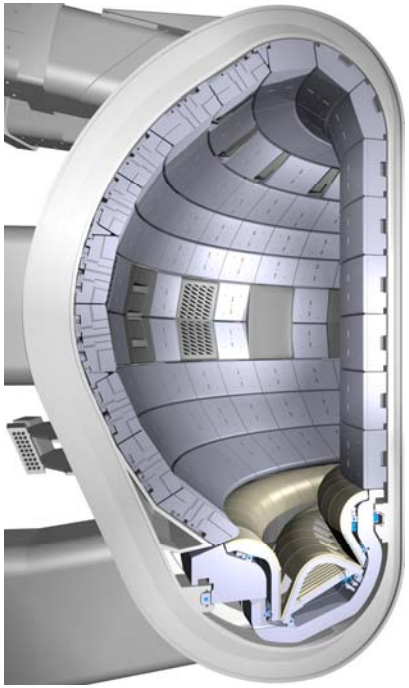
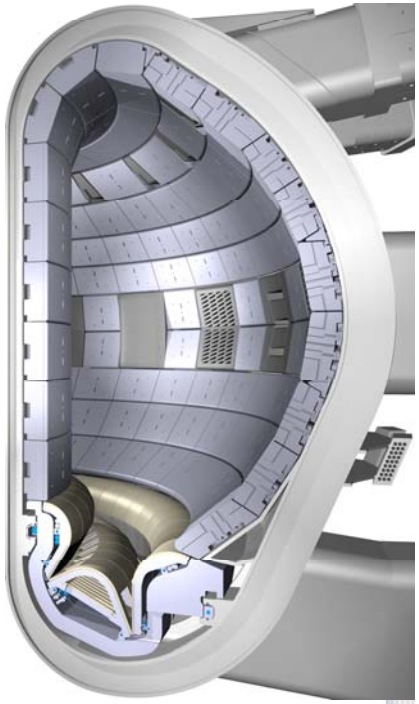
Fusion Energy: Promises Unkept?



Part 1:
Fusion Science +
Fusion History

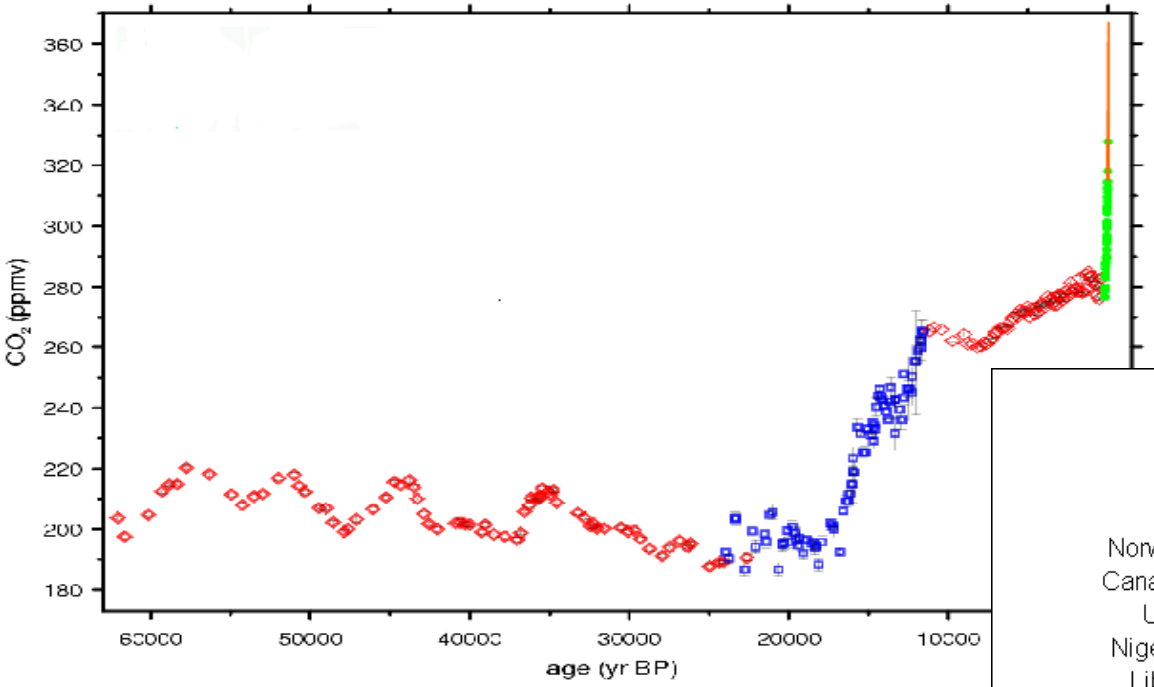


Norbert Holtkamp
ITER Principal Deputy Director General
CERN
Sept 4, 2008

Thanks to

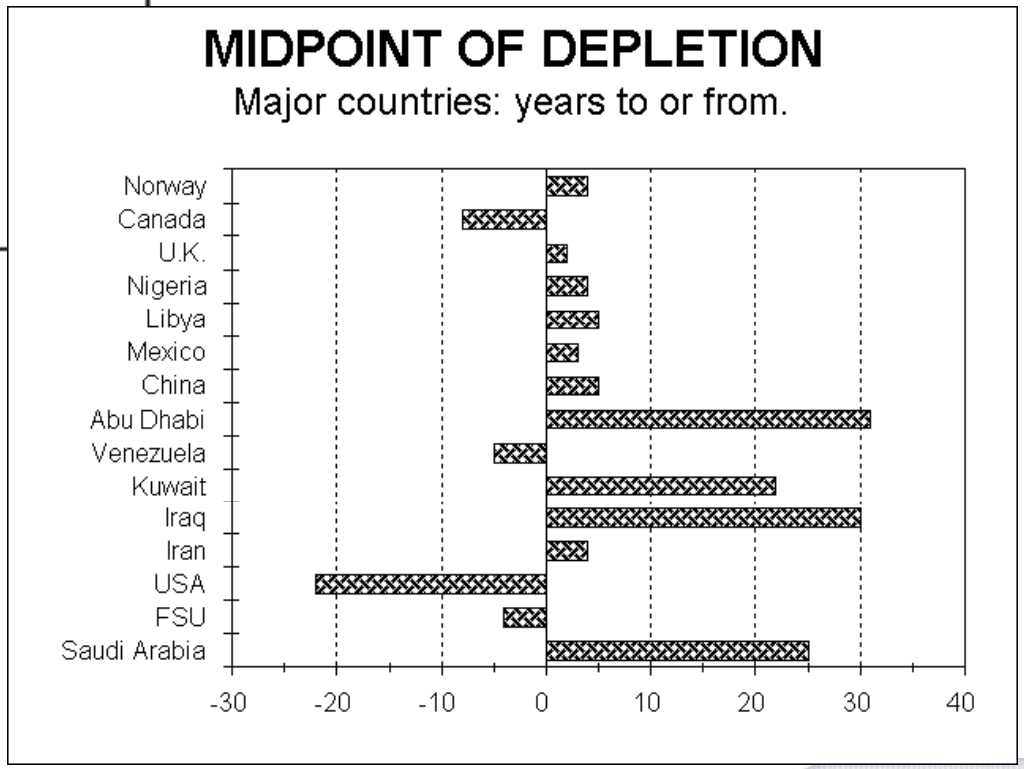
- David Ward, UKAEA presentation on fusion
- David Campbell, ITER Fusion S&T
- Evgeny Velikhov, President Kurchatov Inst.
- Chris Llewellyn-Smith, ex CERN DG
- ITER collaboration
- Many others

Global Warming and How much Oil is left?



