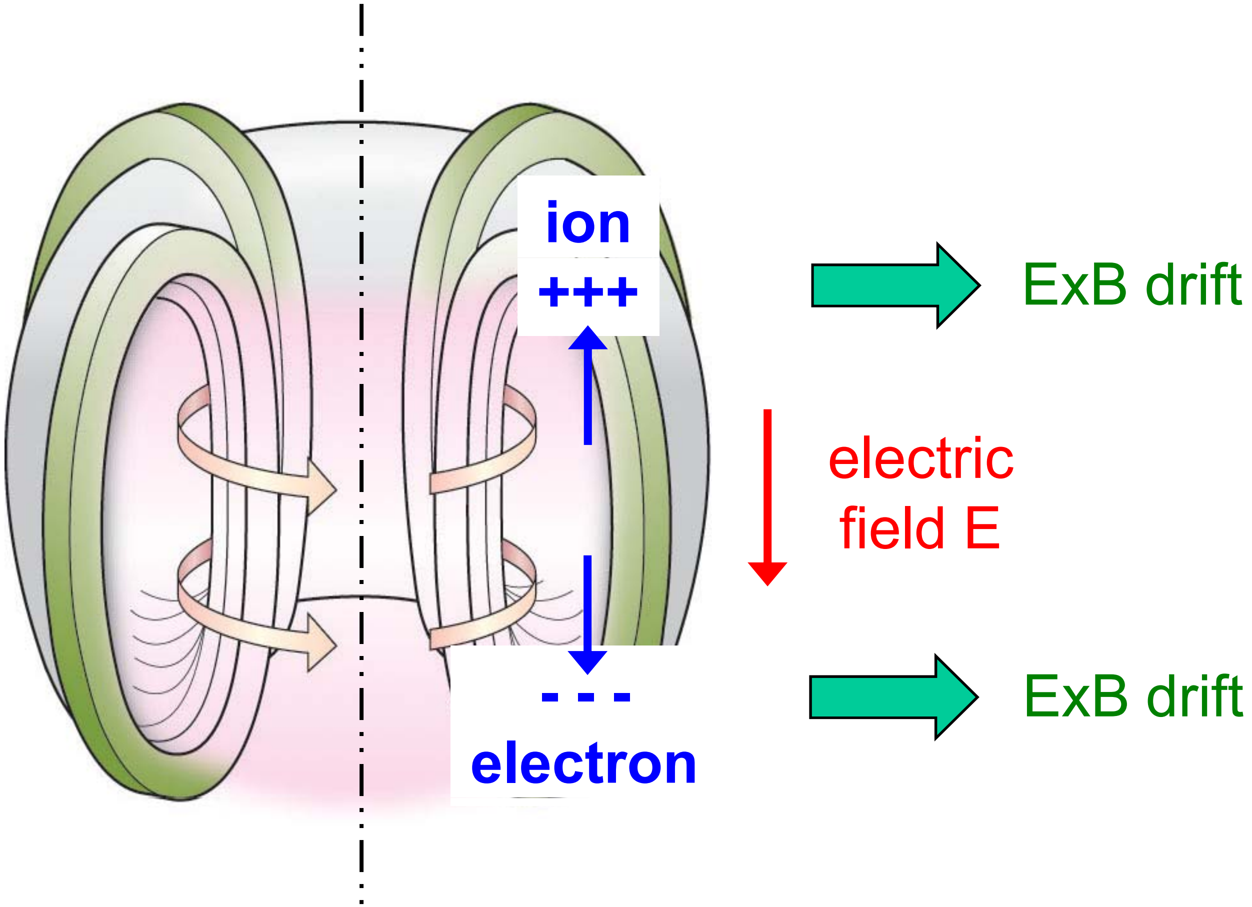
Confinement of the Plasma



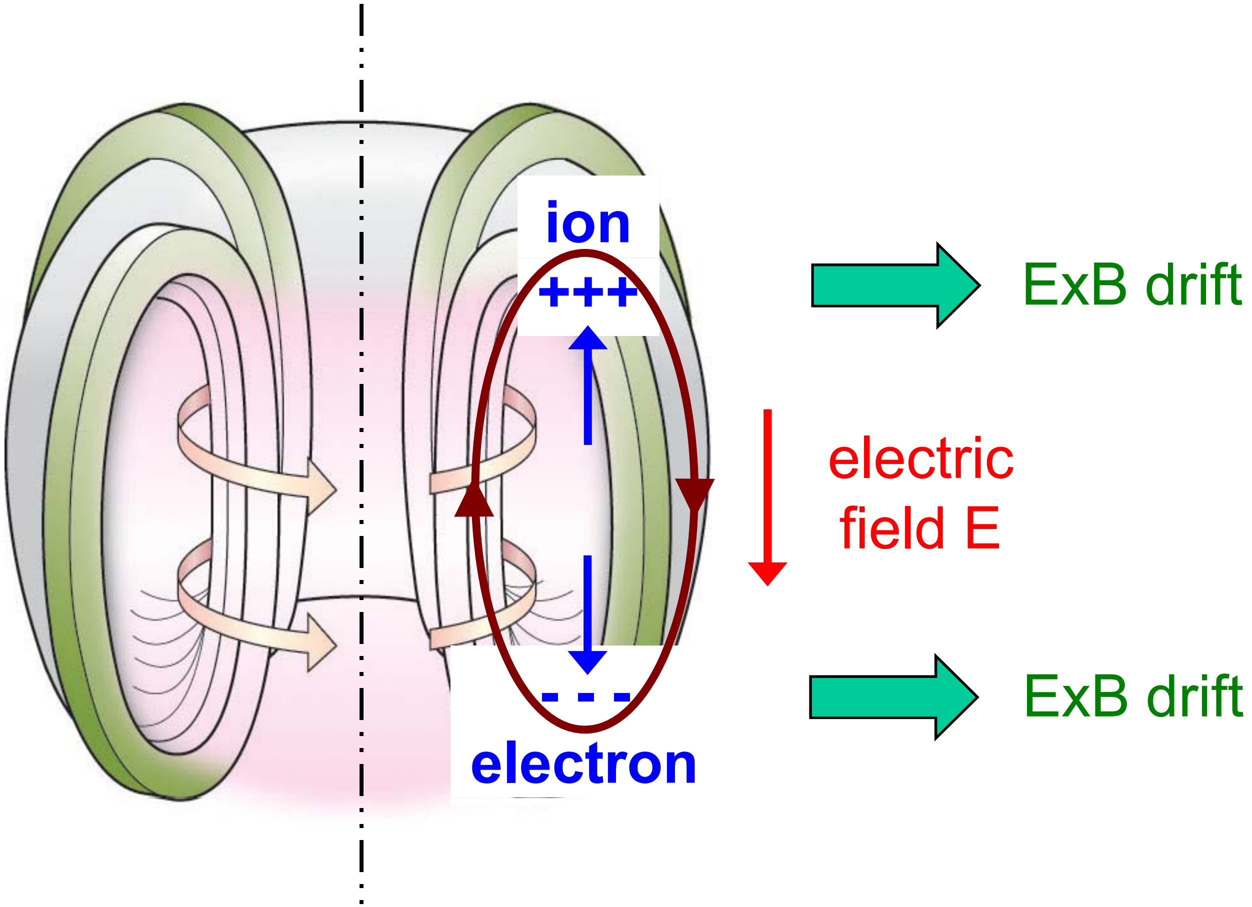
Confinement of the Plasma



Confinement of the Plasma



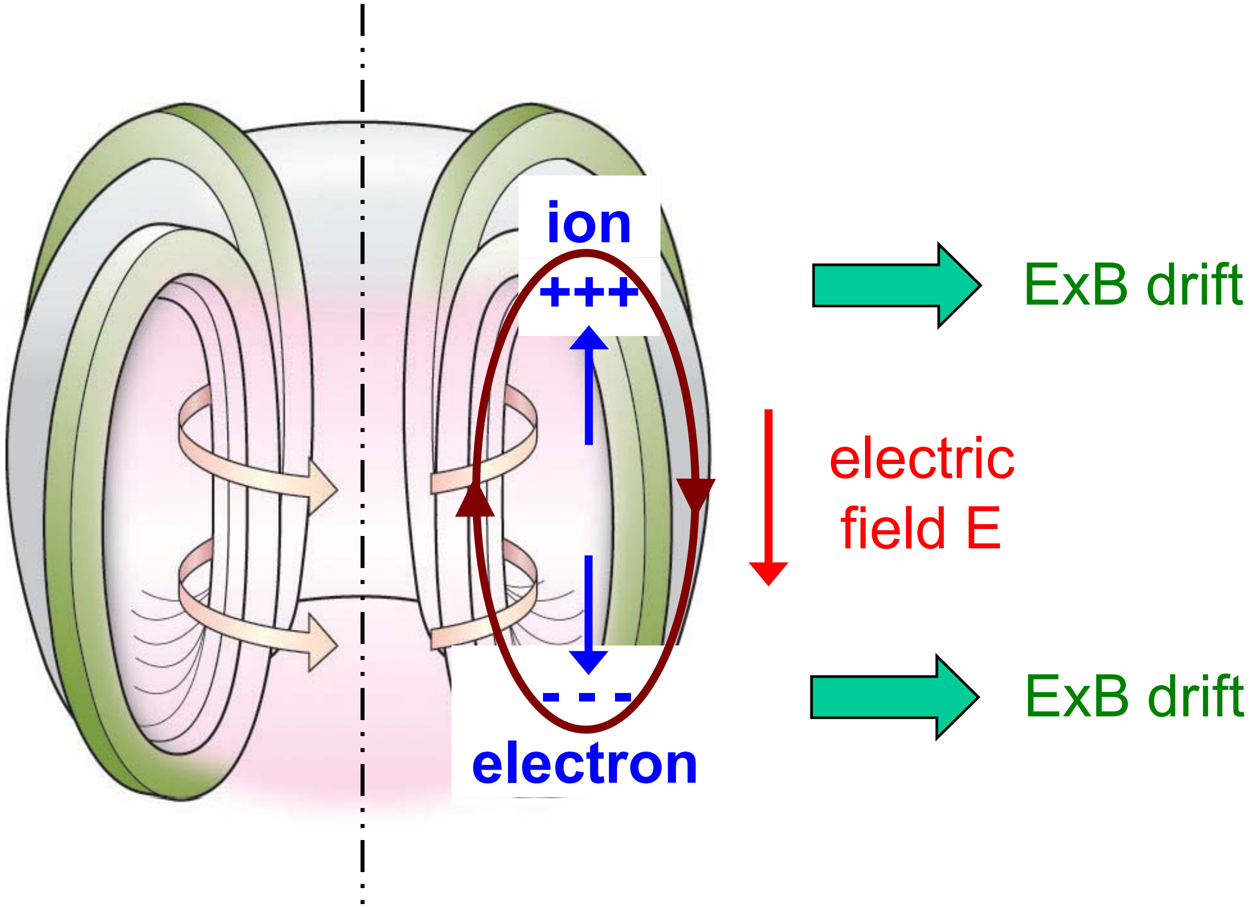
Confinement of the Plasma



Poloidal field should be applied

Then, how to?

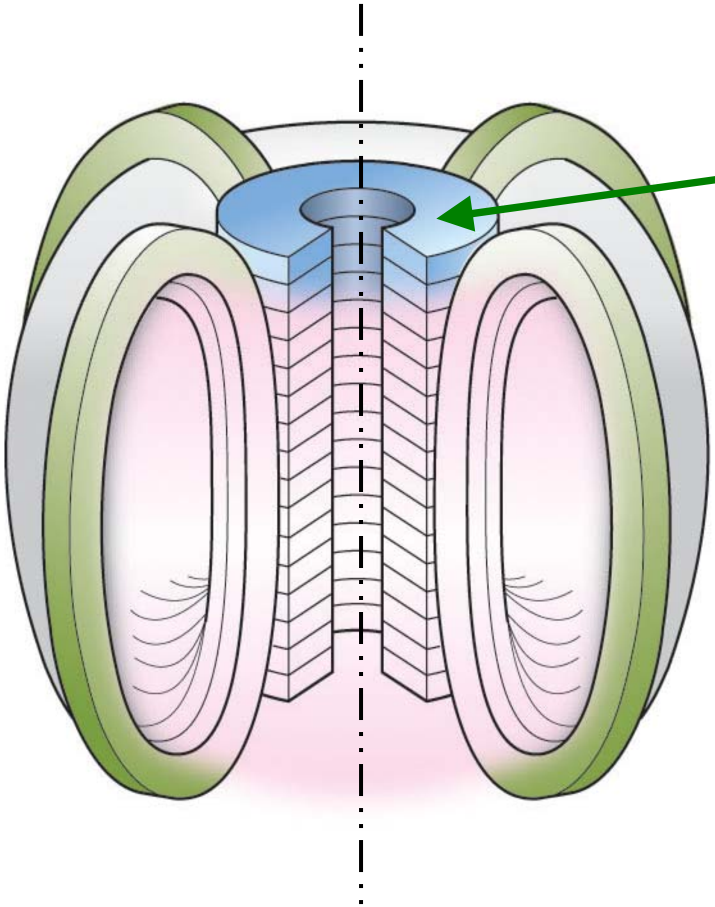
Confinement of the Plasma



Poloidal field should be applied

Drive the plasma current !