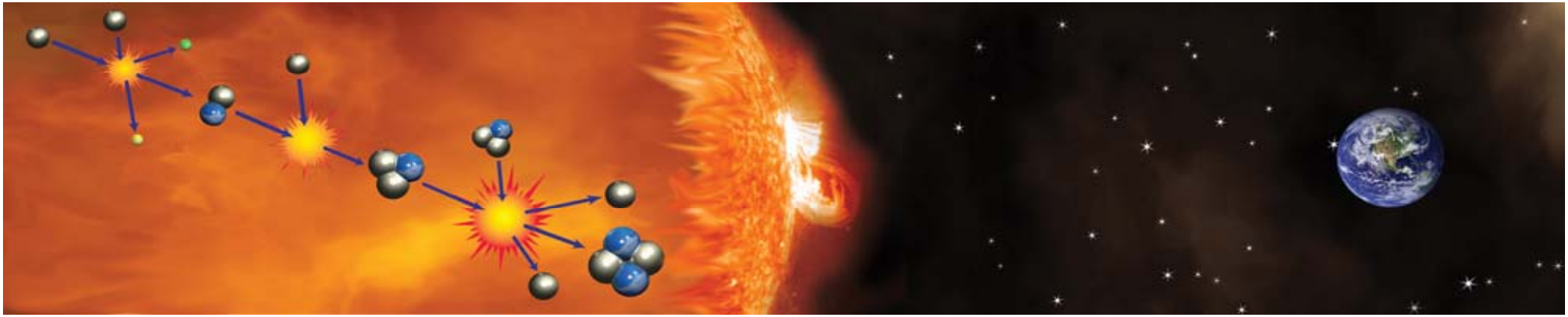
60 000 year CO2 level

Oil reserves



Fusion powers the sun and the stars

"…Prometheus steals fire from the heaven"

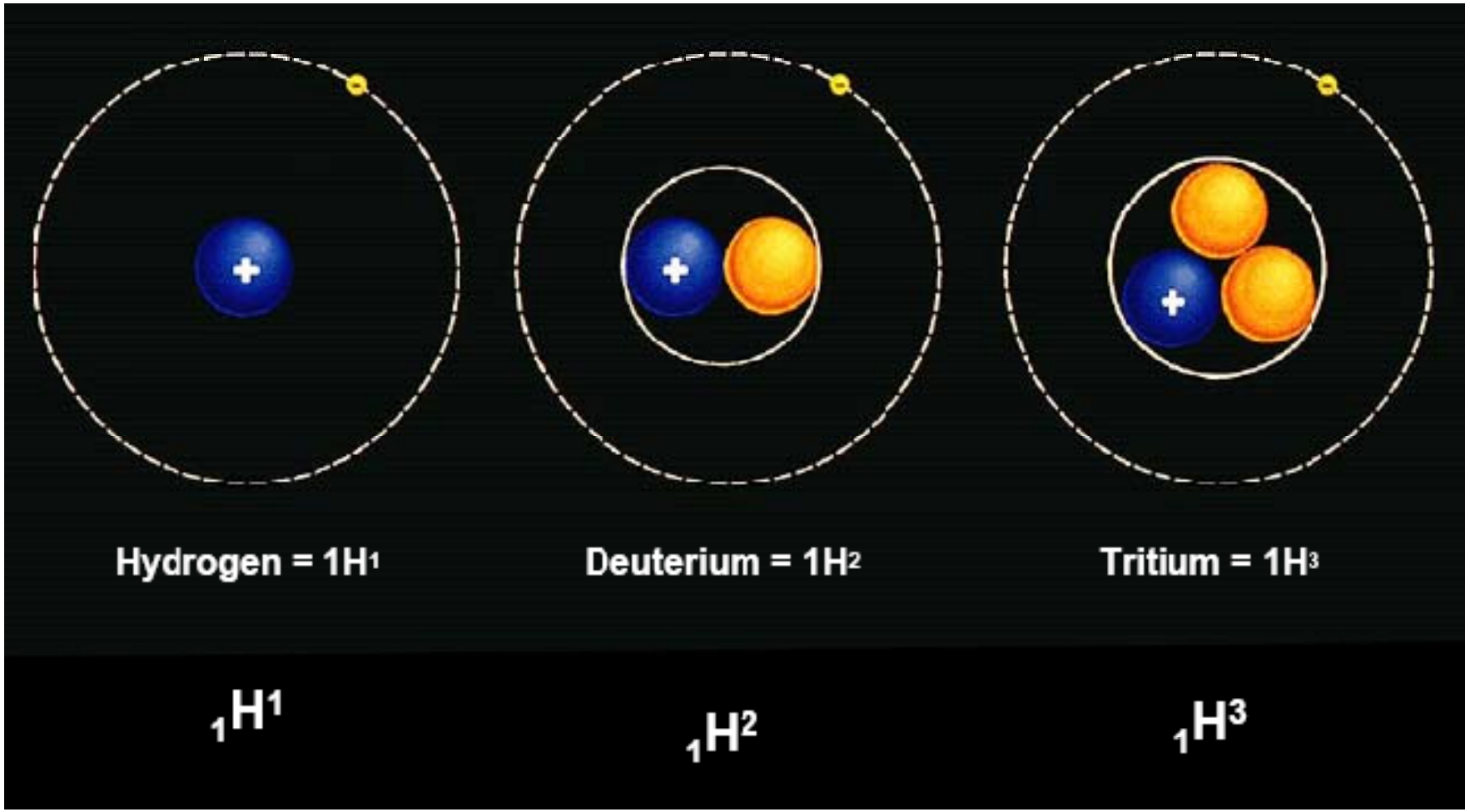


On Earth,

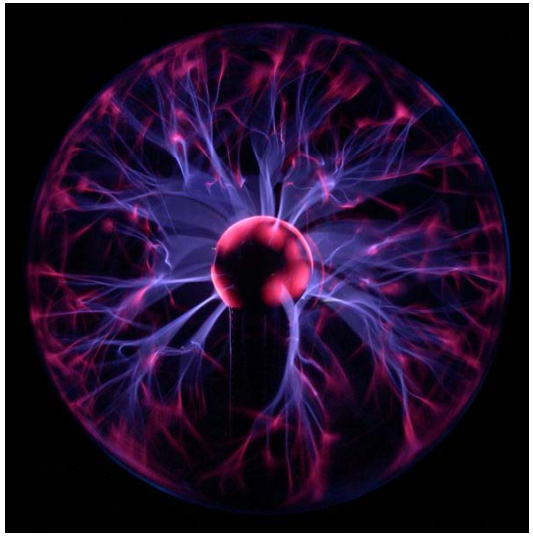
fusion could provide:

- Essentially limitless fuel, available all over the world
- No greenhouse gases
- Intrinsic safety
- No long-lived radioactive waste
- Large-scale energy production