Confinement of the Plasma

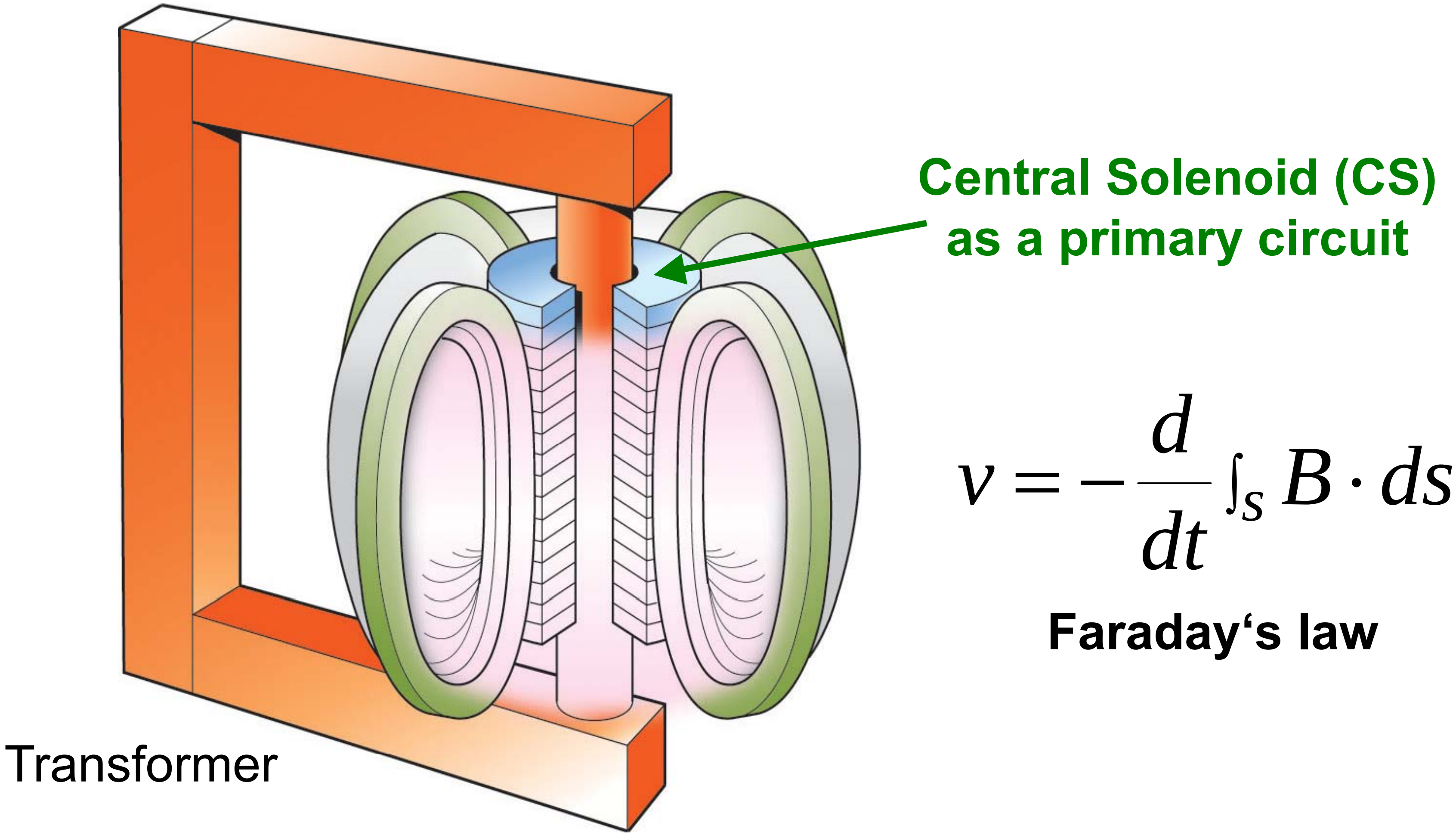


Central Solenoid (CS)
as a primary circuit

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

Faraday's law

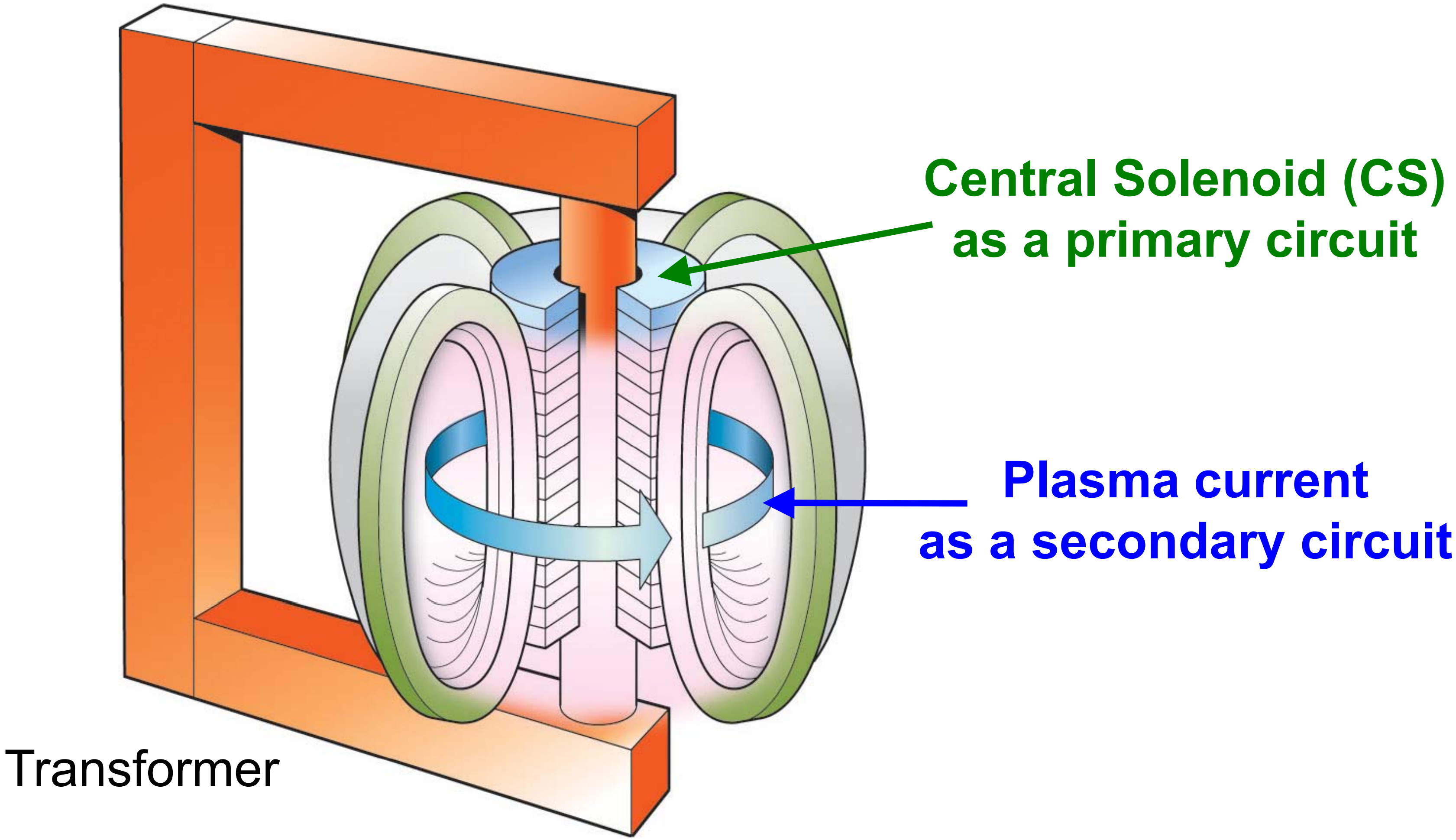
Confinement of the Plasma



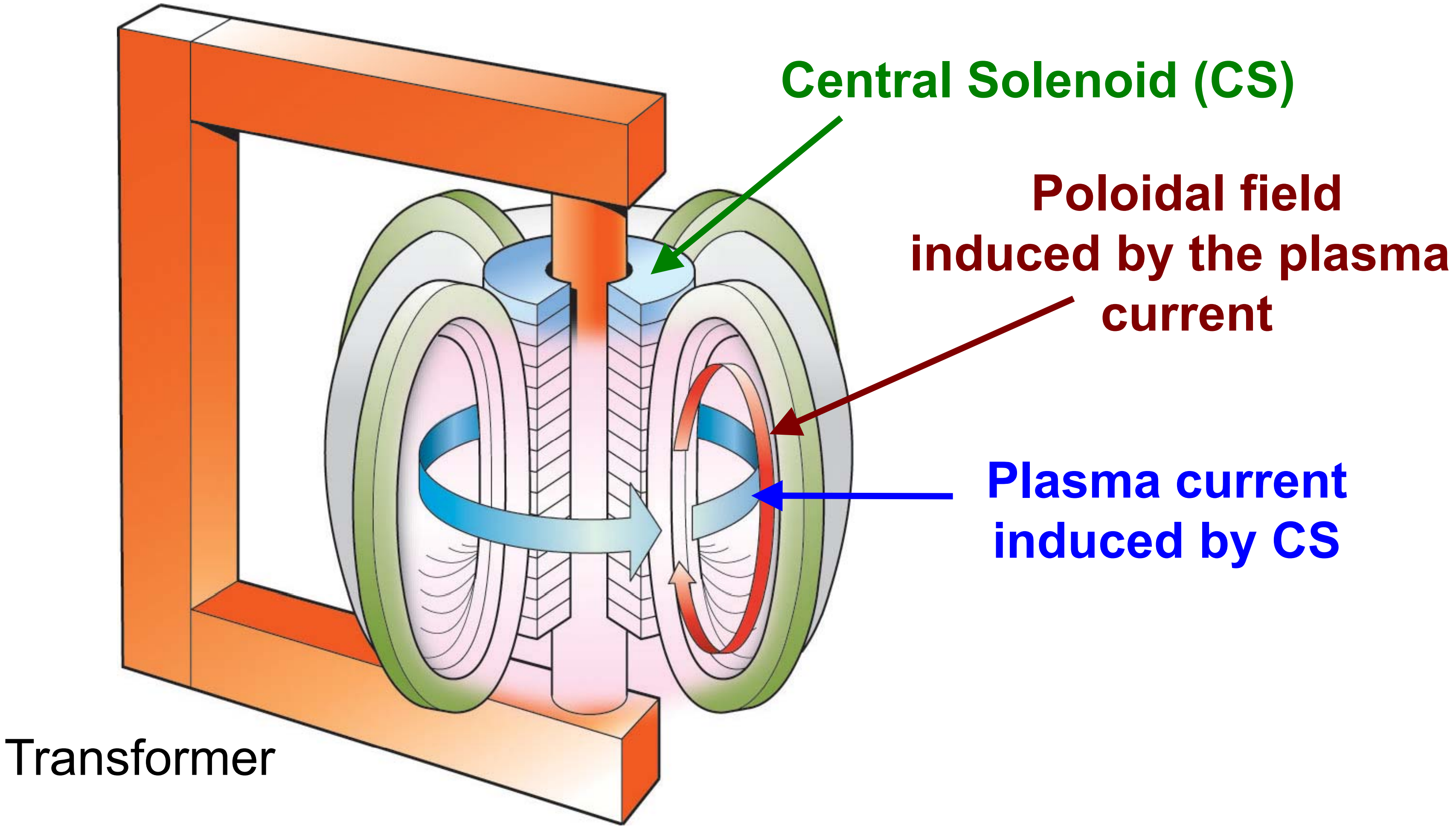
$$v = -\frac{d}{dt}\int_S B \cdot ds$$

Faraday's law

Confinement of the Plasma



Confinement of the Plasma



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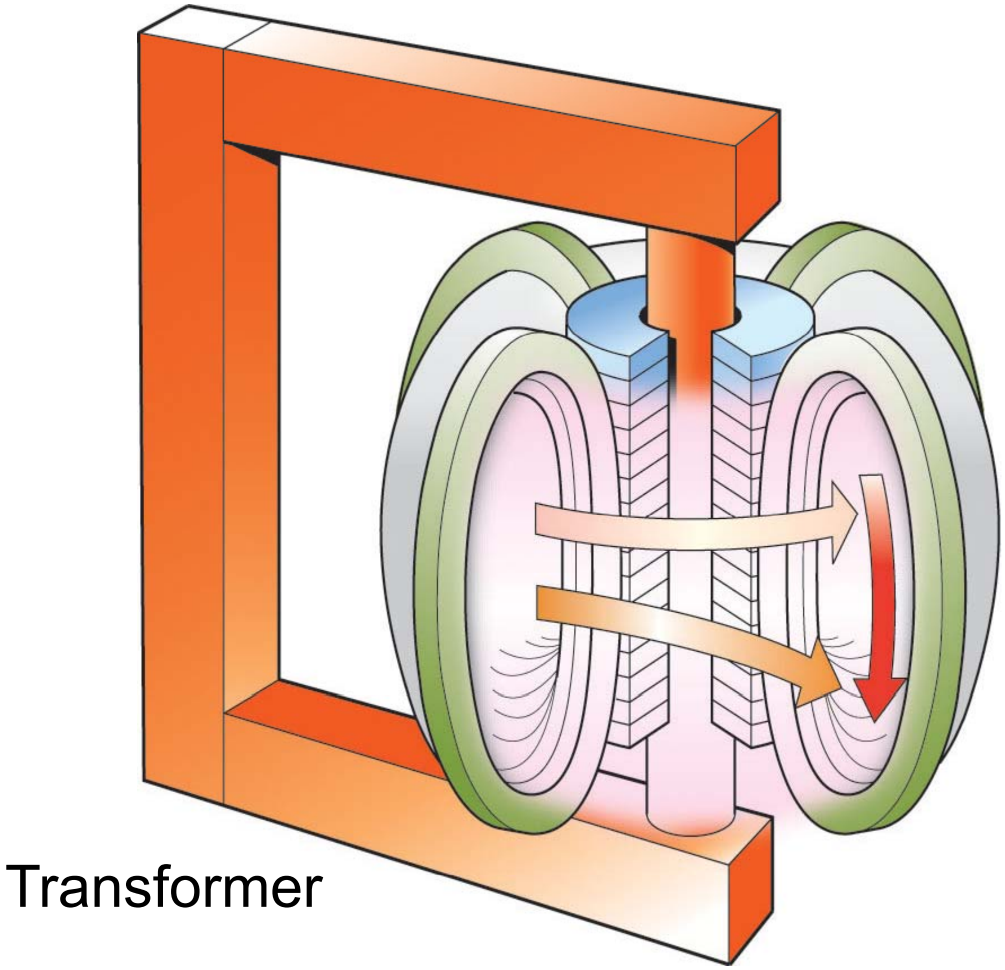
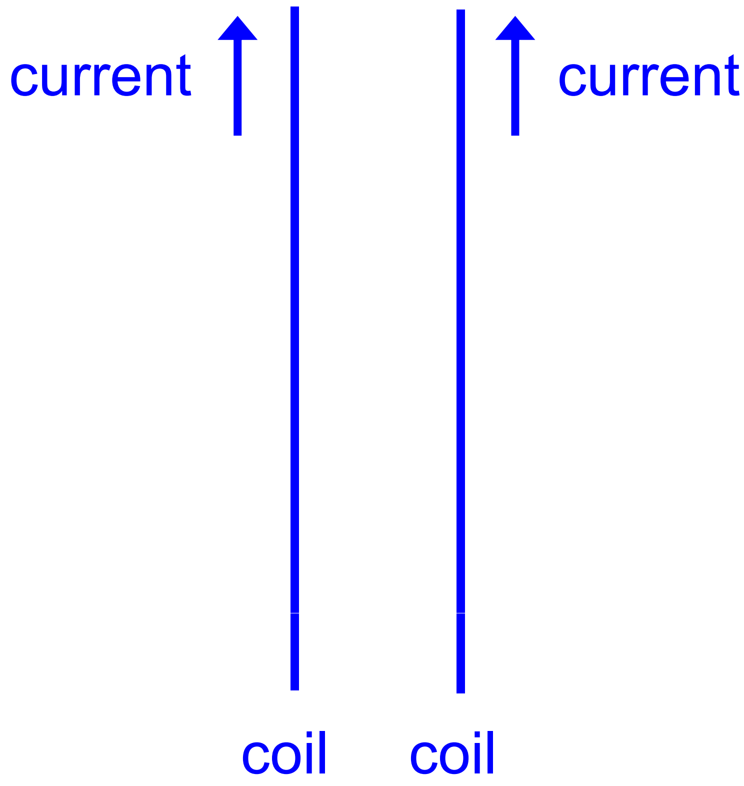
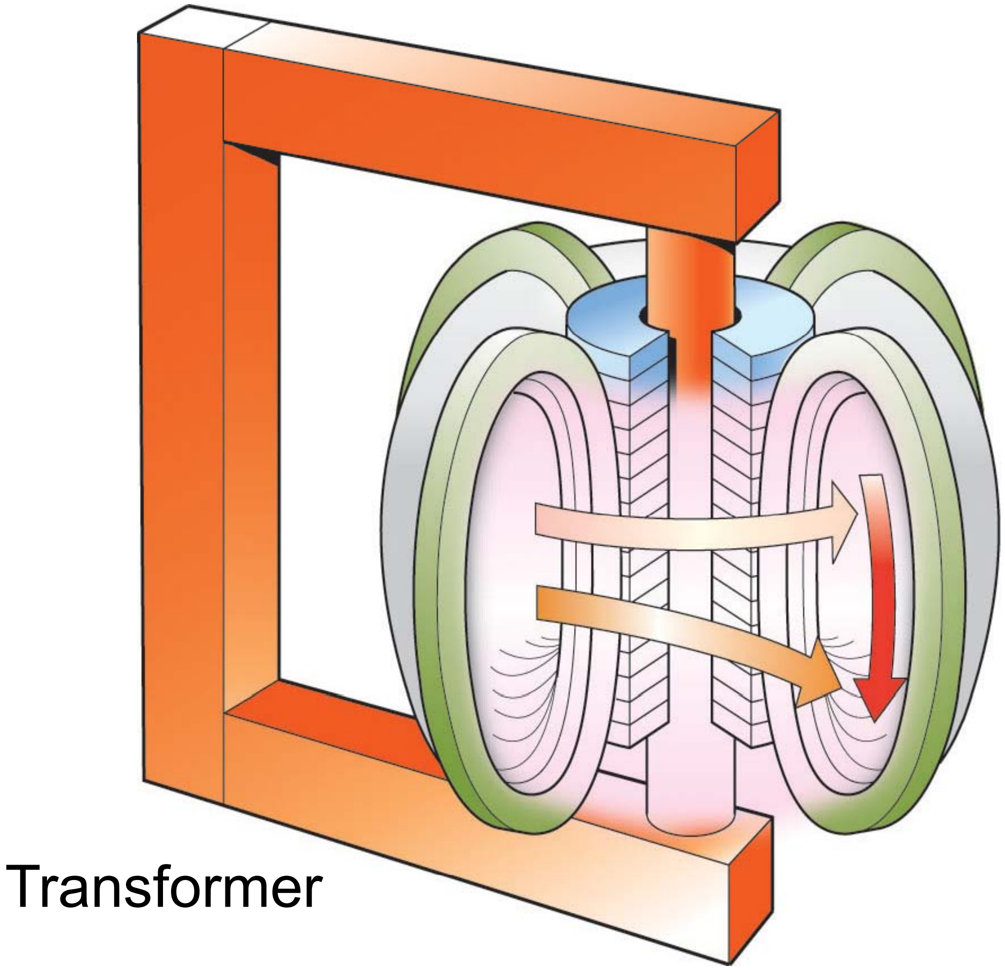
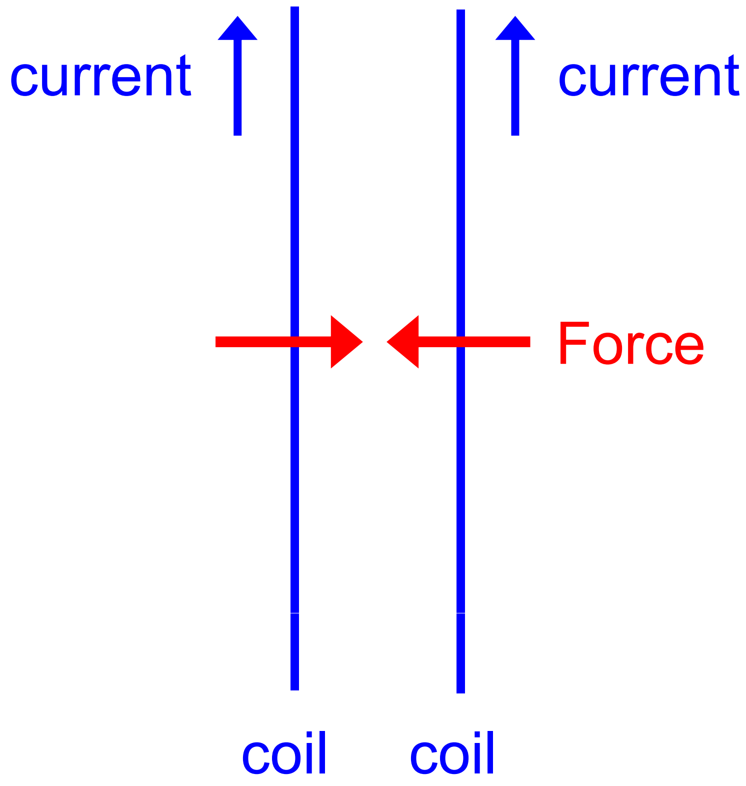