Atomic Physics

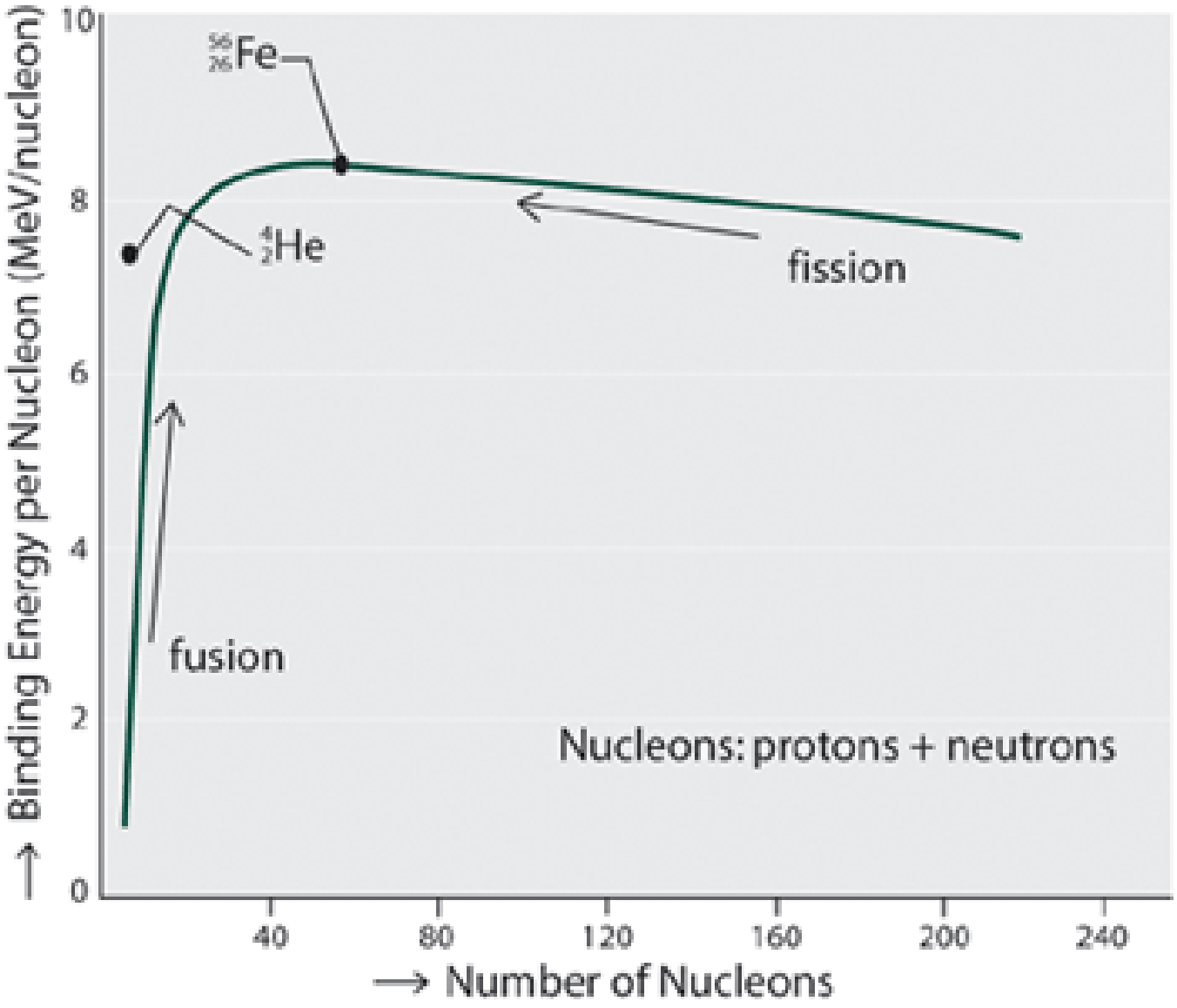


What's a Plasma



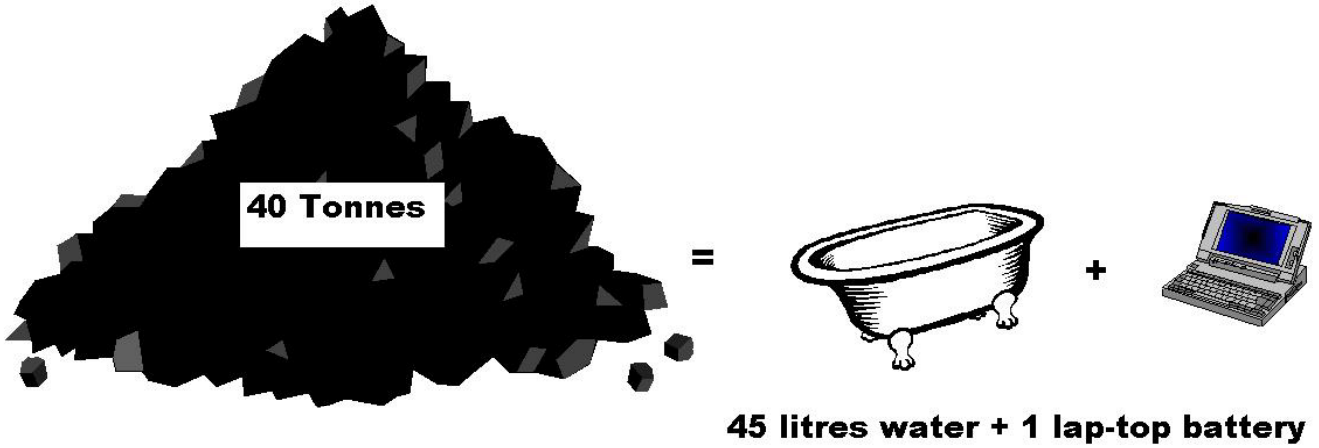
- Plasma is an ionized gas,
- A certain proportion of electrons are free, rather than being bound to an atom or molecule.
- The ability of the positive and negative charges to move somewhat independently makes the plasma electrically conductive so that it responds strongly to electromagnetic fields.

Nuclear Physics: $E=mc^2$



Fusion Fuel

- Raw fuel of a fusion reactor is water and lithium*



- Lithium in one laptop battery + half a bath-full of ordinary water **(-> one egg cup full of heavy water)** ⇒ 200,000 kW-hours
- = (current UK electricity production)/(population of the UK) for 30 years

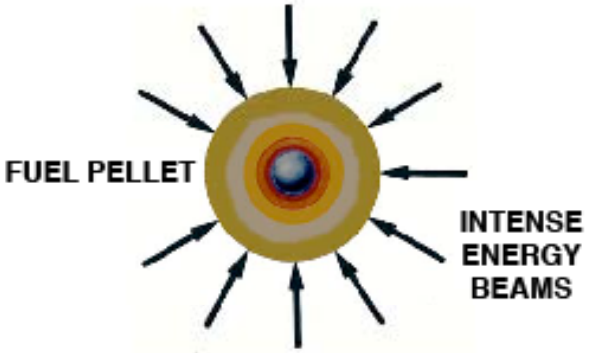
* ***deuterium/hydrogen = 1/6700***

+ tritium from: neutron (from fusion) + lithium → tritium + helium

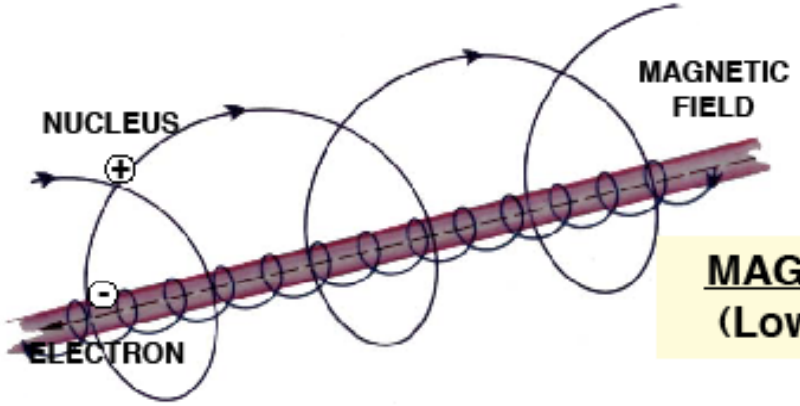
Courtesy: CLS

Three Ways to Fusion in the Universe

GRAVITATIONAL CONFINEMENT
(High density for billions of years)



INERTIAL CONFINEMENT
(High density for less than a billionth of a second)