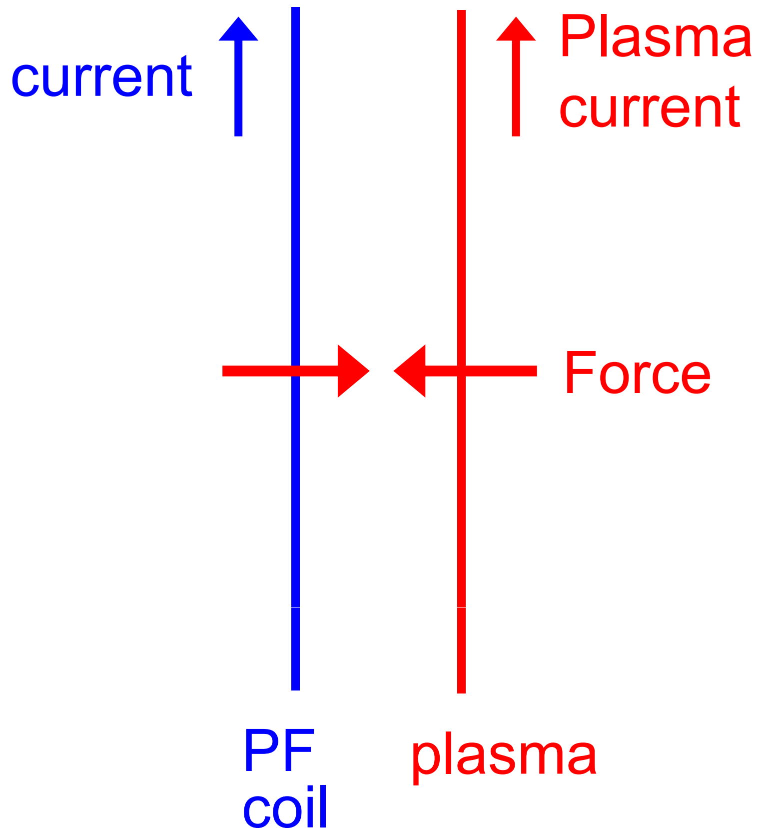


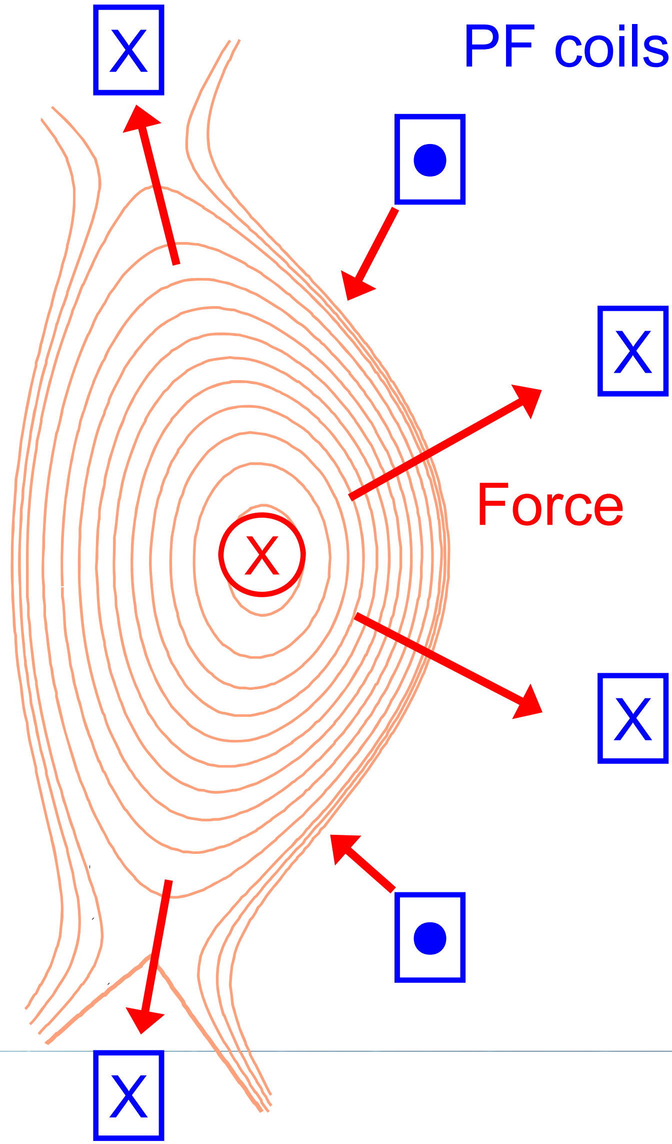
Confinement of the Plasma





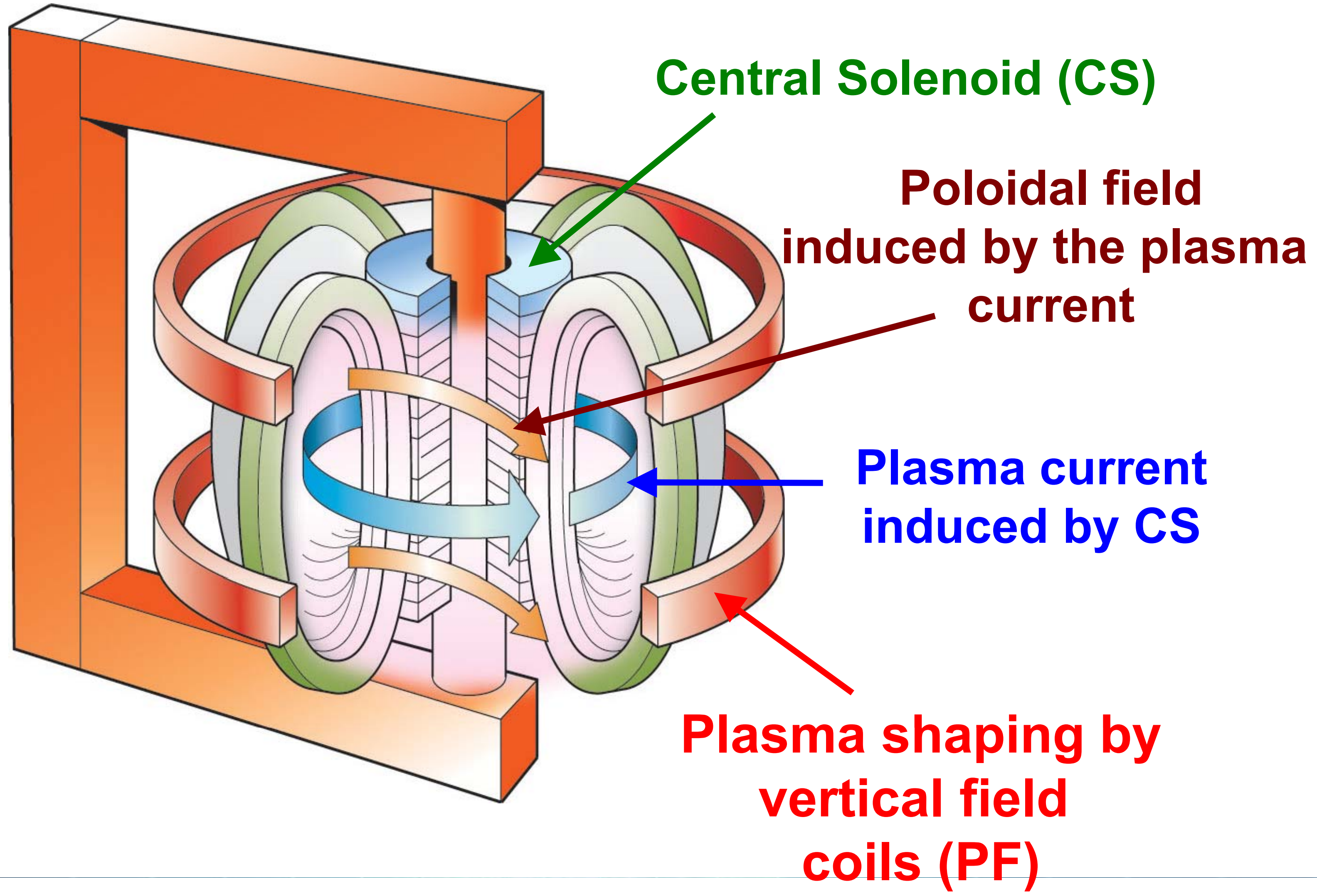
Confinement of the Plasma





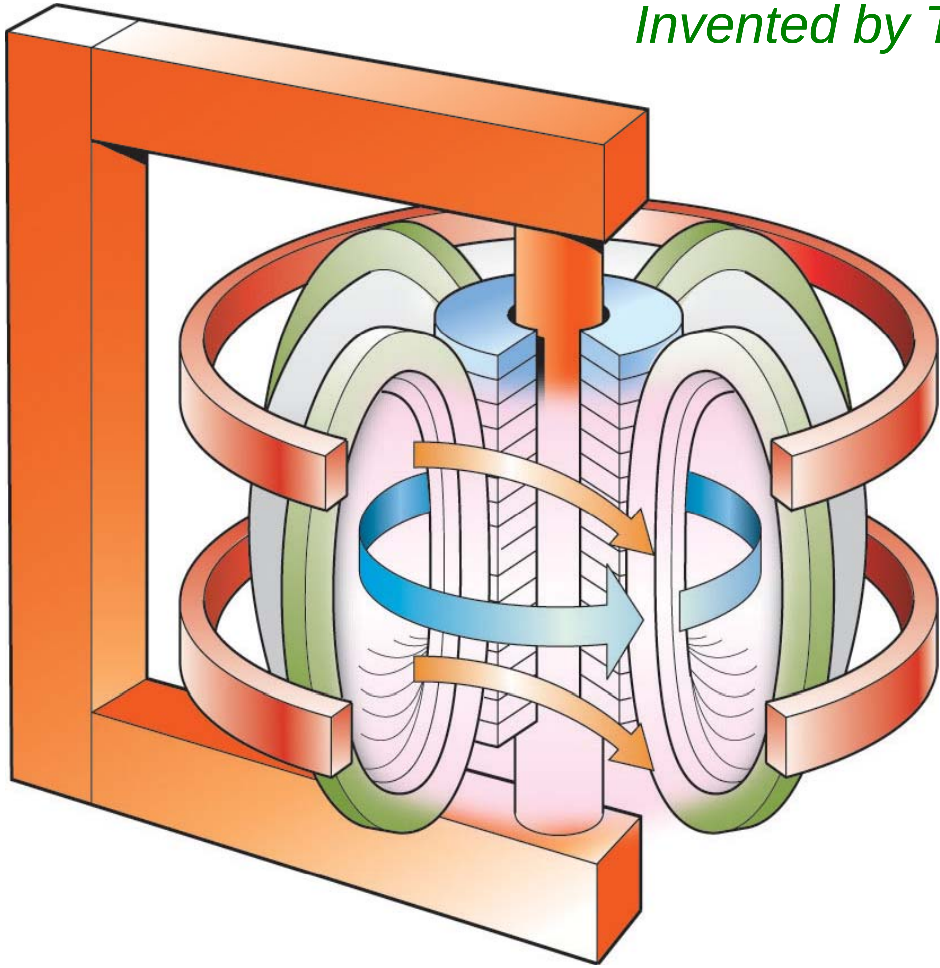
Plasma shaping by PF coils

Confinement of the Plasma



Tokamak

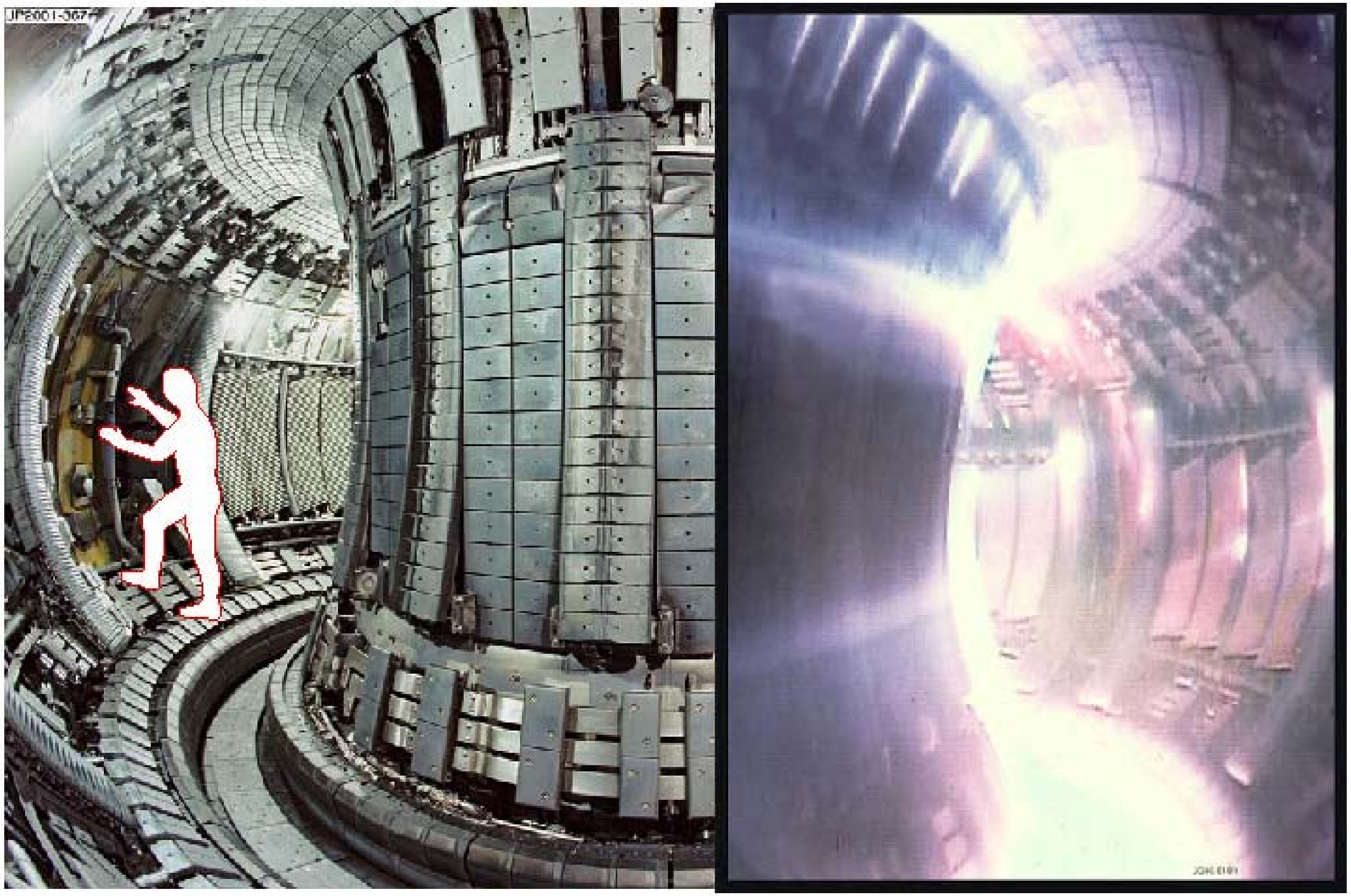
Invented by Tamm and Sakharov in 1952



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

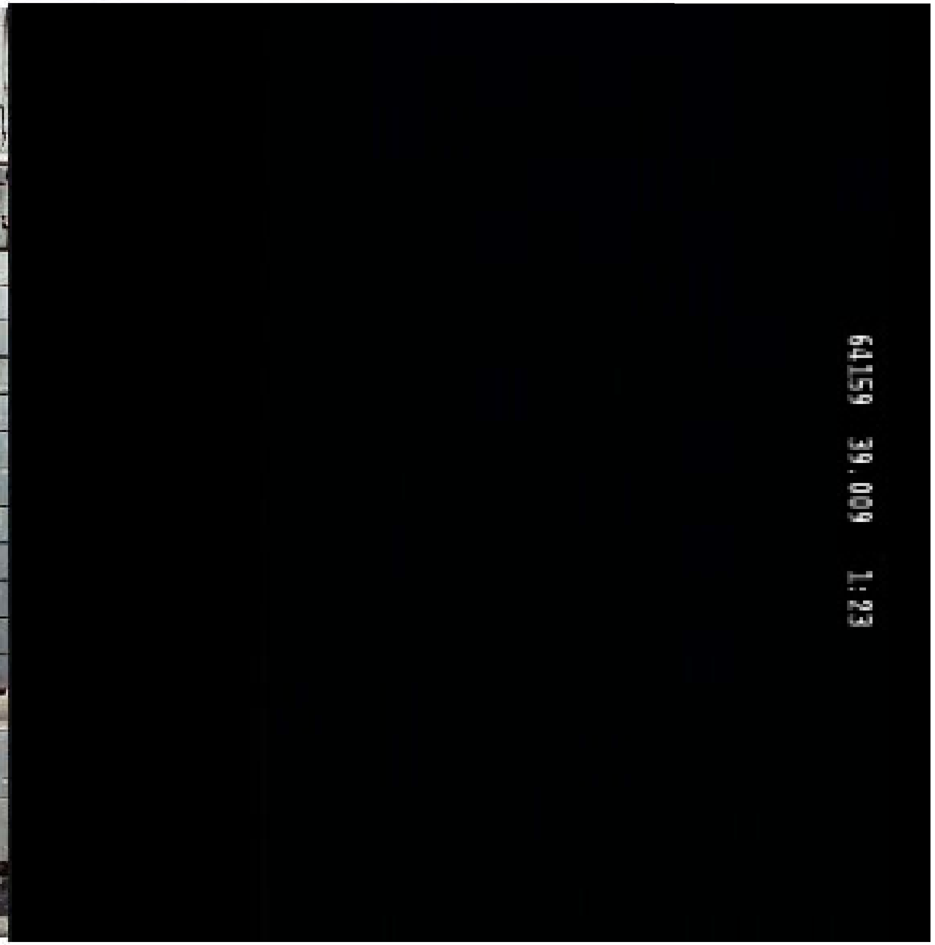
Tokamak

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



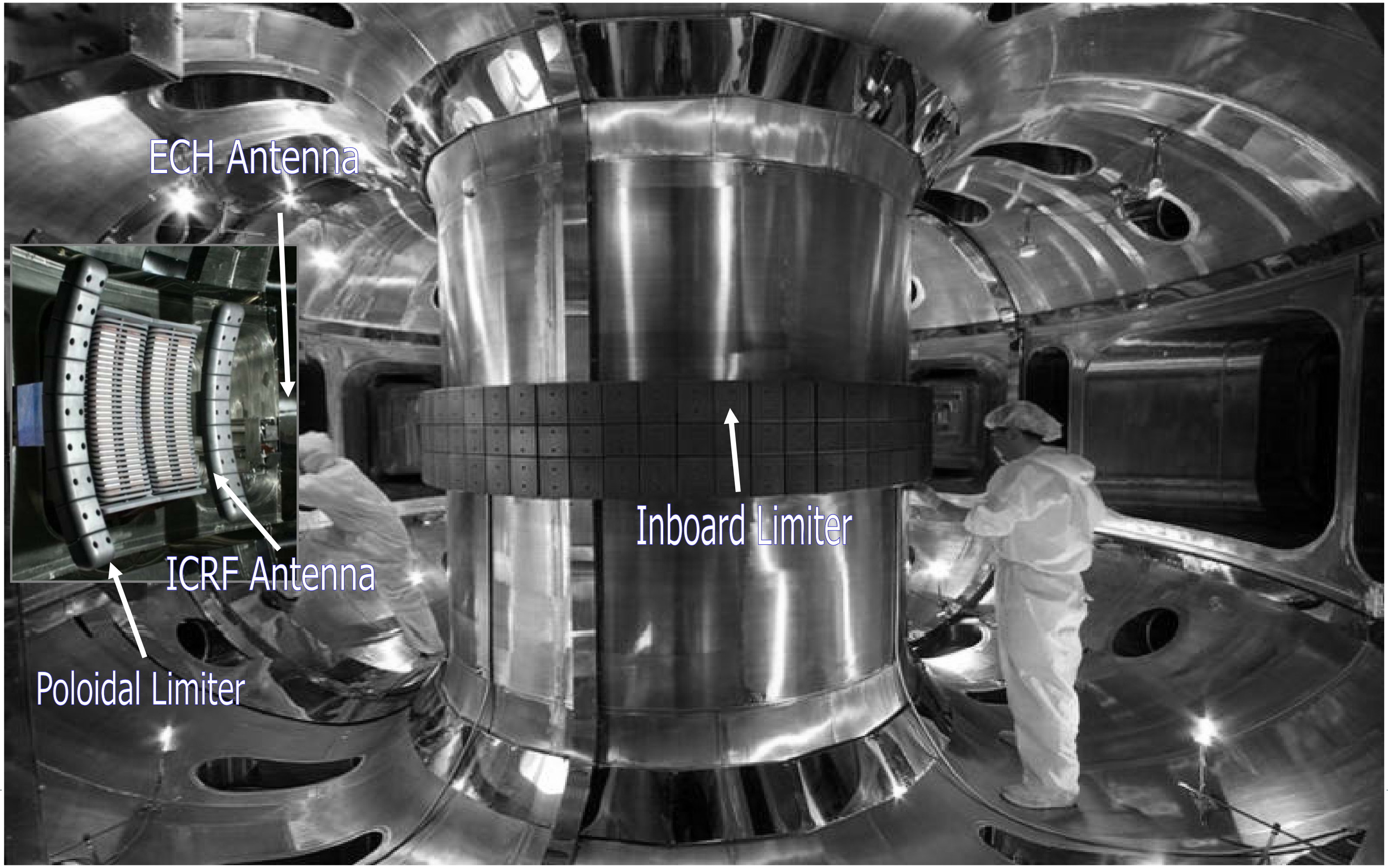
Tokamak

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

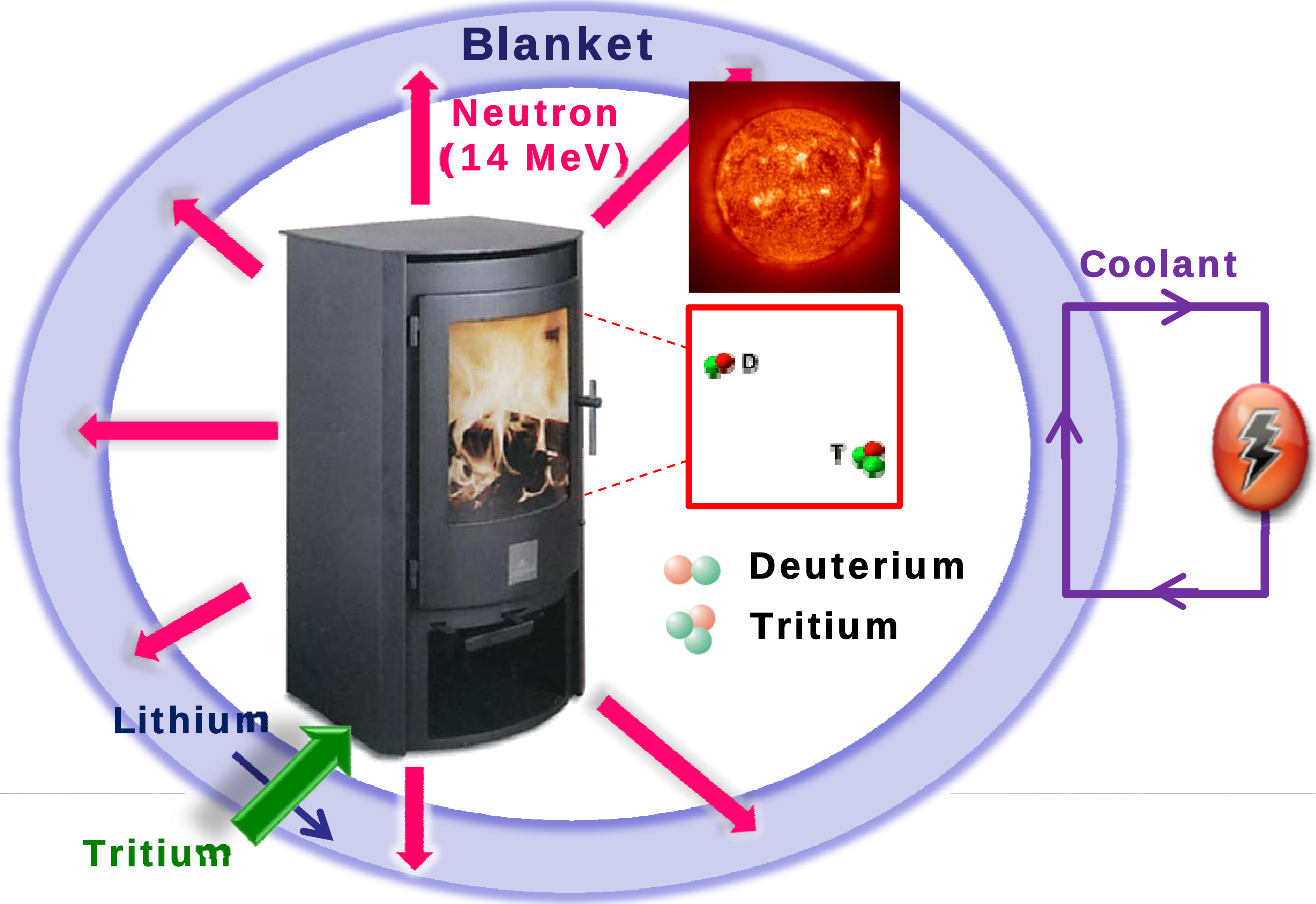


Tokamak

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



Fusion Power Plant System



Blanket

Blanket Functions:

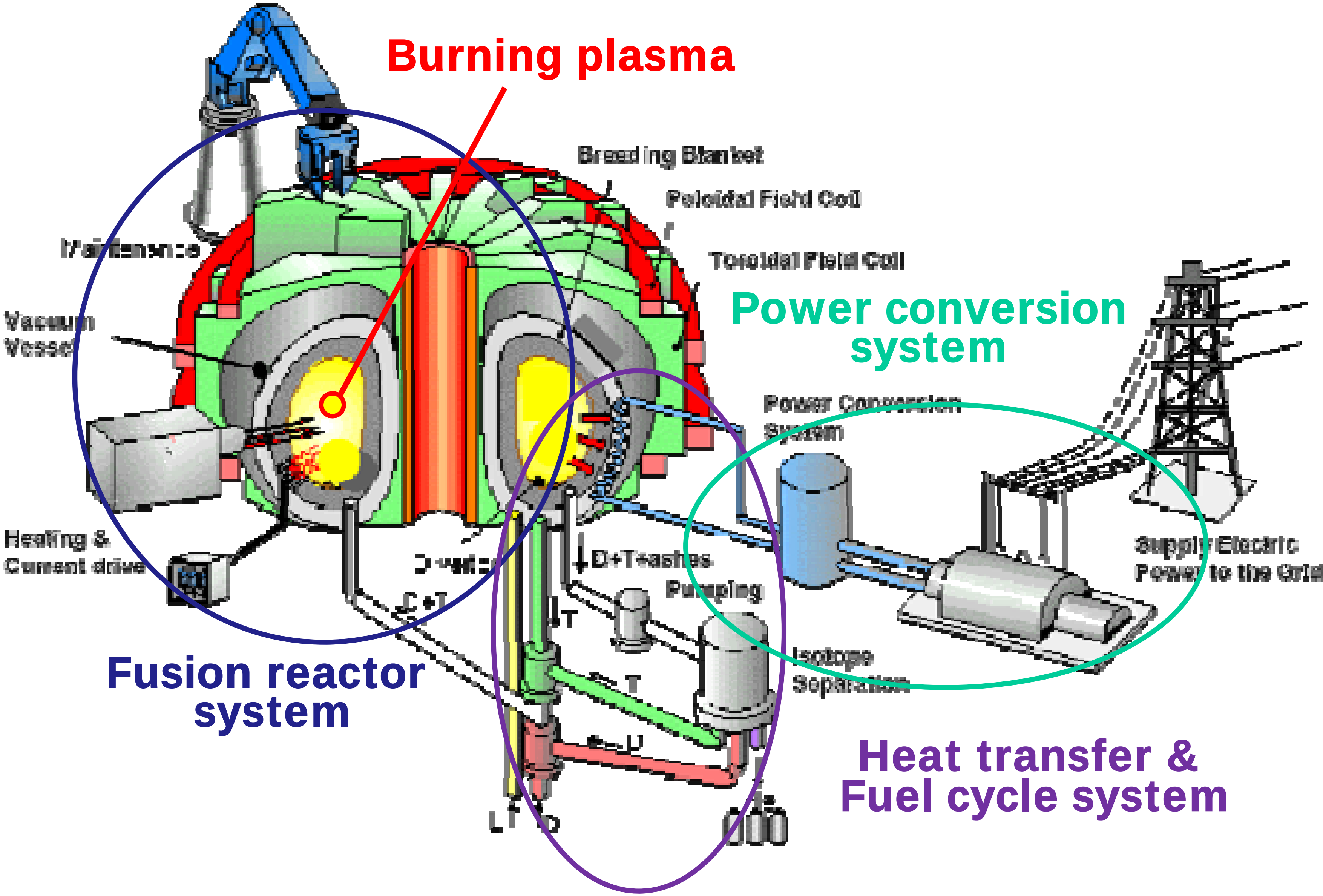
A. Power Extraction
   - Convert kinetic energy of neutrons and secondary gamma rays into heat
   - Absorb plasma radiation on the first wall
   - Extract the heat (at high temperature, for energy conversion)

B. Tritium Breeding
   - Tritium breeding, extraction, and control
   - Must have lithium in some form for tritium breeding

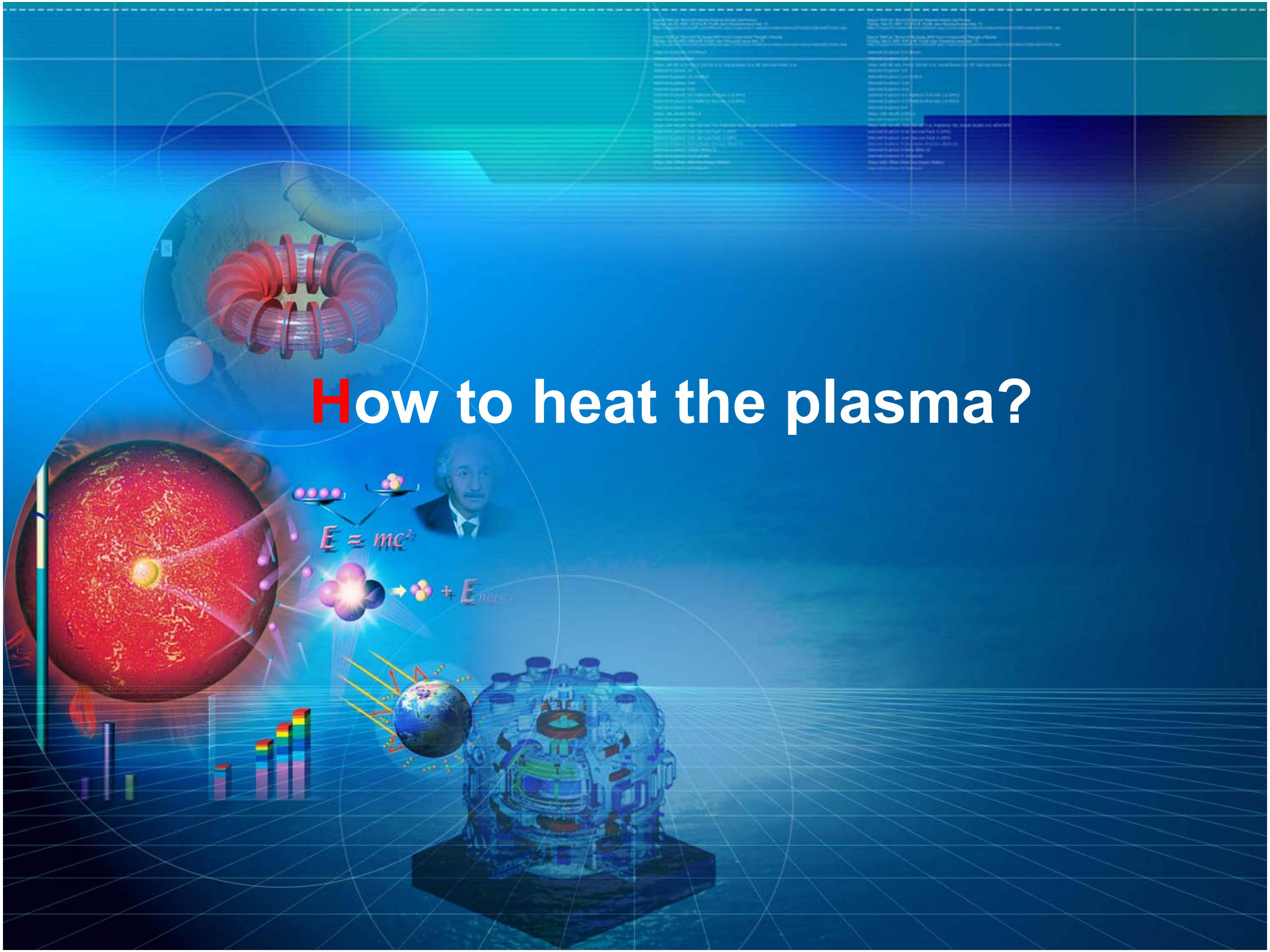
C. Physical Boundary for the Plasma (First wall)
   - Physical boundary surrounding the plasma, inside the vacuum vessel
   - Provide access for plasma heating, fueling
   - Must be compatible with plasma operation
   - Innovative blanket concepts can improve plasma stability and confinement

D. Radiation Shielding of the Vacuum Vessel

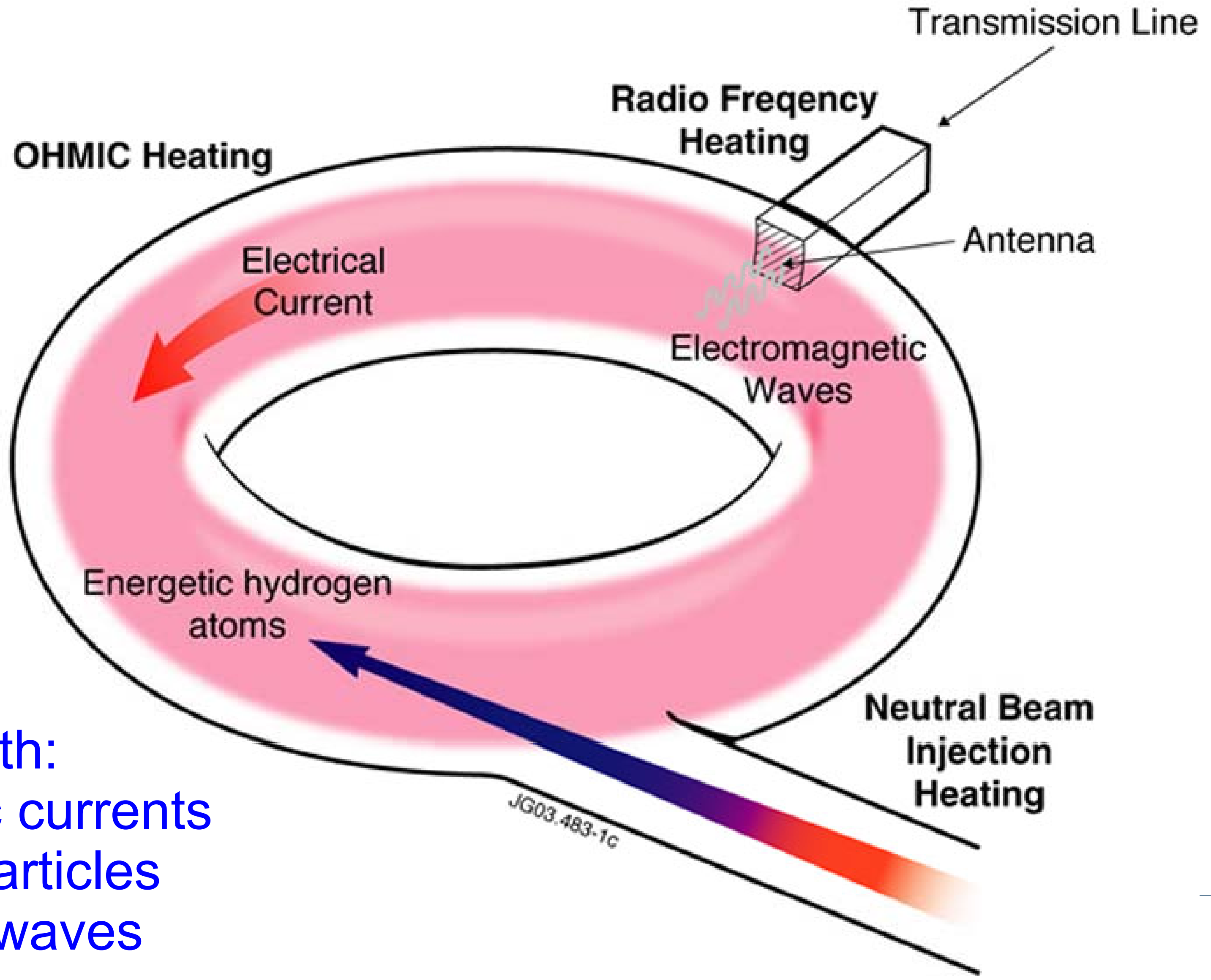
Fusion Power Plant System



How to heat the plasma?



Plasma Heating



Heating with:

- ohmic currents
- fast particles
- microwaves

Plasma Heating – Neutral Beam Injection (NBI)

Injection of a beam of neutral fuel atoms (H, D, T) at high energies (E_b > 50 keV)

⇓

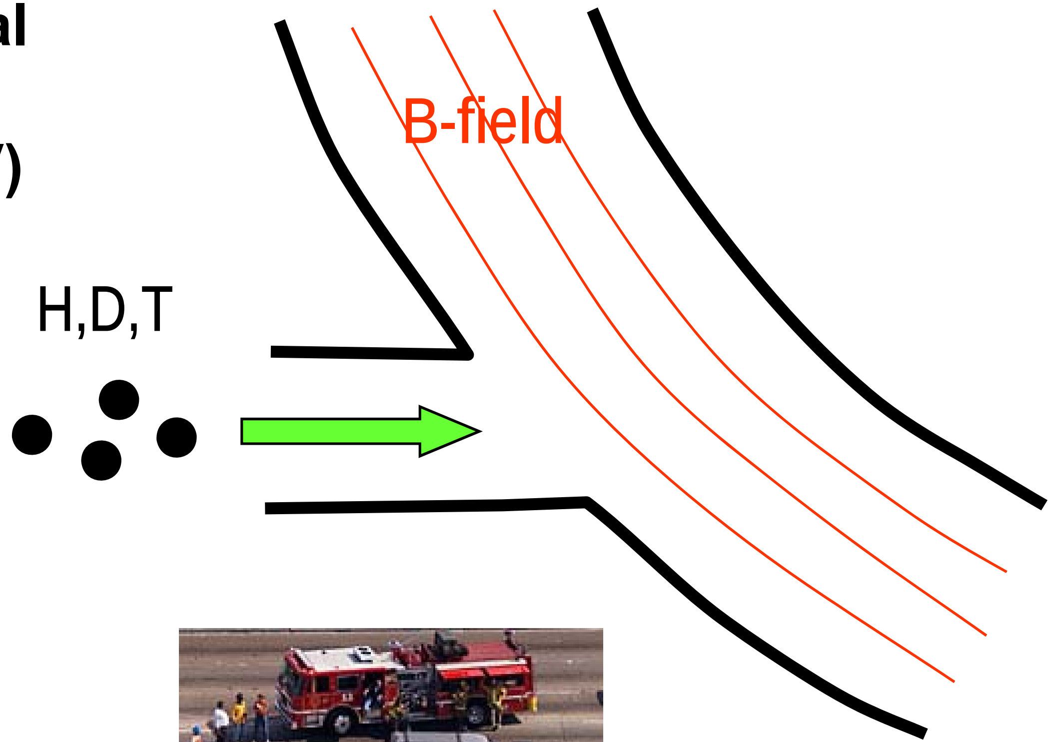
Ionisation in the plasma

⇓

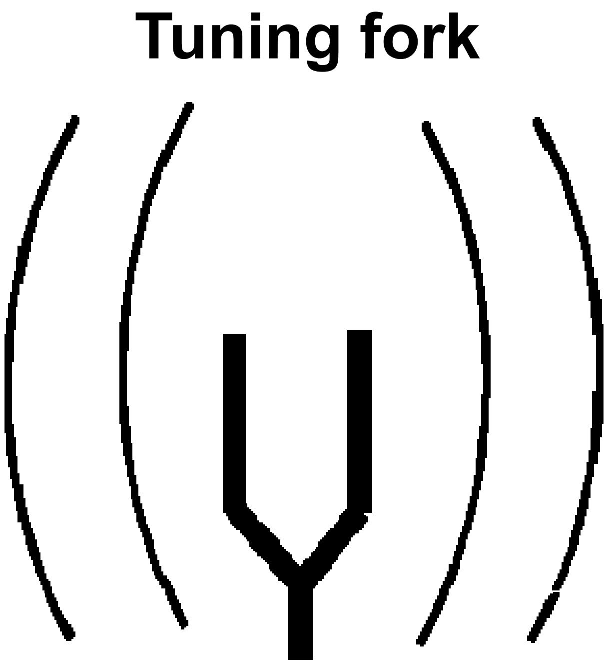
Beam particles confined

⇓

Collisional slowing down

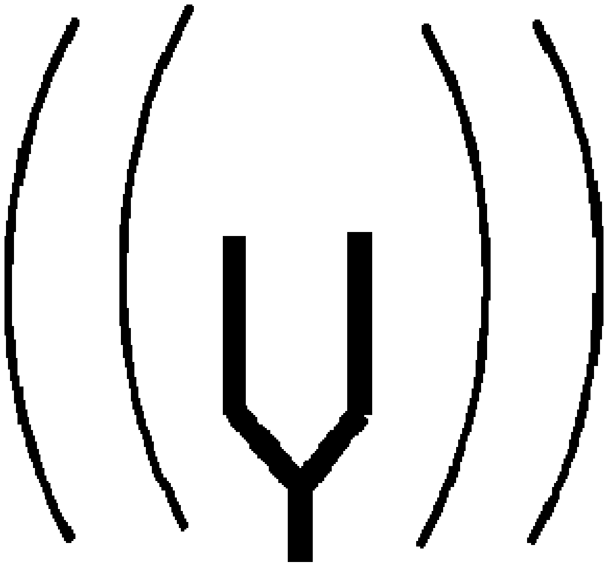


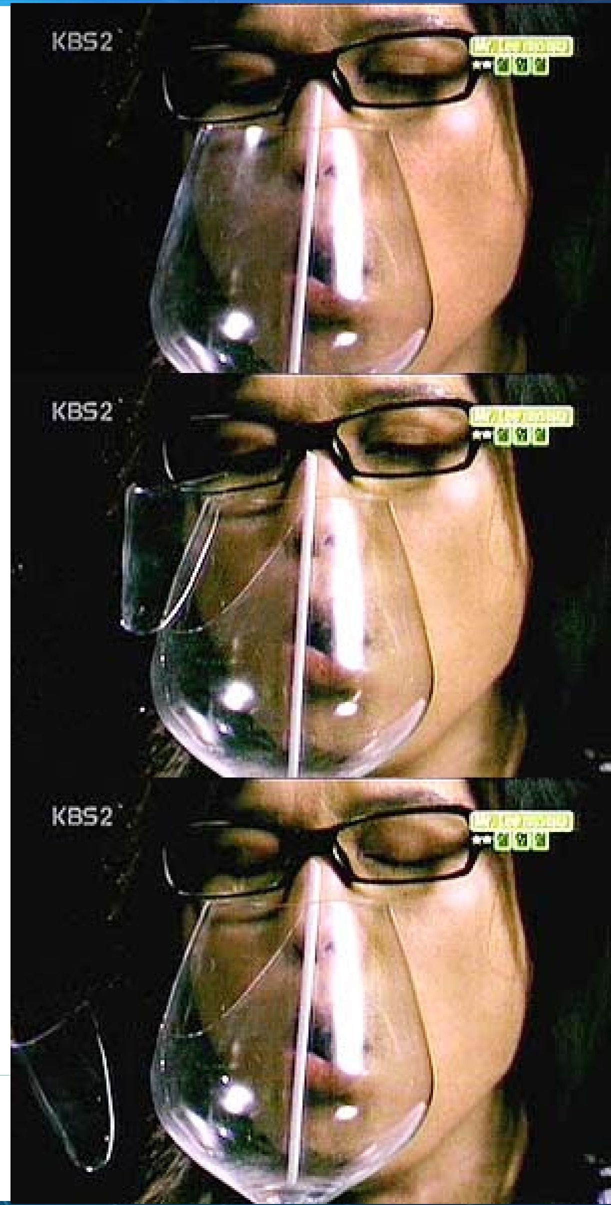
Plasma Heating – Wave (ICRH, ECRH, LHH)