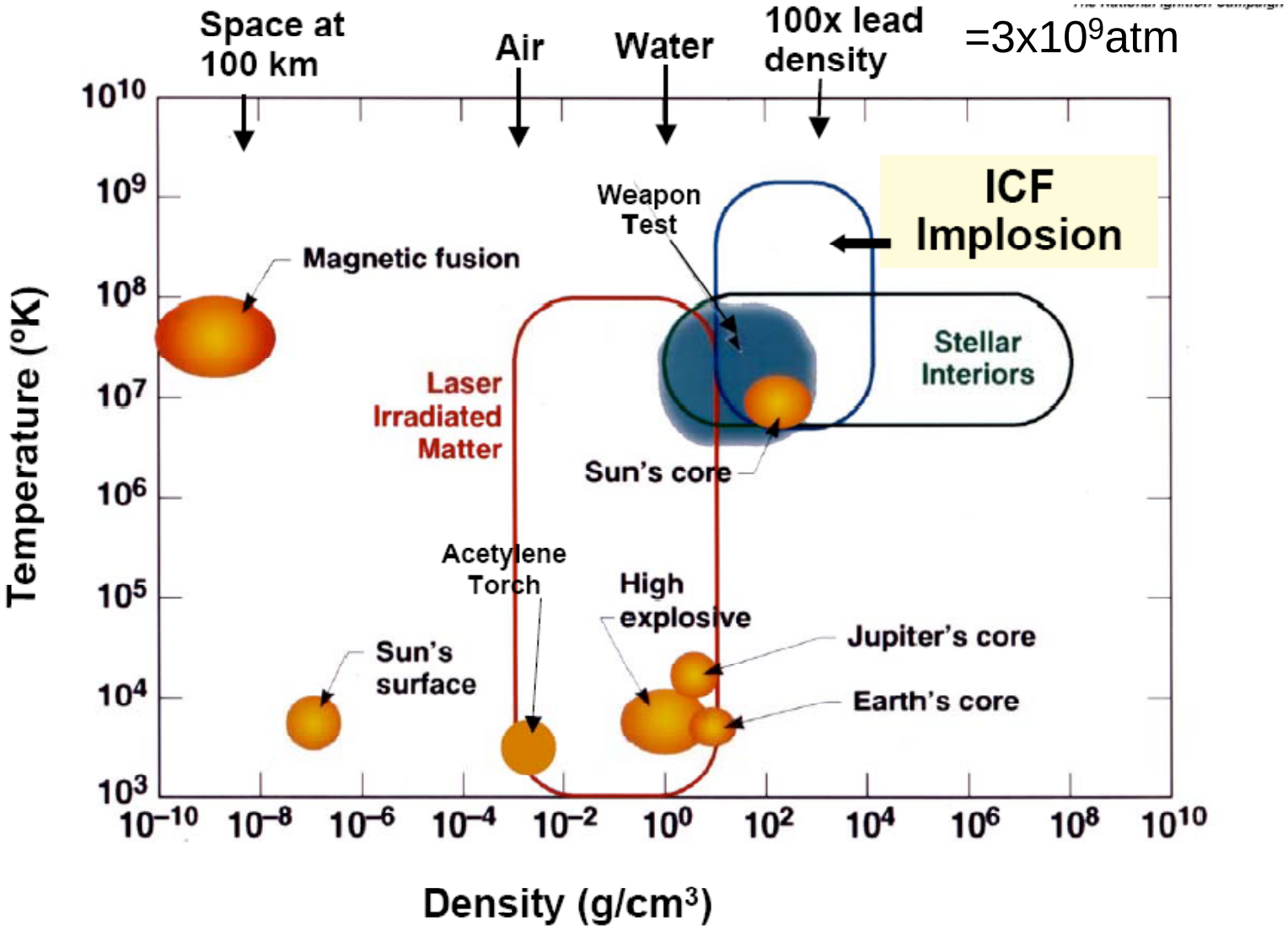


100-200 Million degree

MAGNETIC CONFINEMENT
(Low density for seconds)

Will not talk about cold fusion !

Fusion in the Universe



Comparison

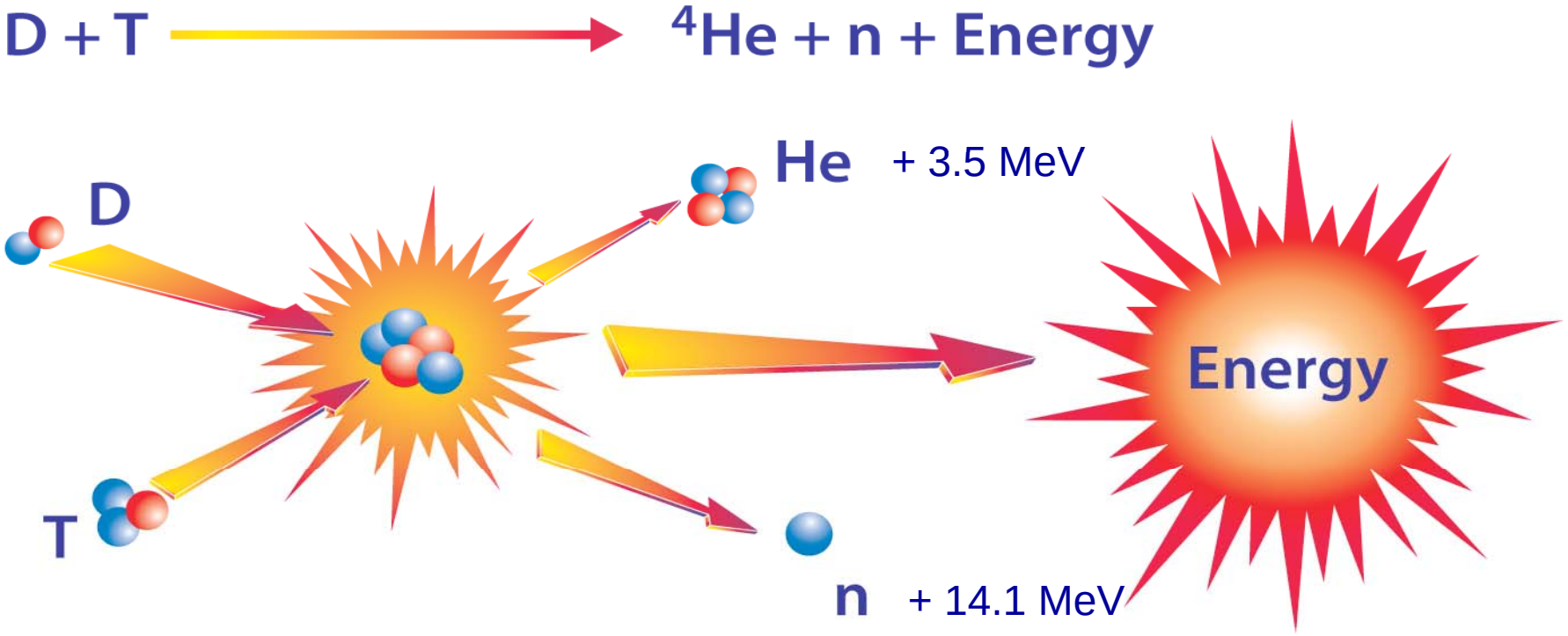
	Density n_e (m^{-3})	Temperature T_e (eV)	°K
Interstellar	10^{+6}	1	10^4
Solar Corona	10^{12}	10^2	10^6
Thermonuclear	10^{20}	10^4	10^8
Laser	10^{26}	10^2	10^6
Air Density	10^{25}	1/40	294

The Fusion Reaction on Earth

"... is not the same as in the Sun"

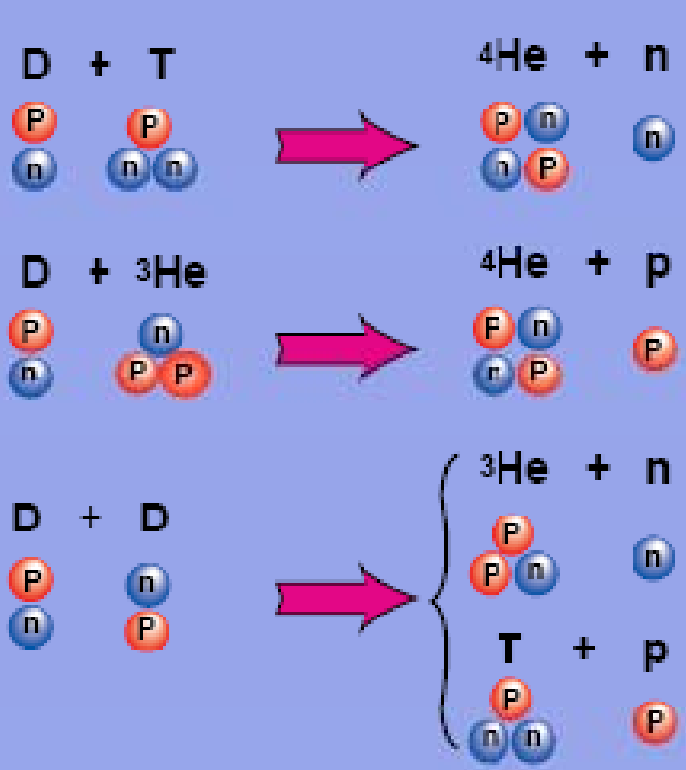
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ + 5.5 eV (chemical)

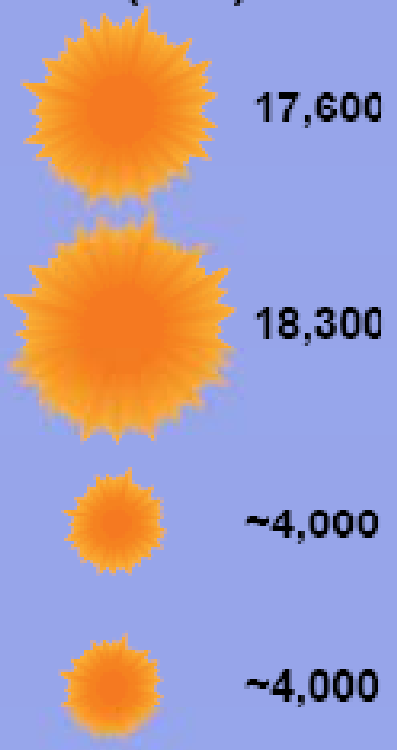
$4\,^1H + 2e \rightarrow 4He + 2\,\upsilon + 6\,\gamma$ + 26.7 MeV (solar process)



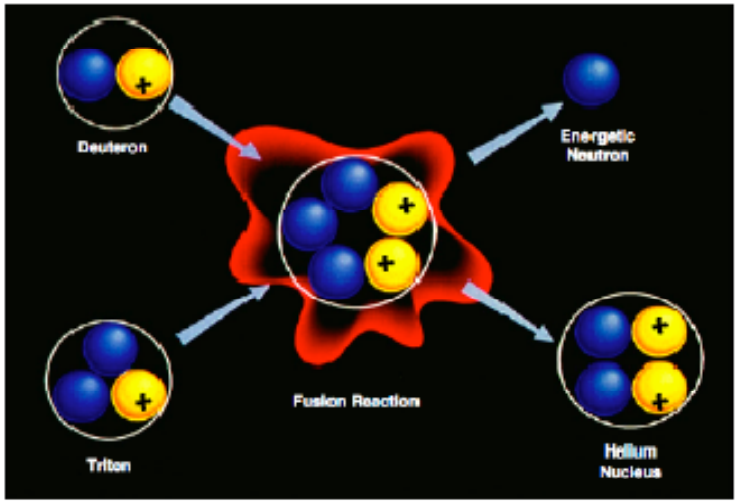
Why D-T: Ignition Temperature

Reaction		Ignition Temperature		Output Energy
Fuel	Product	(millions of °C)	(keV)	(keV)
D + T	^4He + n	45	4	17,600
D + ^3He	^4He + p	350	30	18,300
D + D	^3He + n	400	35	~4,000
	T + p	400	35	~4,000





Why D-T: Cross section

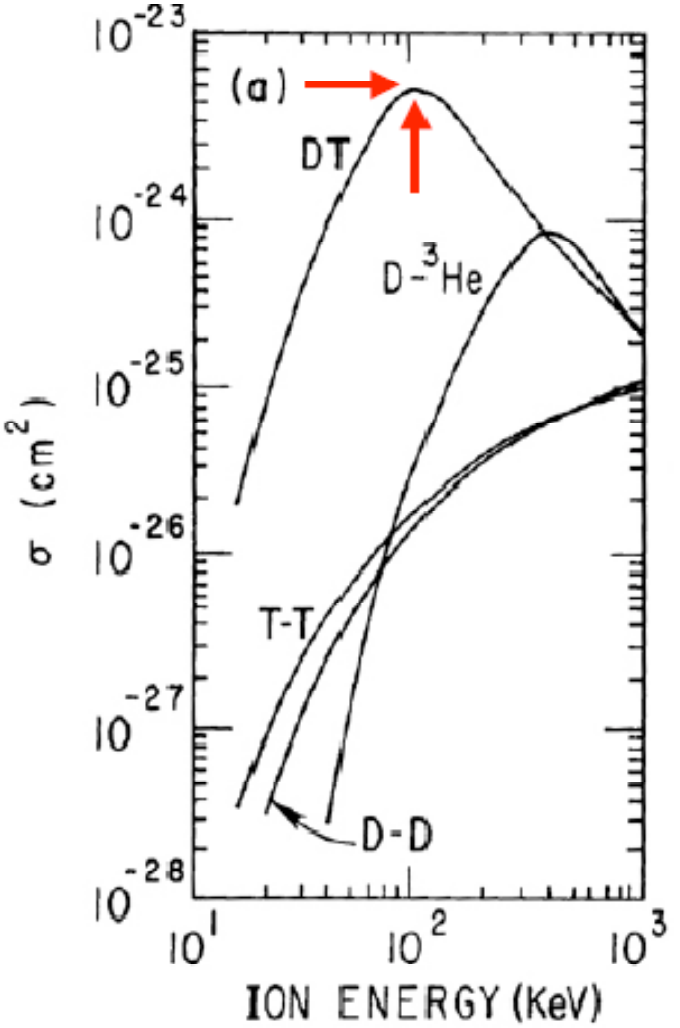


The "easiest" fusion reaction uses hydrogen sotopes: deuterium (D) & tritium (T)

$$ {}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1 $$

(3.5 MeV) (14.1 MeV)

Energy/Fusion: $\varepsilon_f = 17.6$ MeV



Nuclear cross sections

Fusion History: The Russian Point of View…

- 1928.G.Gamov -the theory
- 1930.Olifant,Kurchatov,Sinelnikov, exp.- proton beam, Li target
- 1932.Bucharin proposals to Gamov: Moscows electricity every night!
- Gamov left USSR
- 20 years pausa
- …..*not quite correct!!!*

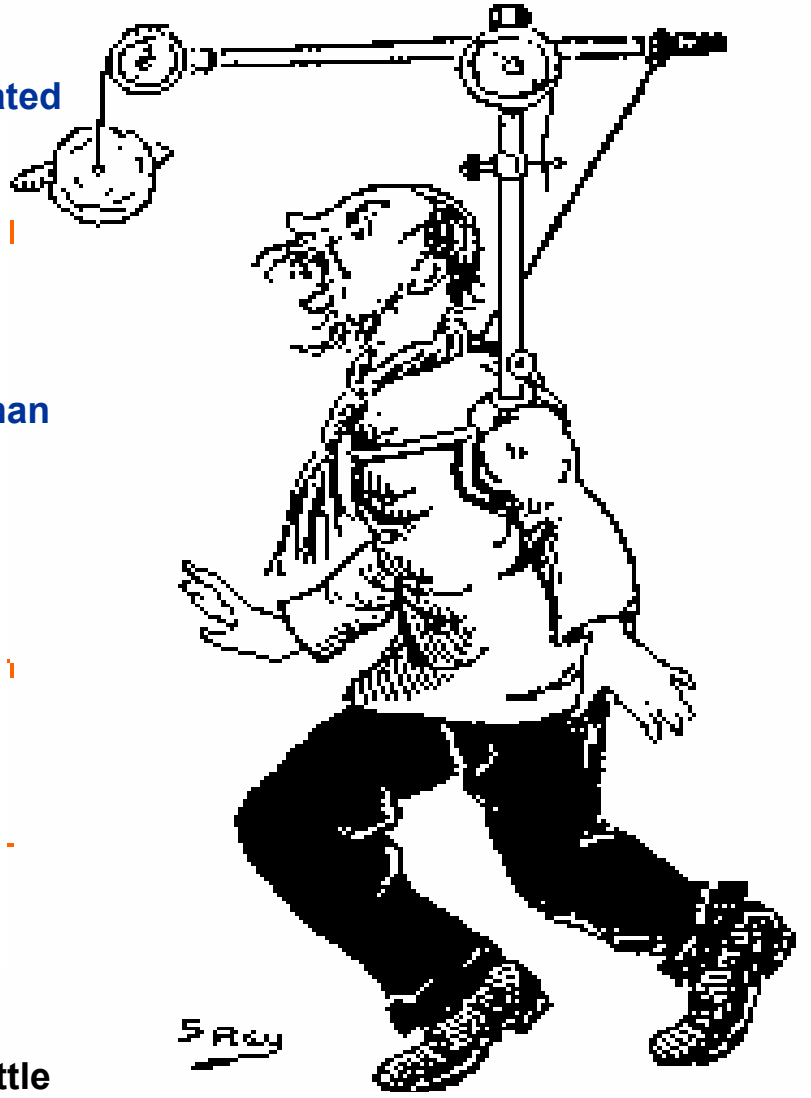
E. Velikhov; AAAS 2008 Annual Meeting

What did the Fusion Community Promise?

A short history of Fusion

- $E = M * C^2$
- 1900: “the Mass deficit” on the sun
- 1920: Hydrogen to Helium “burning” process was speculated
- 1928: Gamow uses “tunnel effect” to explain fusion
- 1934: Rutherford D+T=>He
- C.F. Weizsäcker/H.Bethe: Proton-Proton chain
- 1939: H. Bethe,’Energy Production in Stars’; Nobel P 1968
- 1945: Fermi+Teller: Magnetic confinement of hot plasmas
- 1946: first patent in Britain
- 1951: Péron and the Stellarator; R. Richter: Austrian/German
- 1951: *L. Spitzer*: Stellarator experiment in Princeton. –
- 1950: Sacharow+Tamm first linear device:
  - 1955: first TokamakTMP
- 1955: J.D. Lawson: “Lawson Criterion”
- 1957: ZETA
- 1958: Kurchatov announced effort of Nuclear Fusion
- 1968: L.Artsimowitsch: “Confinement” and the way to “break” even.
- Europe: 1958 foundation of Euratom and the way to JET which was planned in England, thought to be build in Garching and finally began operation in 1983 in Culham.