Plasma Heating – Wave (ICRH, ECRH, LHH)

Tuning fork





Resonance

Plasma Heating – Wave (ICRH, ECRH, LHH)

Excitation of plasma wave (frequency w) near plasma edge

⇓

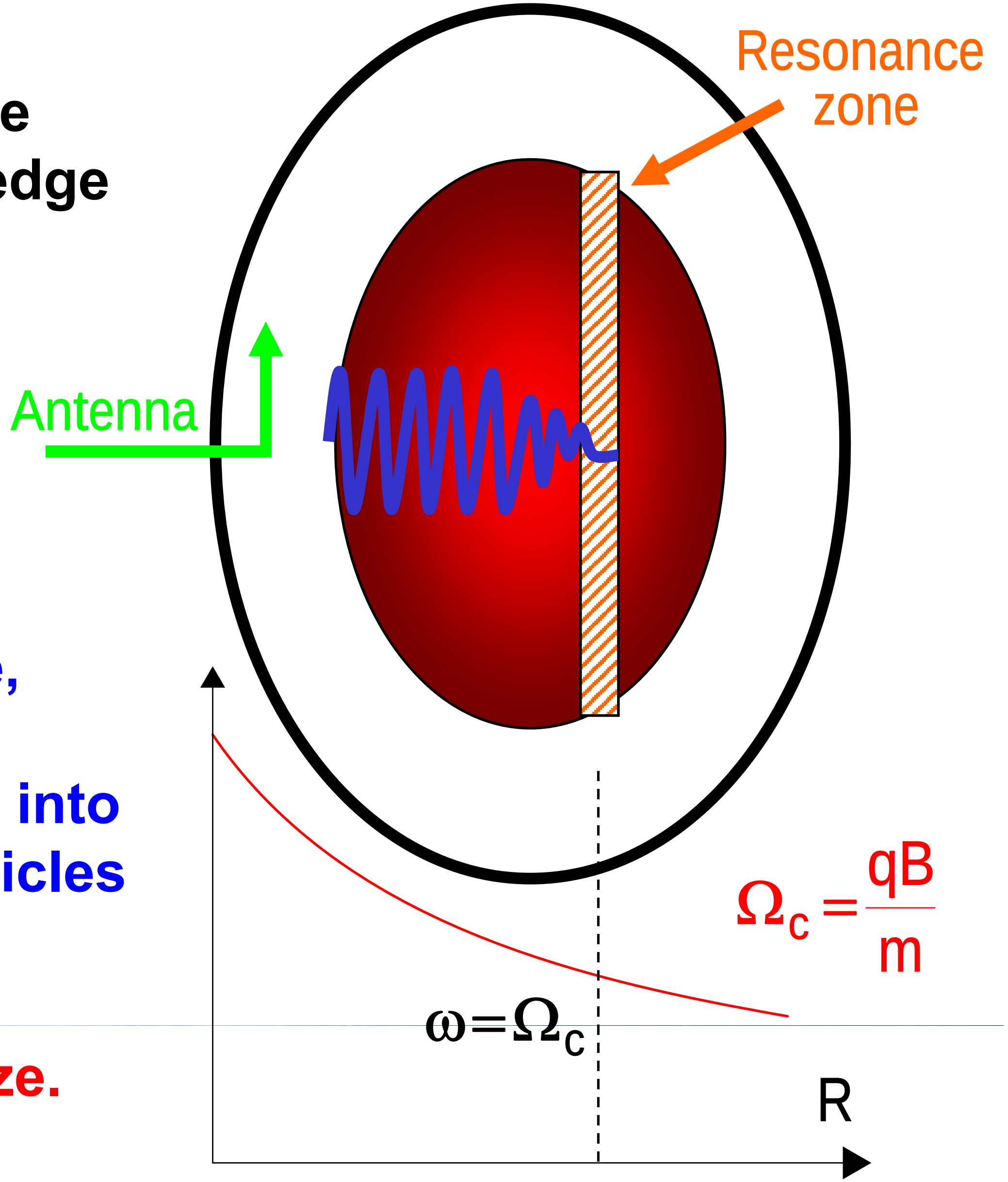
wave transports power into the plasma center

⇓

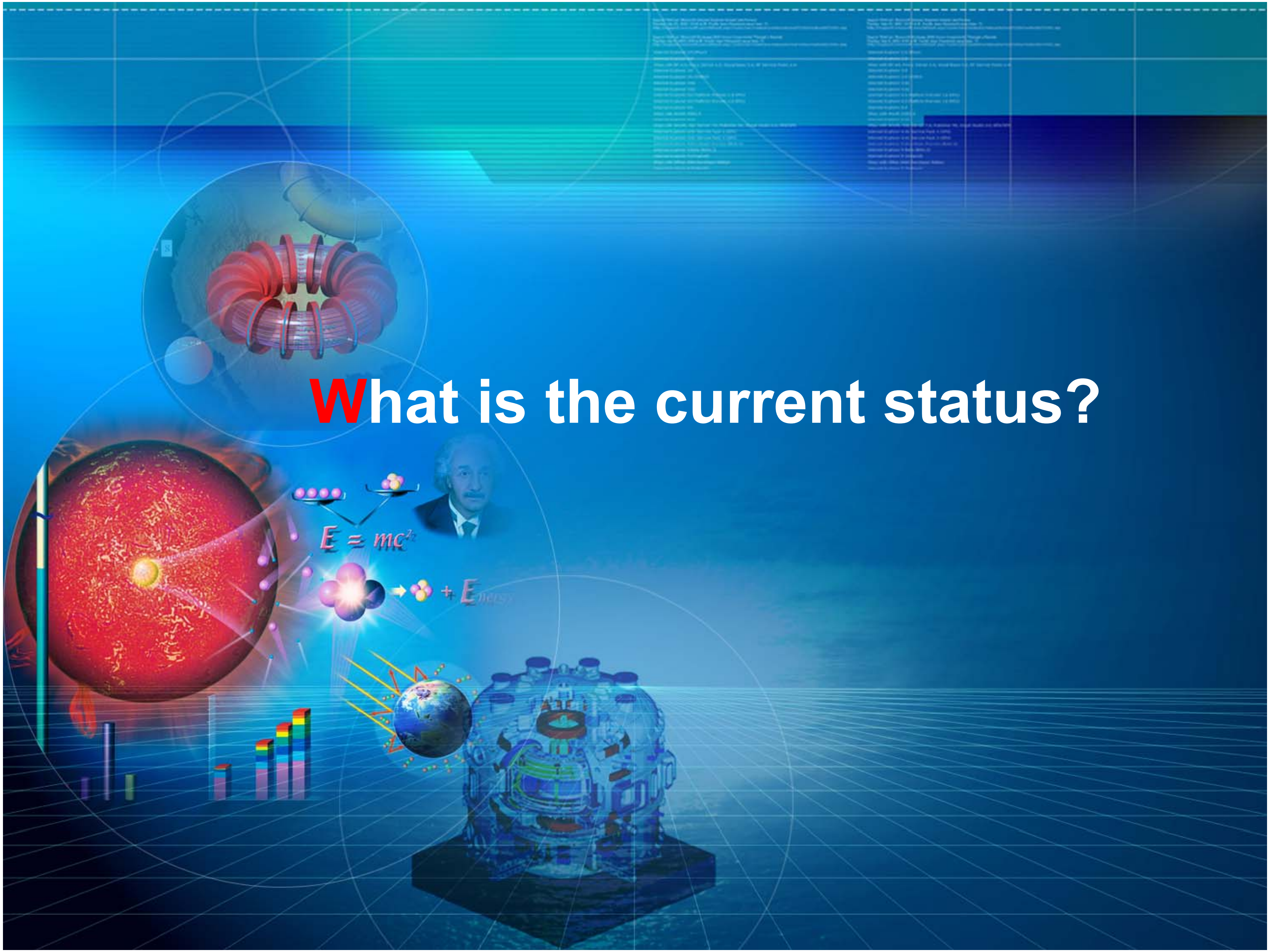
absorption near resonance, e.g. $\omega \approx \Omega_c$, i.e. conversion of wave energy into kinetic energy of resonant particles

⇓

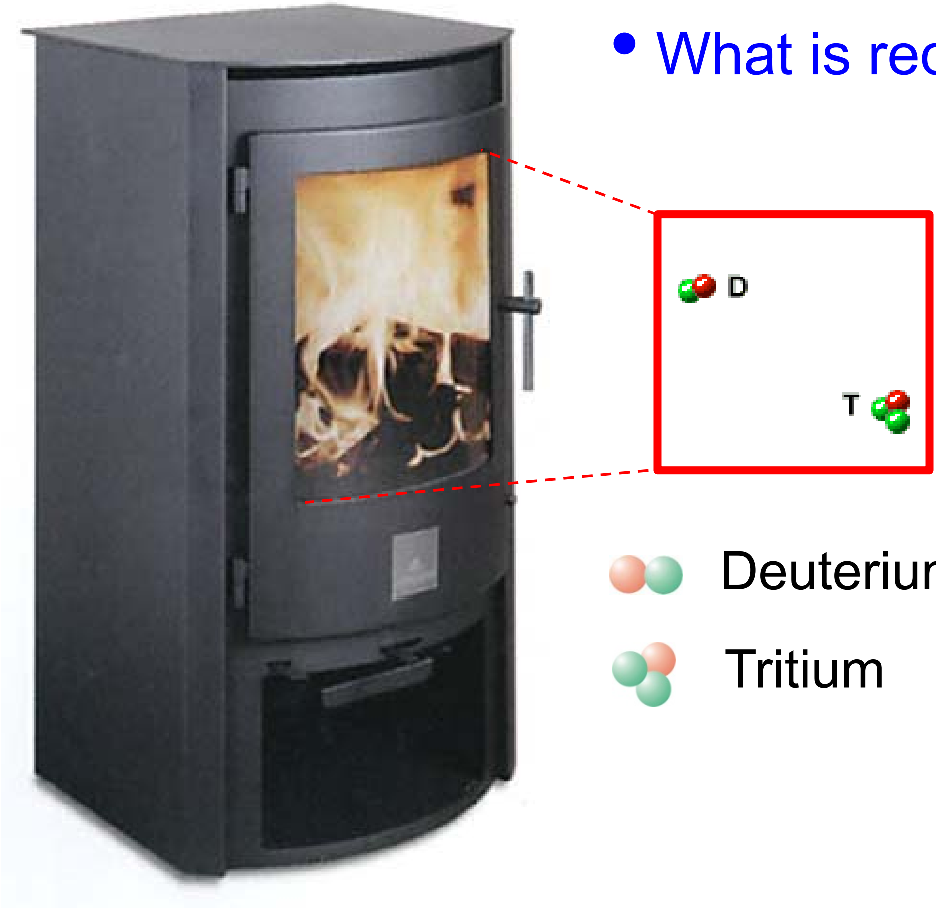
Resonant particles thermalize.



What is the current status?



Fusion Performance



- What is required to light a fire in a stove?
  - Fuel: D, T
  - Amount/density n
  - Heat insulation τ
  - Ignition temperature T

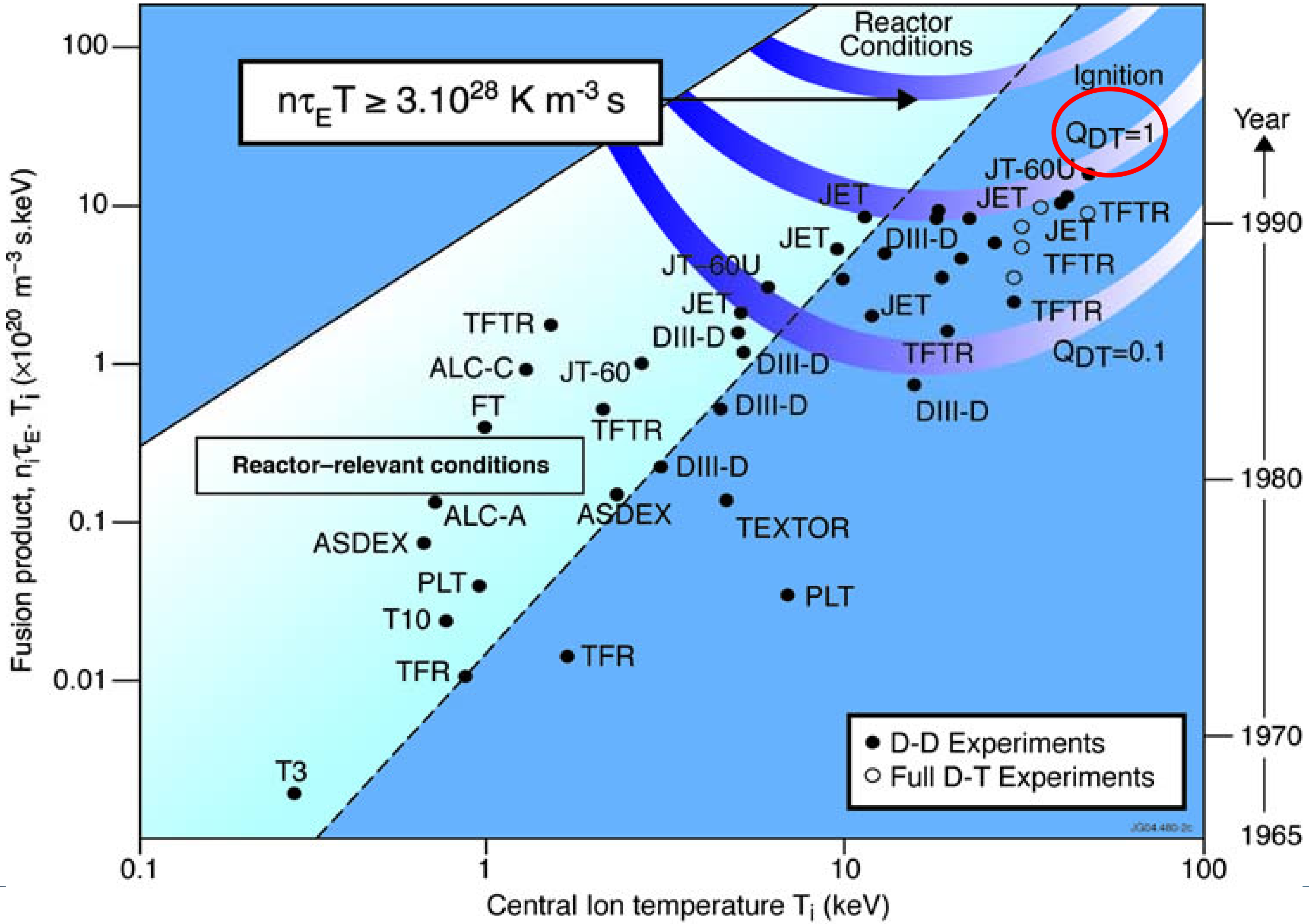
Deuterium

Tritium

$$n \cdot T \cdot \tau \geq ?$$

Criterion (Lawson) required

Status of the Tokamak Research



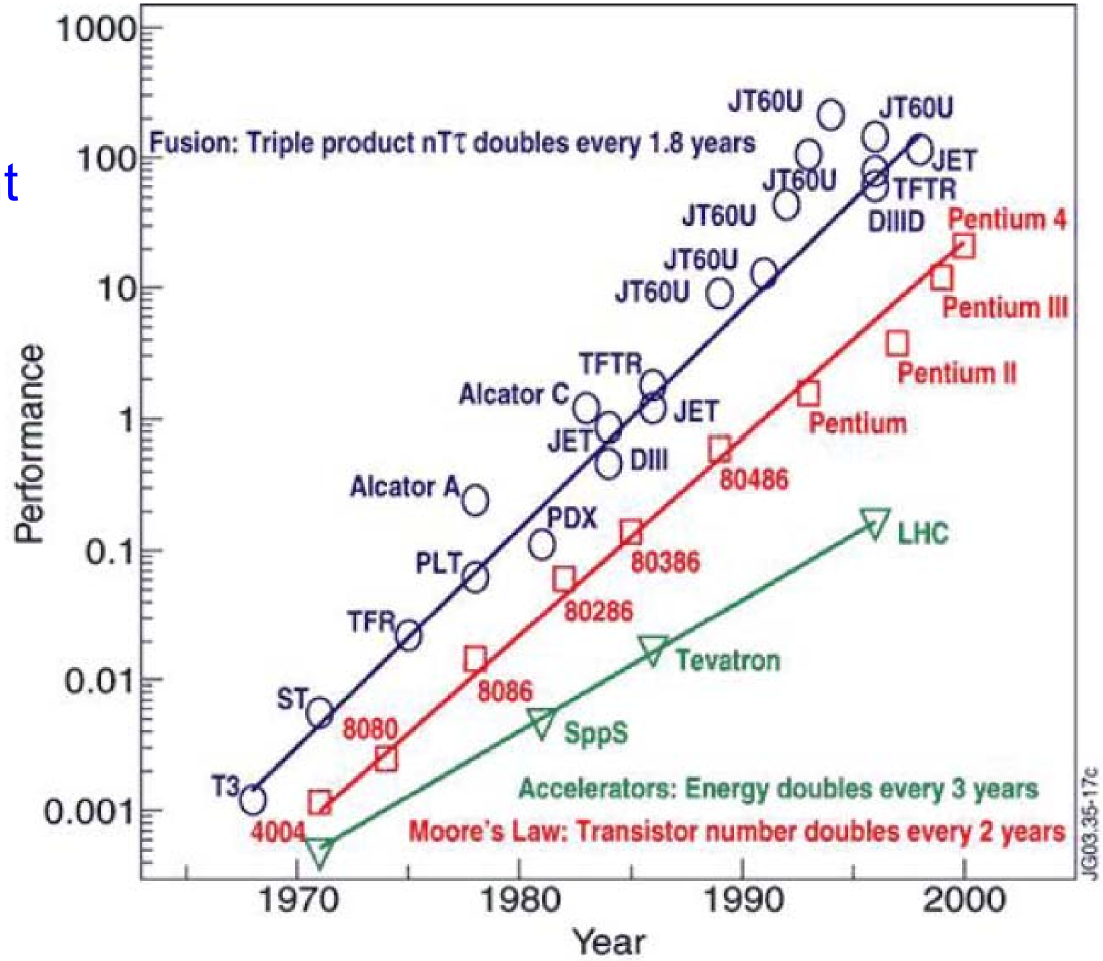
$Q = P_{fus}/P_{ext}$

Status of the Tokamak Research

• Progress in fusion can be compared with the development of computer chips and particle physics accelerator energy.