- Chernobyl disaster led to a decreased interest in nuclear energy…(56 direct death, 47 emergency workers, ~6000 cancer cases)
- In the middle of the ’90s: price per barrel ~20$, and very little investment was done in alternative energies…



The dangling “Carrot” ….

Confinement

- Confinement: the energy balance in a fusion reactor. The particles in a reacting plasma have been heated to a high temperature
- This requires an input of energy which is wasted for ions which are lost before they undergo an energy producing fusion reaction
- Therefore confinement must be sufficiently good so a large enough fraction of the ions react before their energy is lost
- This leads to a simple criterion, first derived by Lawson, that the product the density n in the plasma and the confinement time t must be greater than a given number

Lawson: The Fusion Lingo

- Confinement Time

$$\tau = \frac{\text{Energy in the Plasma}}{\text{Energy lost per sec}}$$

- Density

$$n = 1\text{-}2 \text{ x } 10^{20} \text{ particles m}^{-3}$$

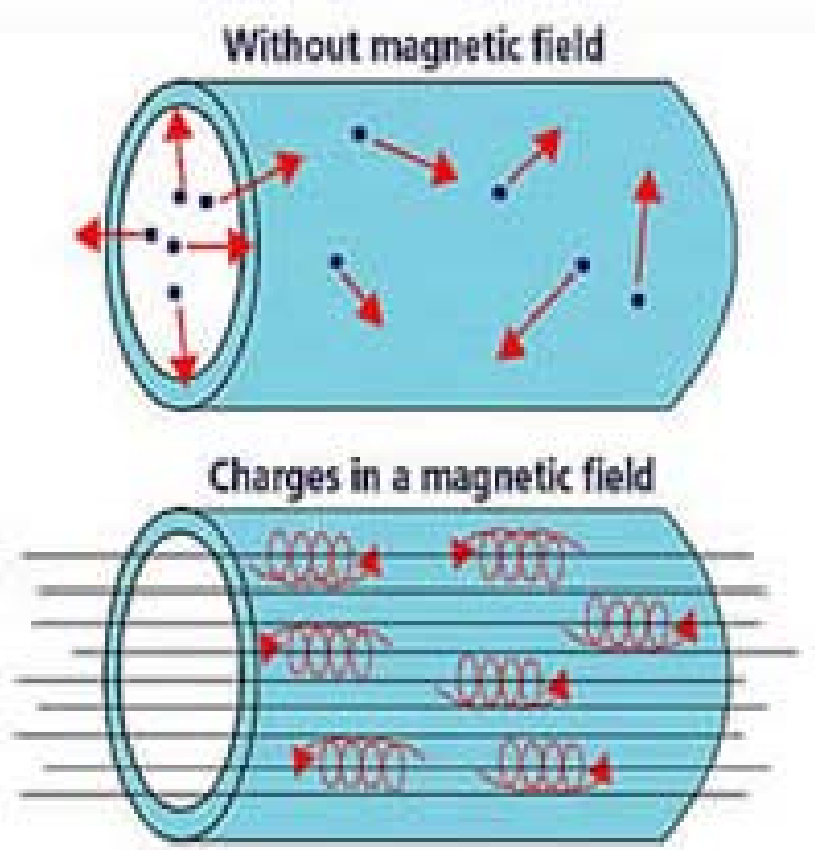
- Temperature

$$100\text{-}200 \text{ Million Kelvin}$$

$$n \cdot \tau \cdot T \geq 3 \cdot 10^{28} \qquad \frac{Kelvin}{m^3 \cdot \text{sec}}$$

Magnetic Confinement

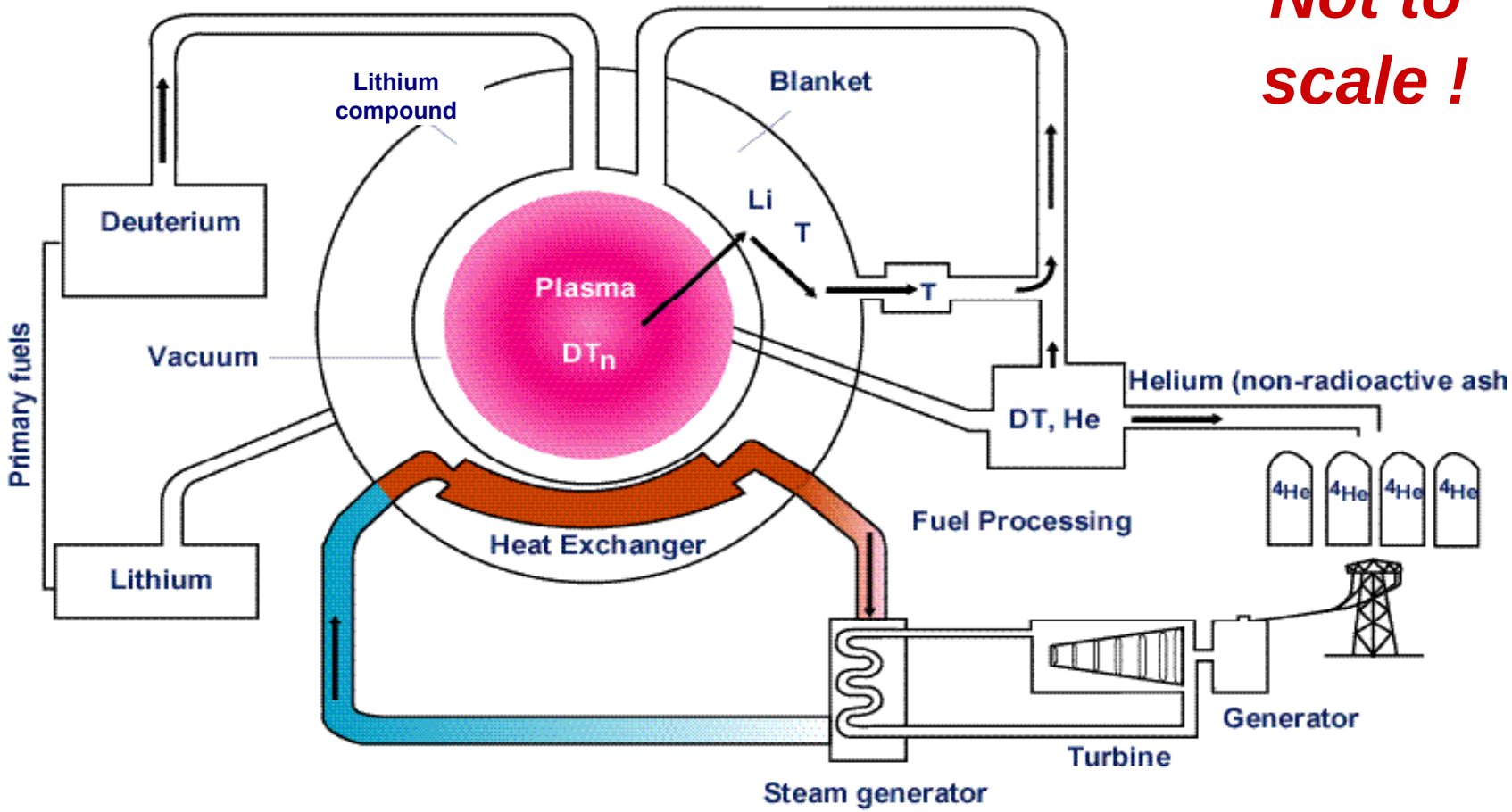
- Lawson:
  - Plasma density
  - Confinement time
  - Plasma temperature
- But: the plasma does not behave !!!
  - Instabilities
  - Material problems
  - contamination