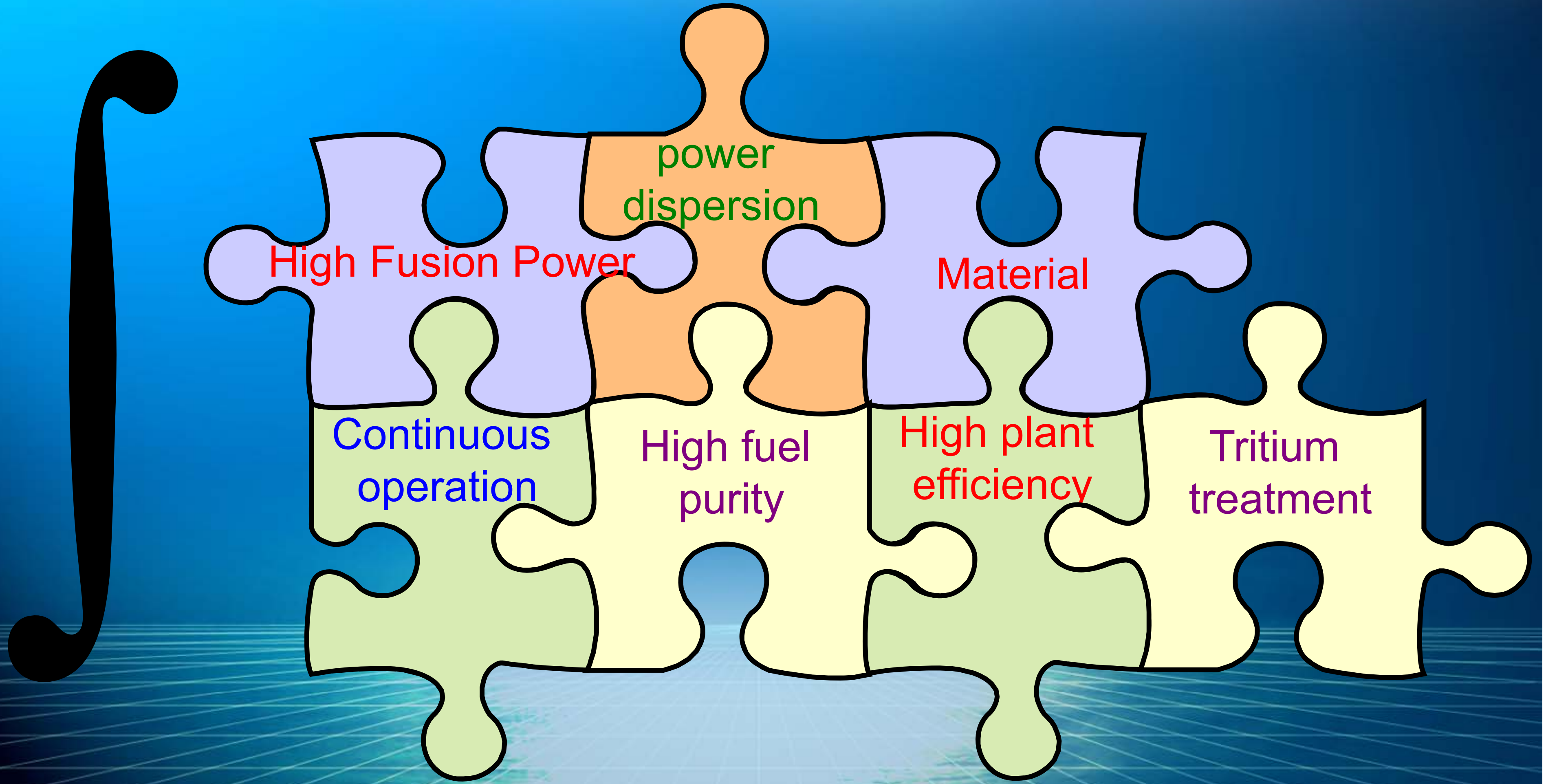
• Present machines produce significant fusion power:

- TFTR (USA) 10 MW (1994)
- JET (EU) 16 MW (Q=0.7) (1997)



What are the critical issues?

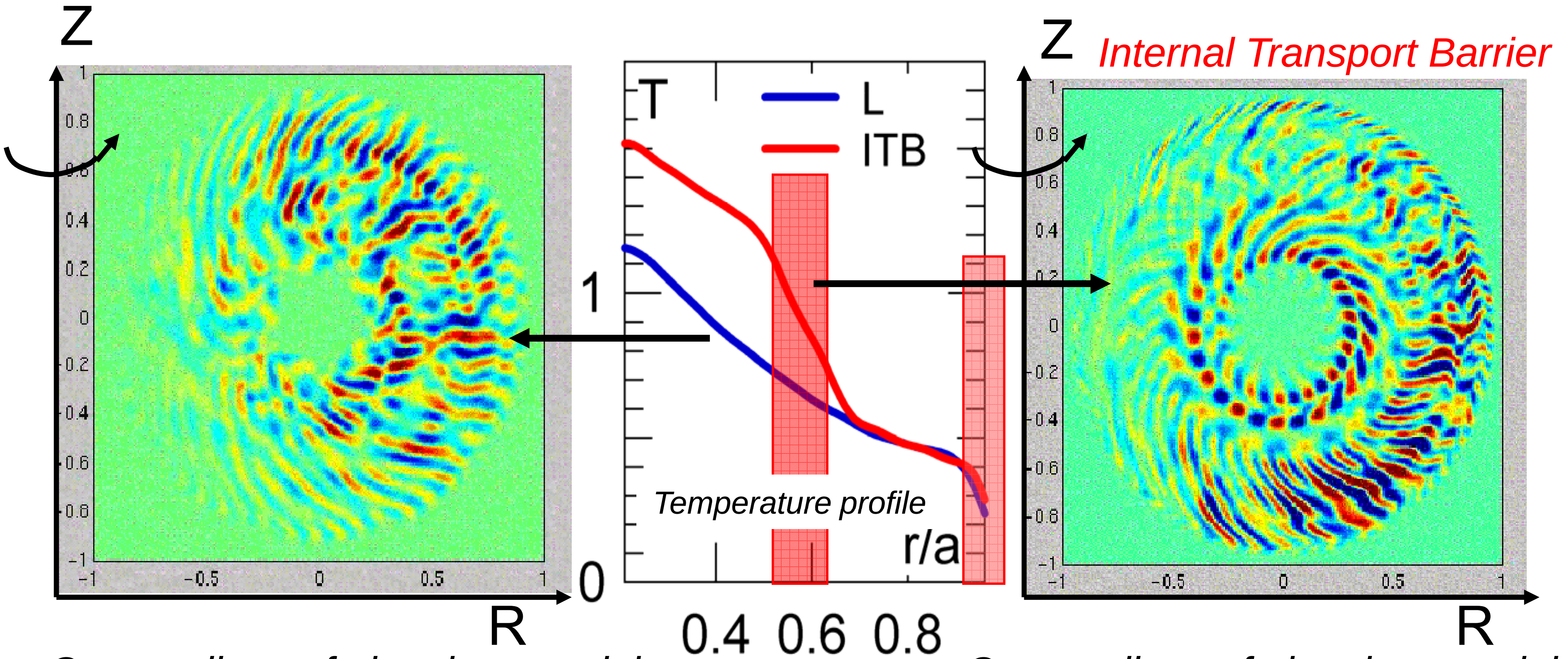
Critical Issues on the Fusion Development



How to increase the fusion power?

Stabilisation of Plasma Turbulence

- **Turbulence stabilisation → Increase of plasma pressure**
  → High fusion power



Contour lines of electric potential. *Contour lines of electric potential.*

Stabilisation of Plasma Turbulence

Gyrokinetic Simulations of Plasma Microinstabilities

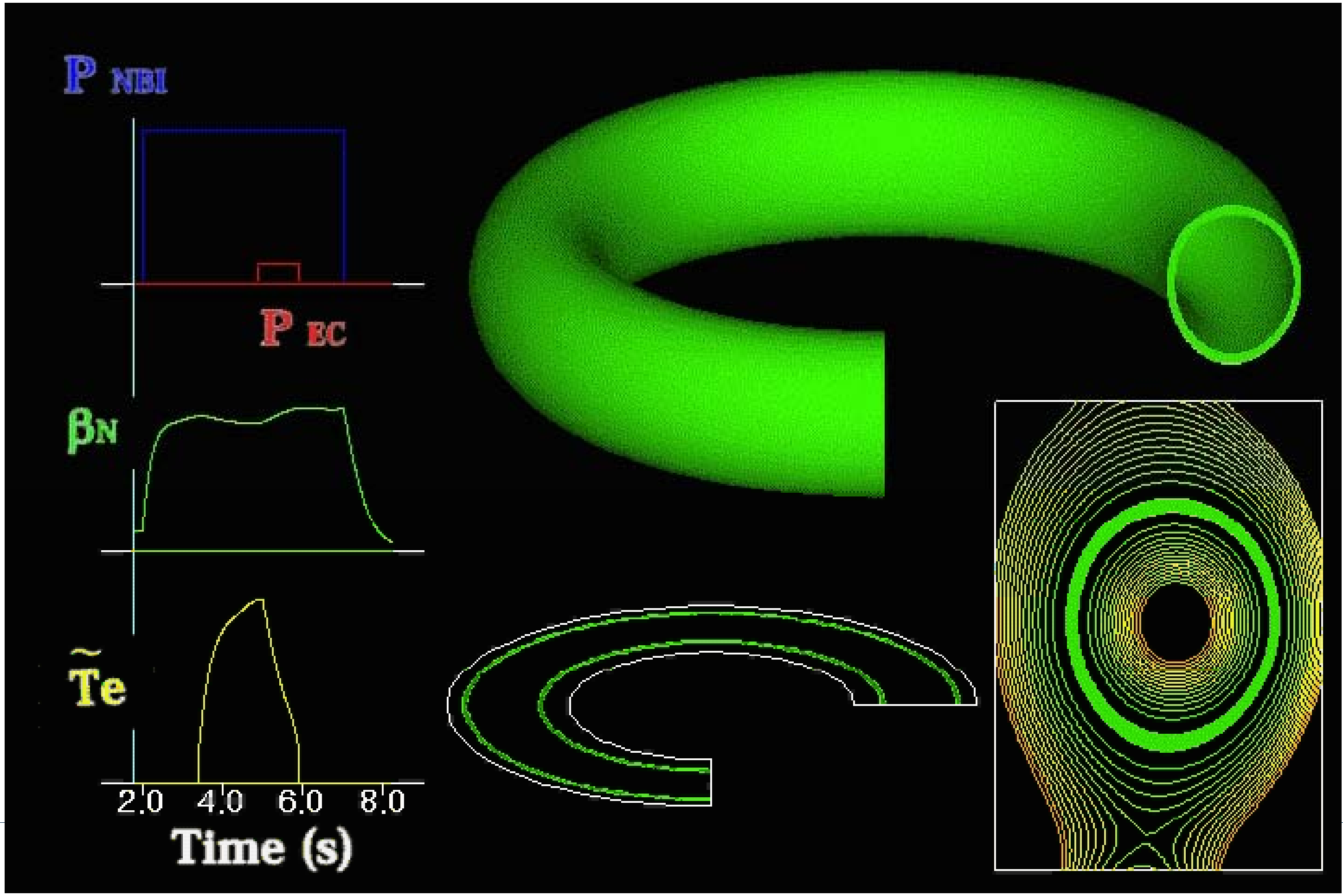
simulation by

Zhihong Lin et al.

Science 281, 1835 (1998)