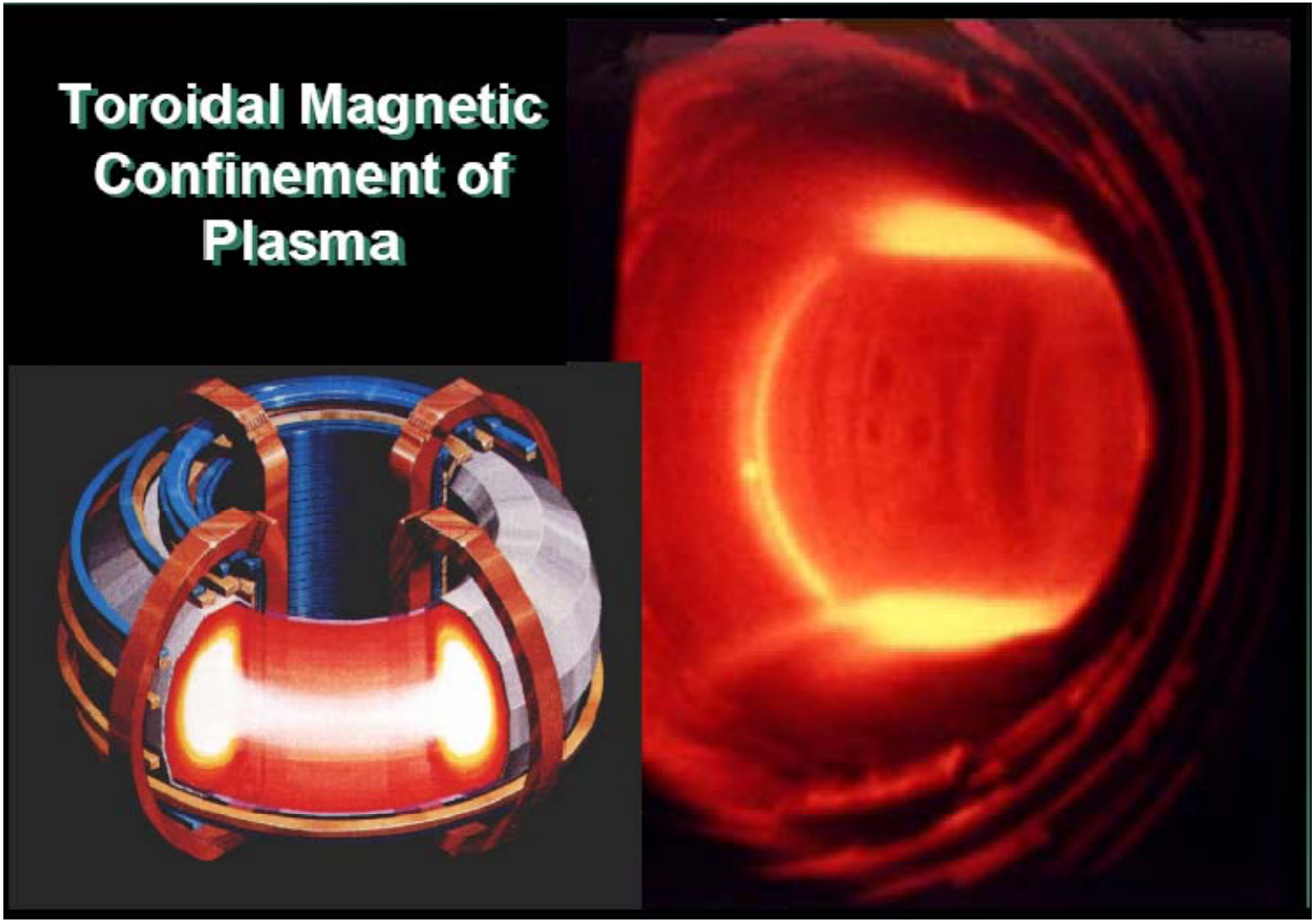
Basic Ingredients for Fusion

- A large Vacuum tube to hold gas
- A magnetic field
- Radio frequency heating

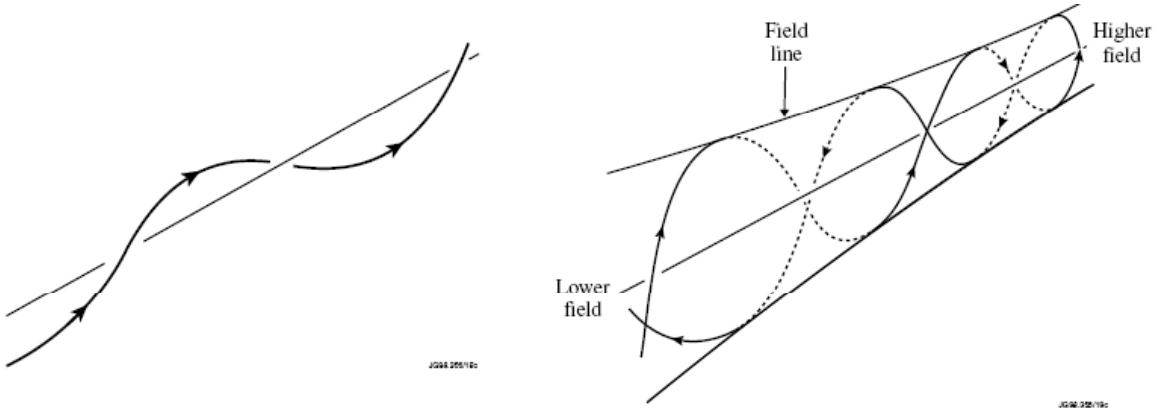
A Fusion power plant would be like…



The Basic Tokamak



The Torus



Magnetic Bottle

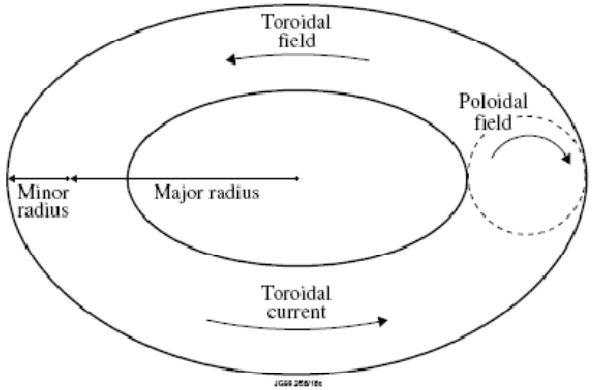
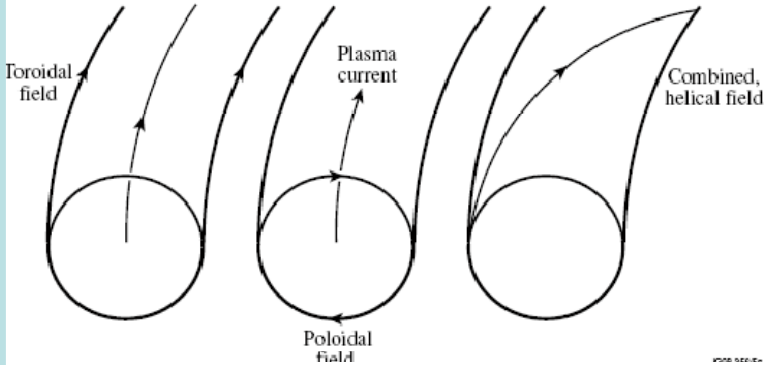
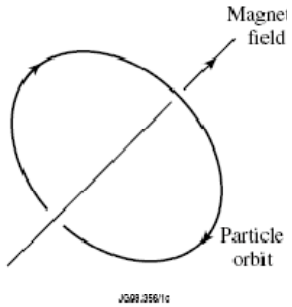


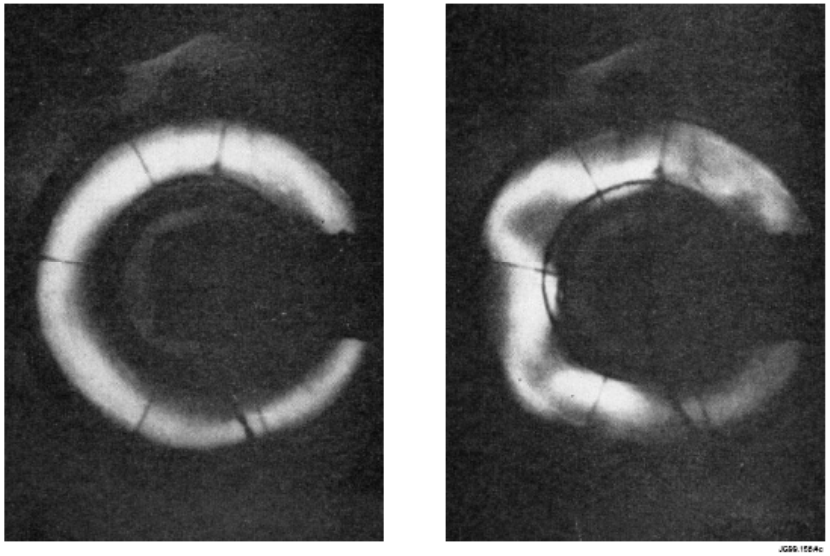
Figure 3.1. The currents and fields in a tokamak plasma.