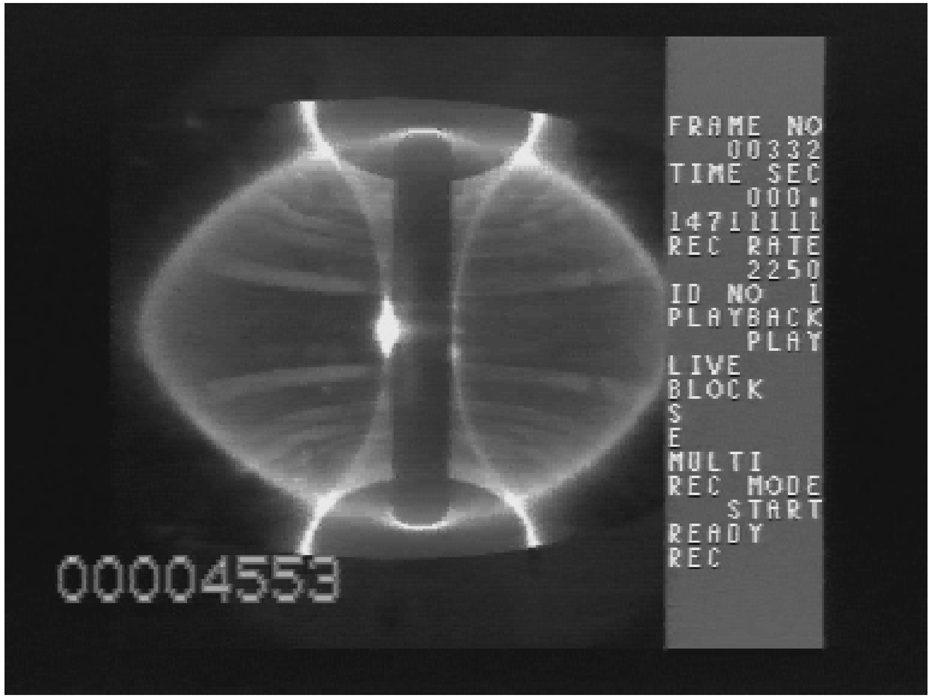
Suppression of Plasma Instabilities

- **Suppression of Neoclassical Tearing Mode by ECCD**



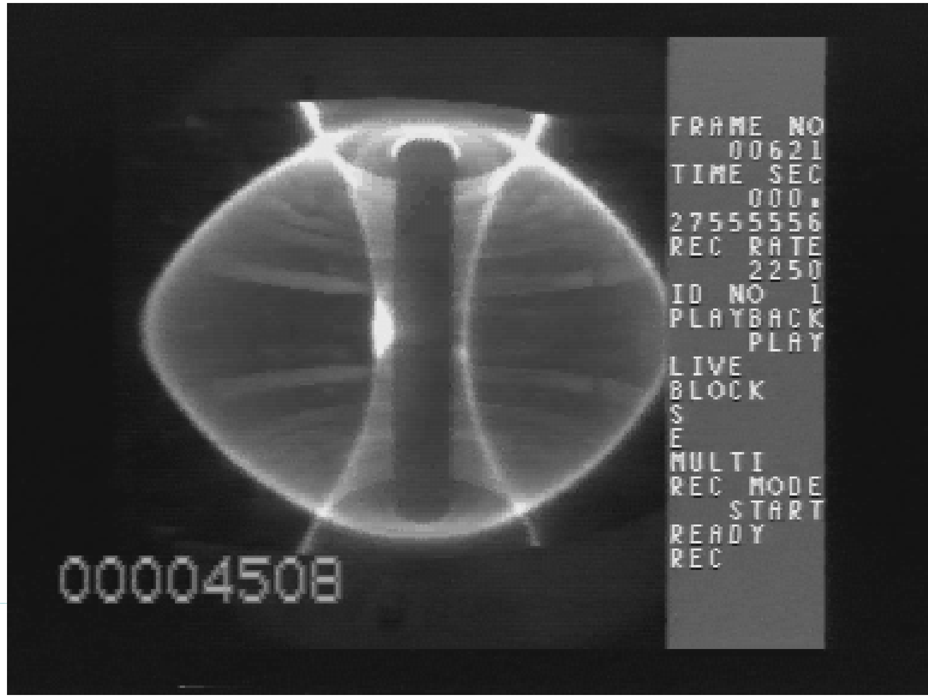
Edge Region Instability and Disruption

MAST
MEGA-AMPERE SPHERICAL TOKAMAK

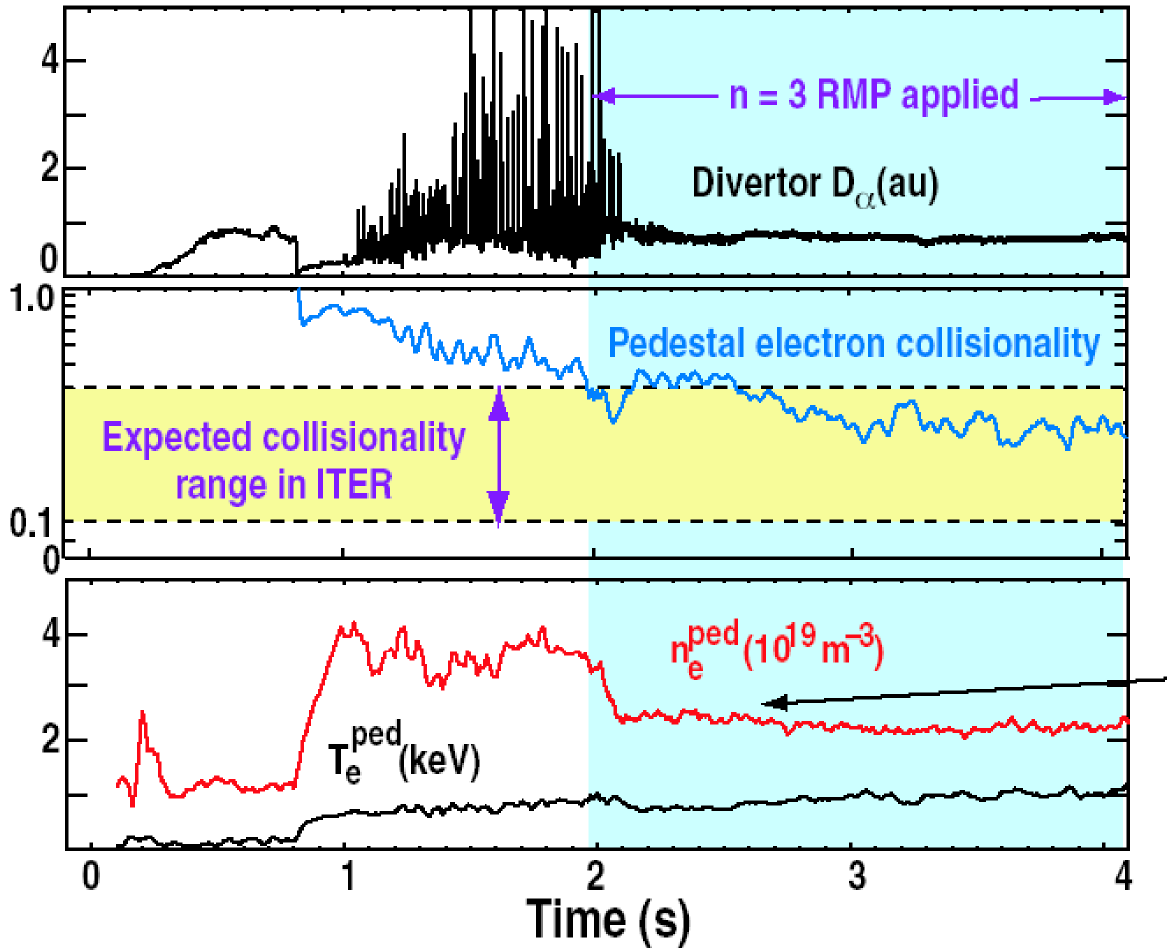


Edge Localised Mode

Disruption



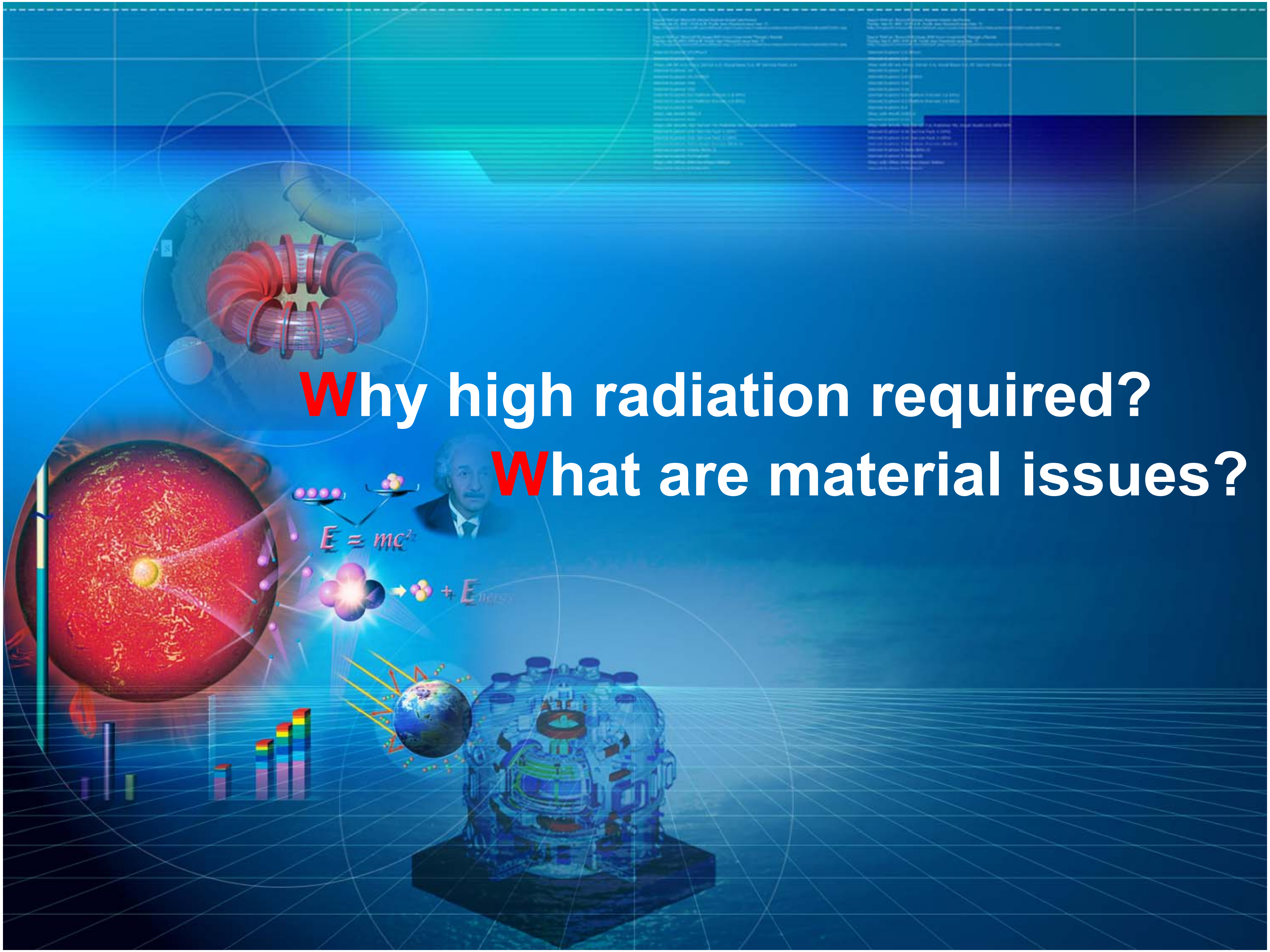
Suppression of ELMs



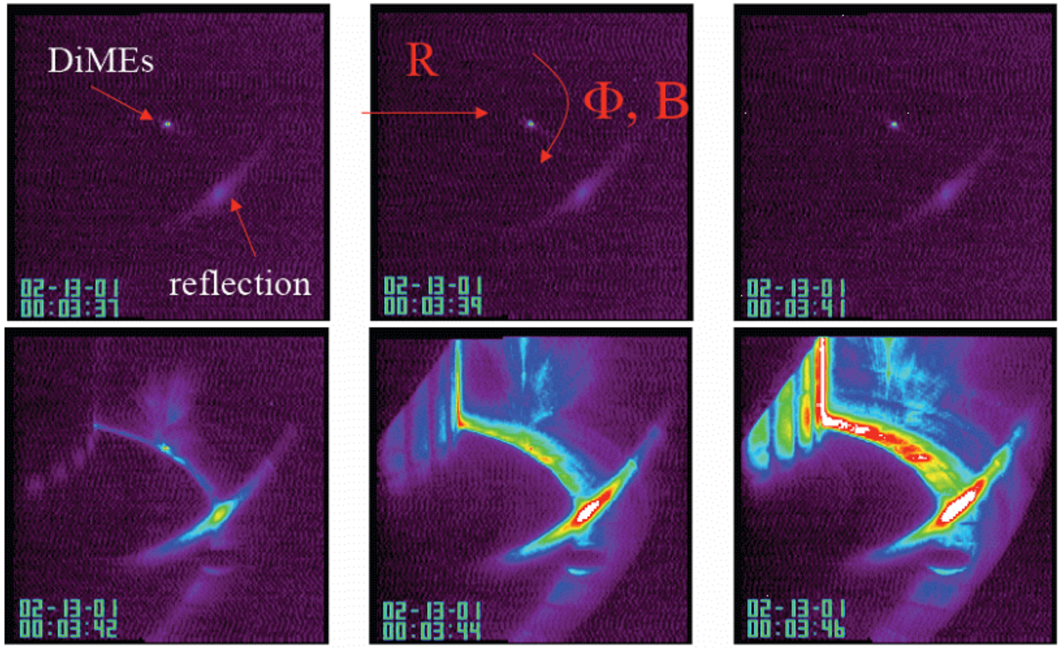
- Suppression of ELMs by helical field on DIII-D

Why high radiation required?

What are material issues?

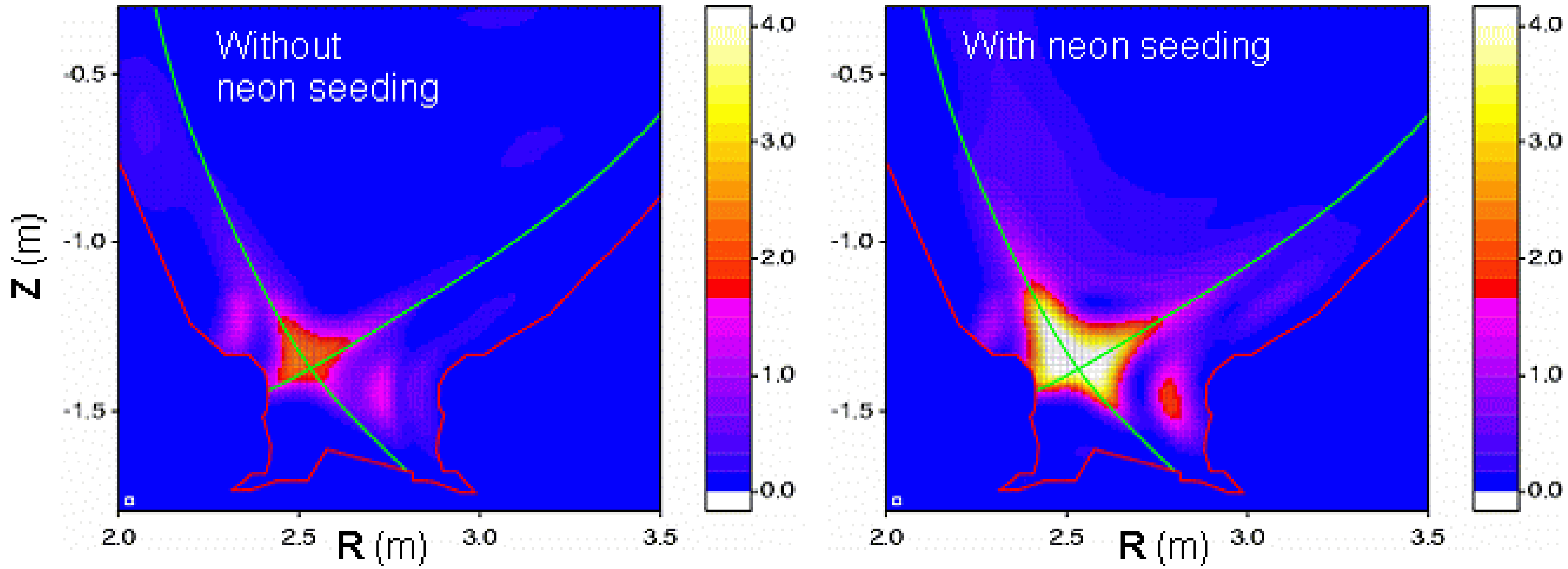


Plasma–Wall interactions



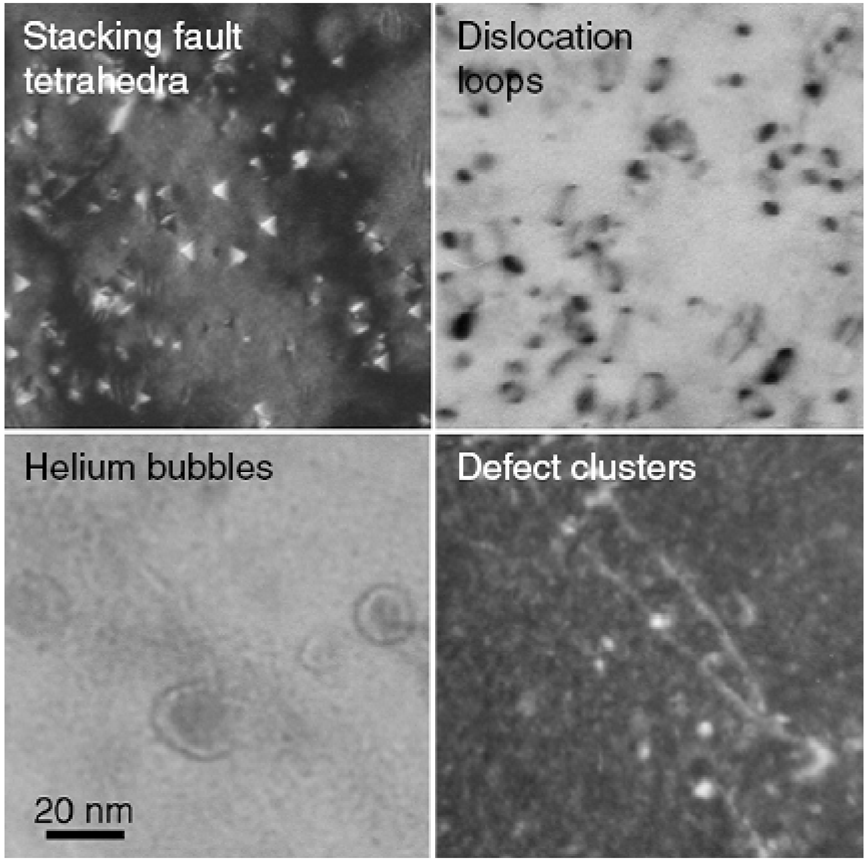
- High heat flux to the surrounding materials

Radiation Induced by Impurity Seeding



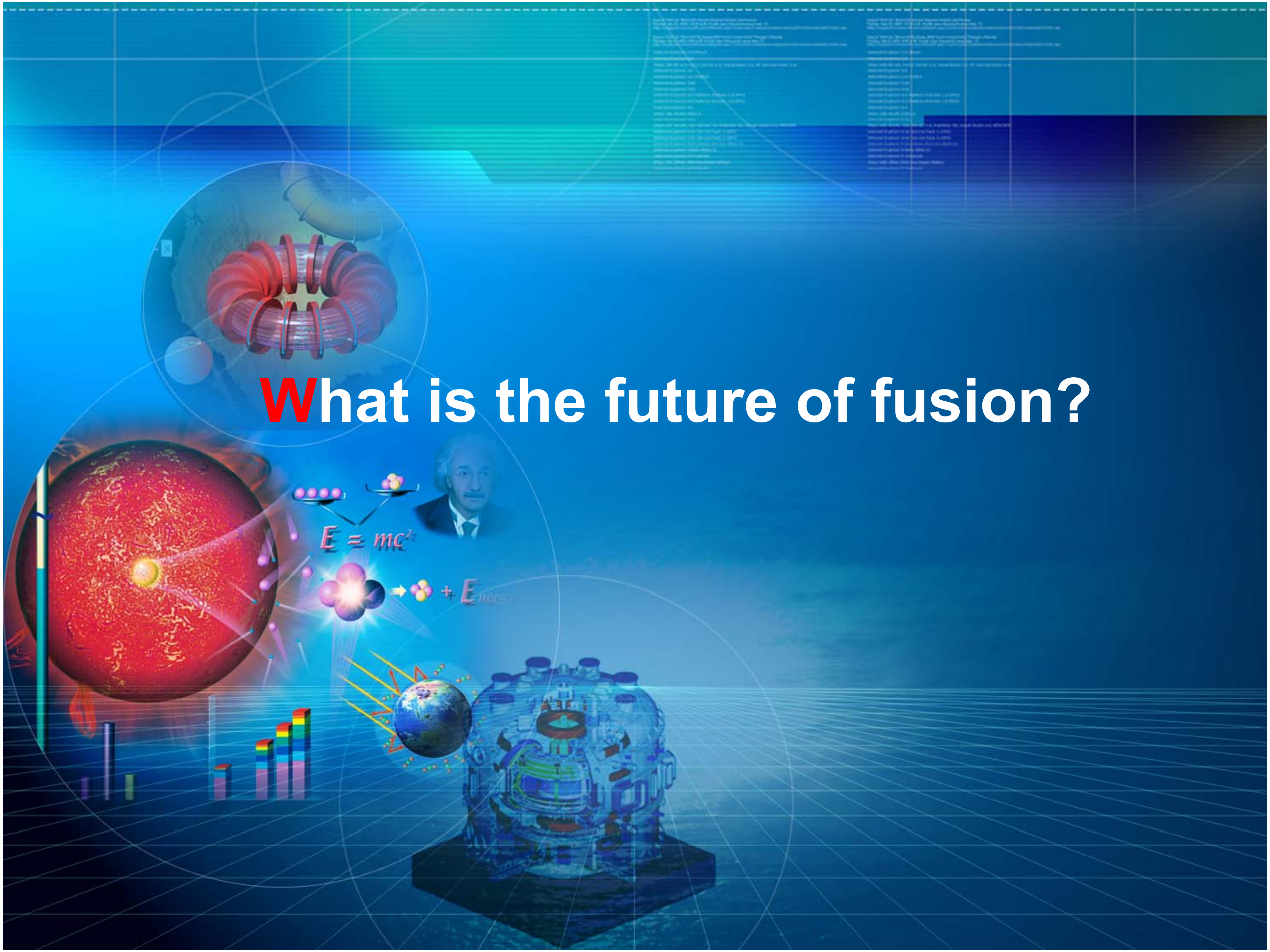
- Heat flux to materials reduced by radiation emission

Radioactivation of Materials

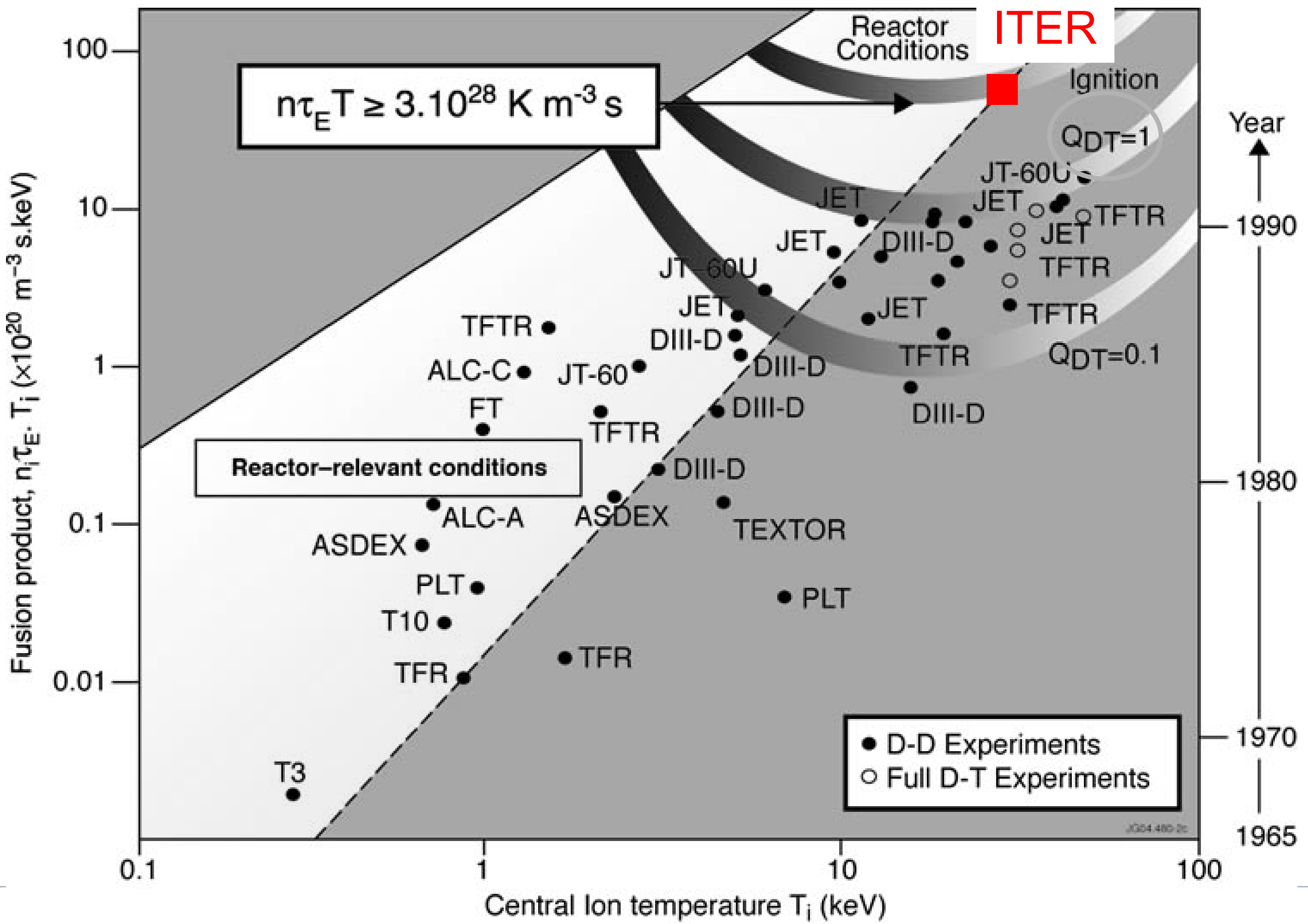


- Neutron impacts on materials

What is the future of fusion?



Status of the Tokamak Research



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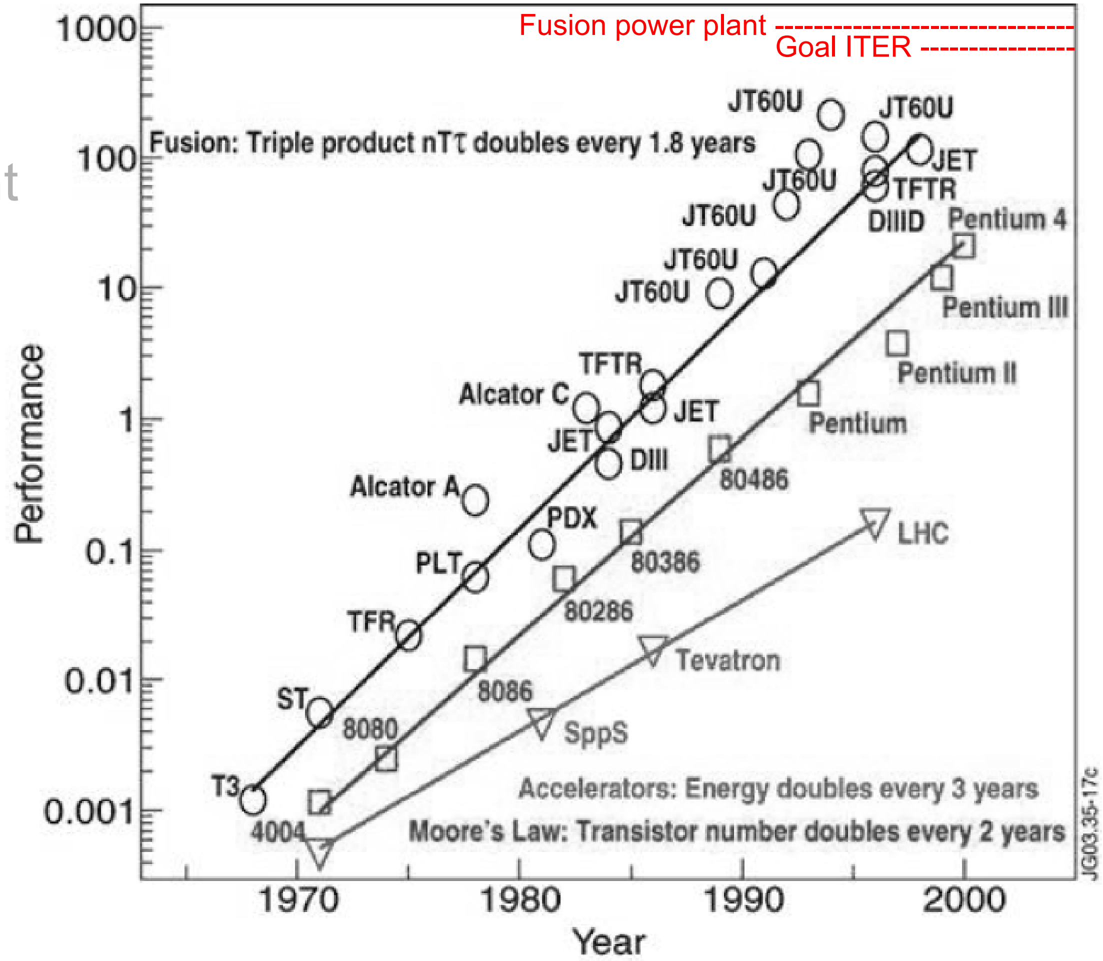
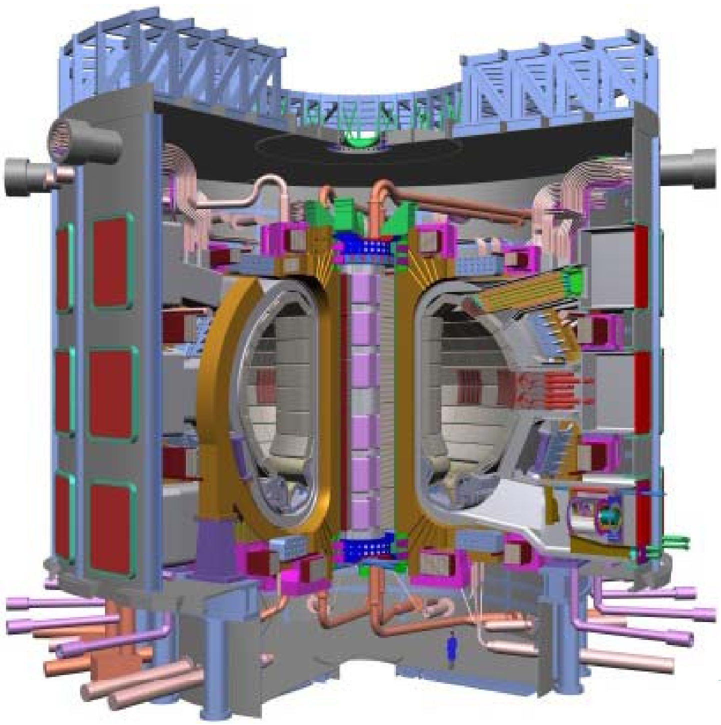
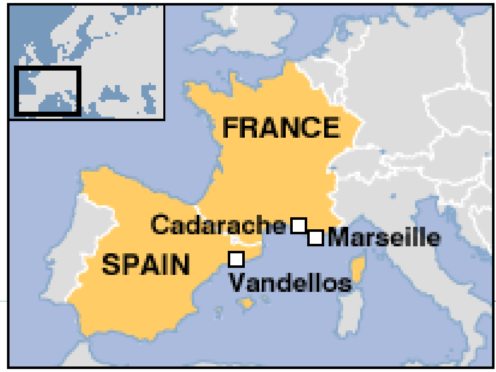


ITER Project

- **I**nternational **T**hermonuclear **E**xperimental **R**eactor
  - "the way" in Latin
  - the essential next step in the development of fusion

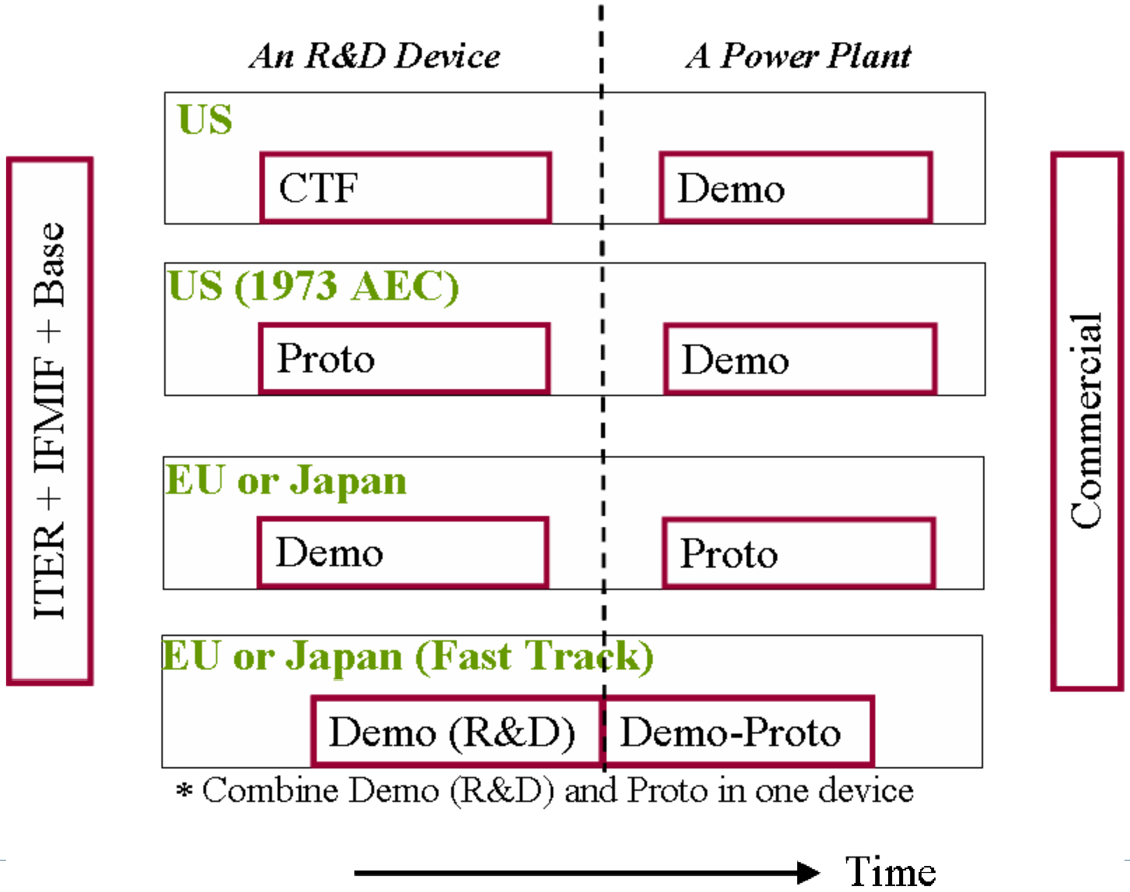


- Objective - To demonstrate the scientific and technological feasibility of fusion power.
  - The world's biggest international research project



Fusion Energy Development

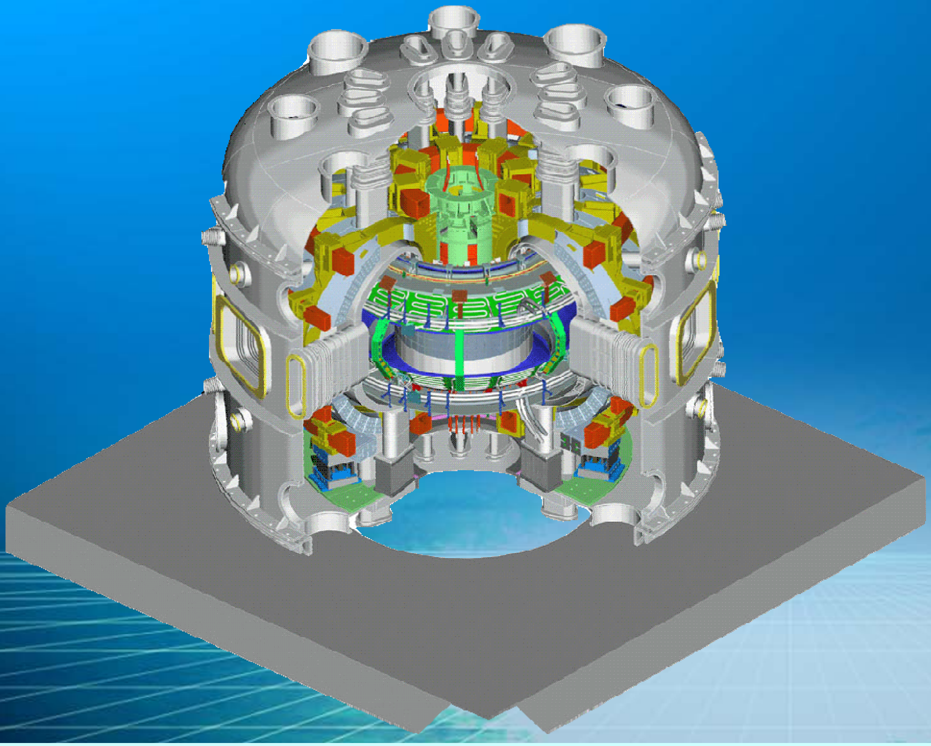
- **The Fast Track Approach**

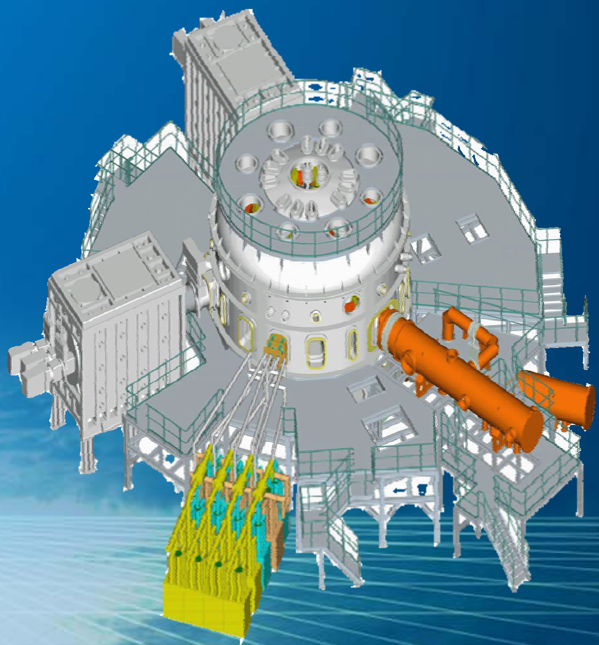


KSTAR Project

KSTAR

- **K**orea **S**uperconducting **T**okamak **A**dvanced **R**esearch
  - superconducting tokamak using ITER-relevant magnets
  - capability of reactor-relevant plasma performances





- Objective - To integrate optimised plasma performance and continuous operation as a step toward an attractive tokamak fusion reactor

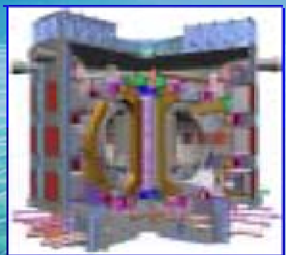
Korean Plan for Fusion Energy Development

2007년 이후
KSTAR

- 고성능, 고효율 장시간 운전연구

2015년
ITER

- 연료 연구
- 열이용 연구
- 재료 연구
- 공학 연구



2020년대 중반
DEMO

- 실질적인 발전 실현
- 시스템 최적화
- 경제성 구현

2030년대
상용화

- 대용량 전기생산

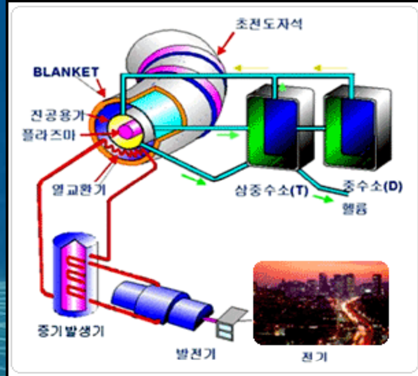
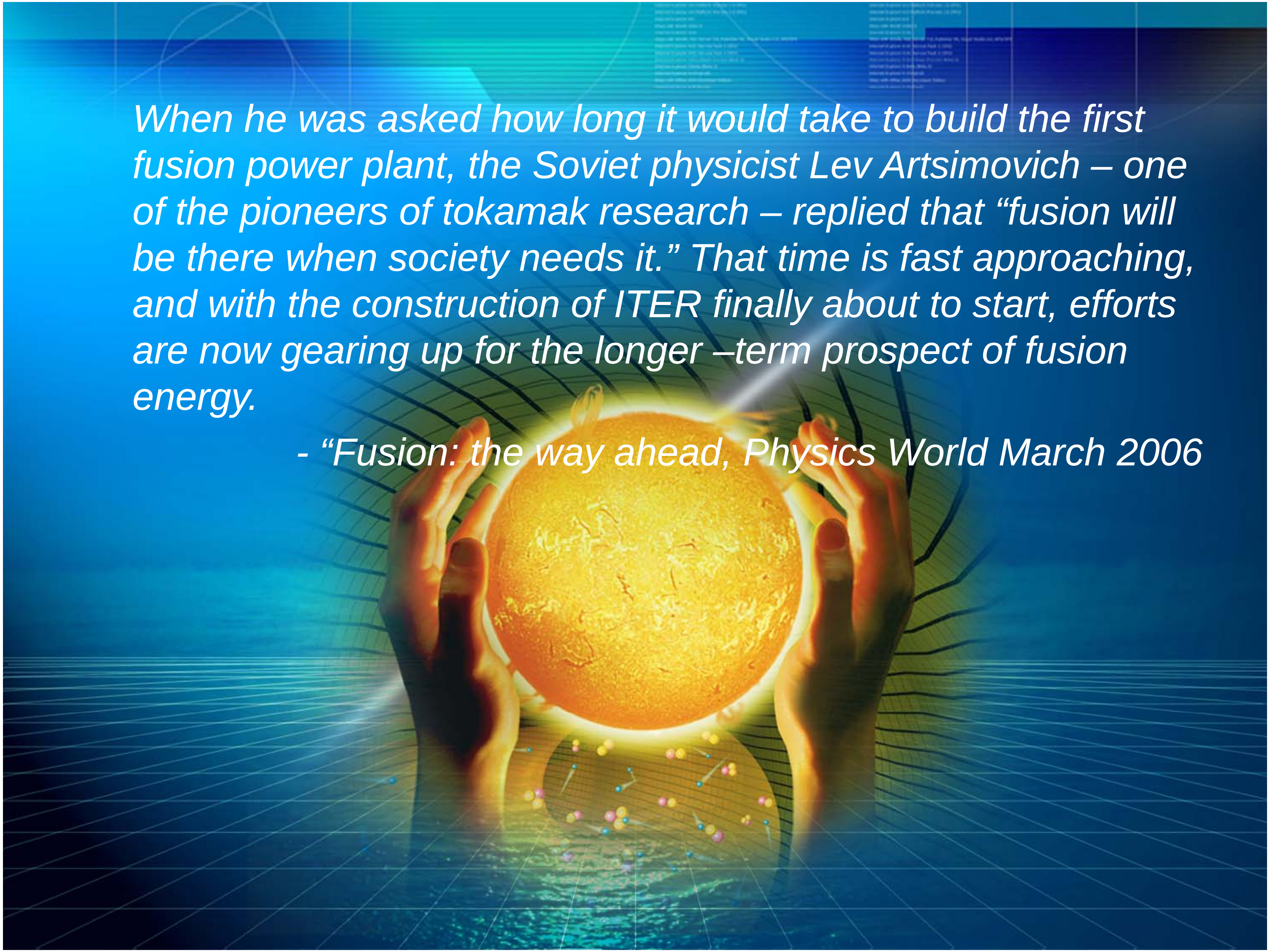


그림 15. 핵융합발전의 원리

Summary

I	What is nuclear fusion?
II	How to confine the hot sun?
III	How to heat the plasma?
IV	What is the current status?
V	What are the critical issues?
VI	What is the future of fusion?
VII	Closing remarks


When he was asked how long it would take to build the first fusion power plant, the Soviet physicist Lev Artsimovich – one of the pioneers of tokamak research – replied that "fusion will be there when society needs it." That time is fast approaching, and with the construction of ITER finally about to start, efforts are now gearing up for the longer –term prospect of fusion energy.
- "Fusion: the way ahead, Physics World March 2006


"The entire cost of the fusion development programme is equal to only a week of spending in the international energy markets."
- I. Cook, IAEA 2005