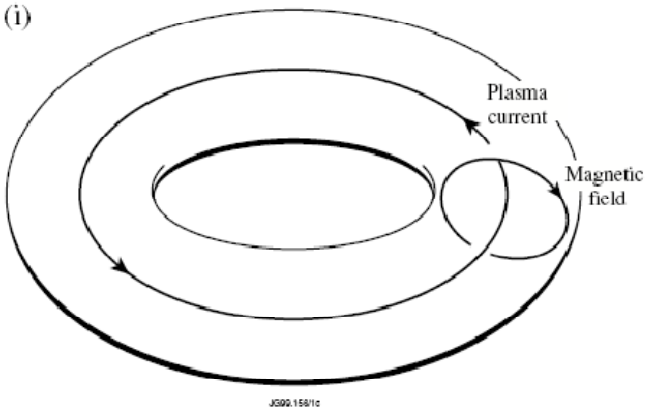
- Ohmic heating:~R*I^2
- Resistivity dependent on temperature of electrons: $\approx \frac{1}{T_e^{3/2}}$
- The ohmic heating is very strong at low temperatures but becomes less effective at higher temperatures



Life is not that easy…







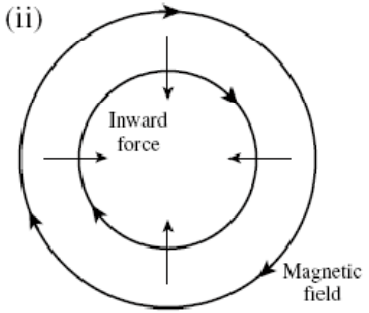
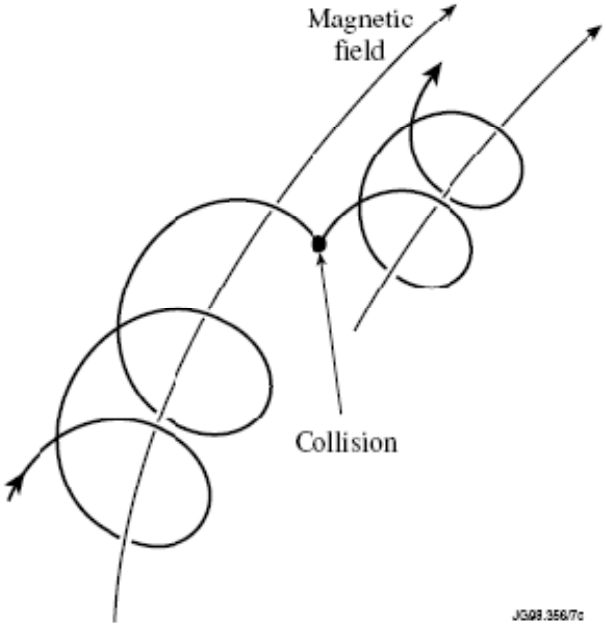
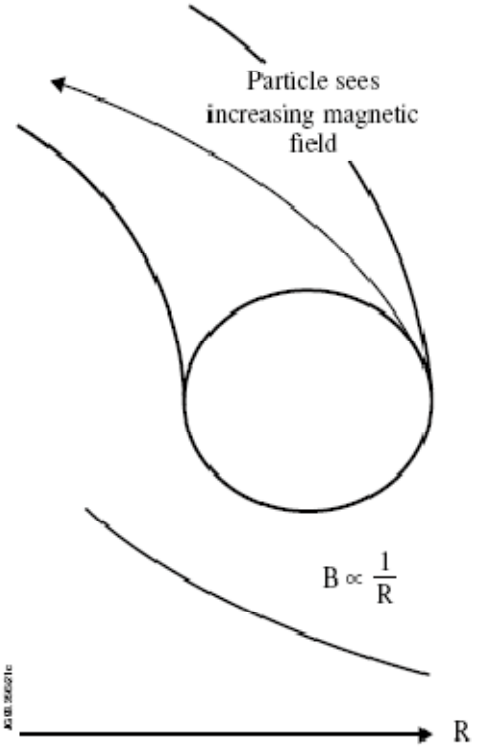


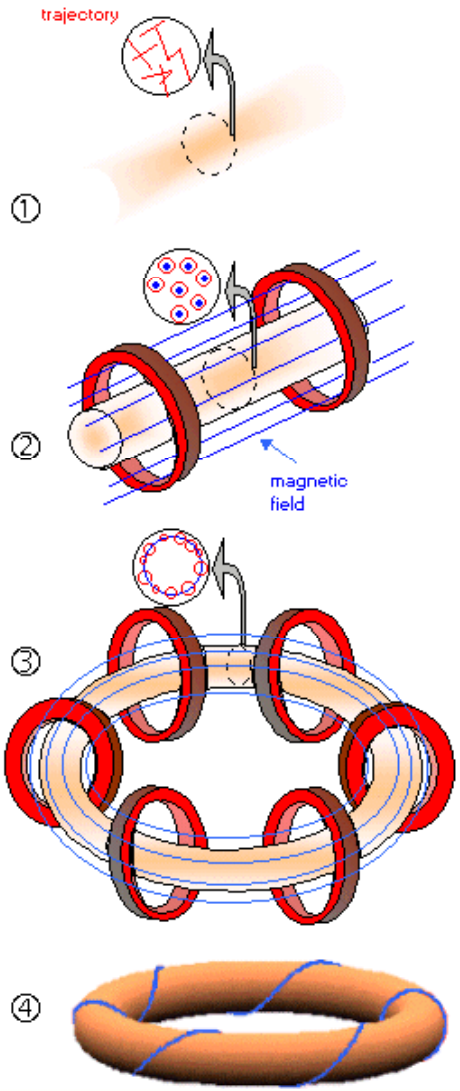
Figure 1.3. Photographs from early pinch experiments showing how the discharge initially forms a symmetric toroidal ring, but then develops a kink instability.

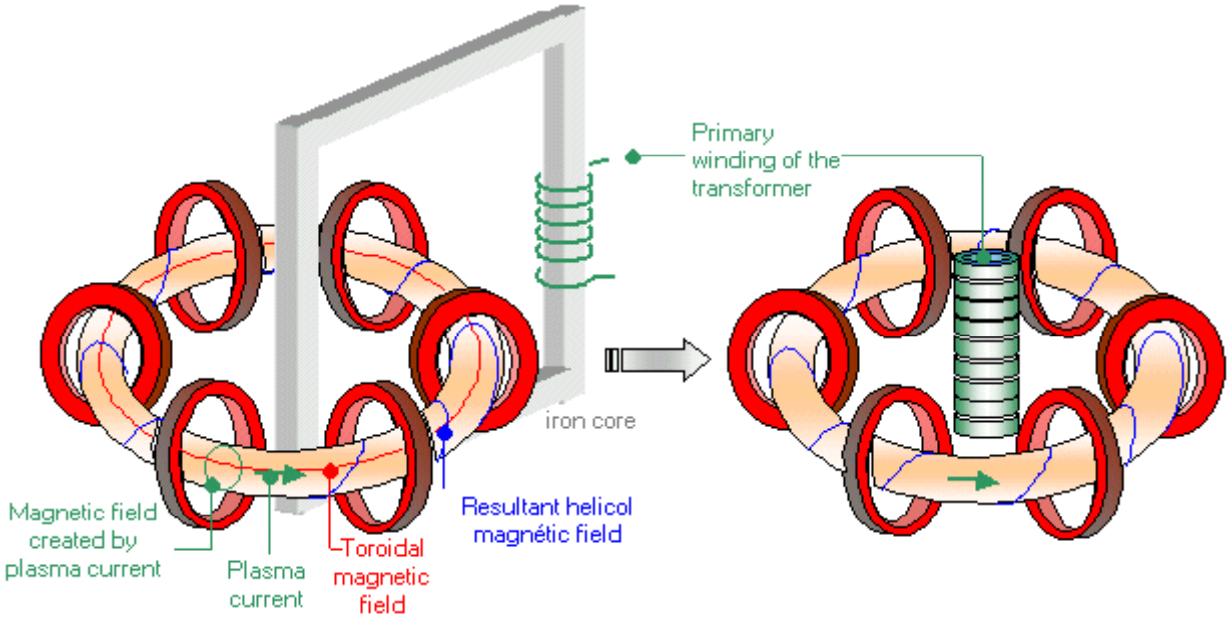
Plasma Stability

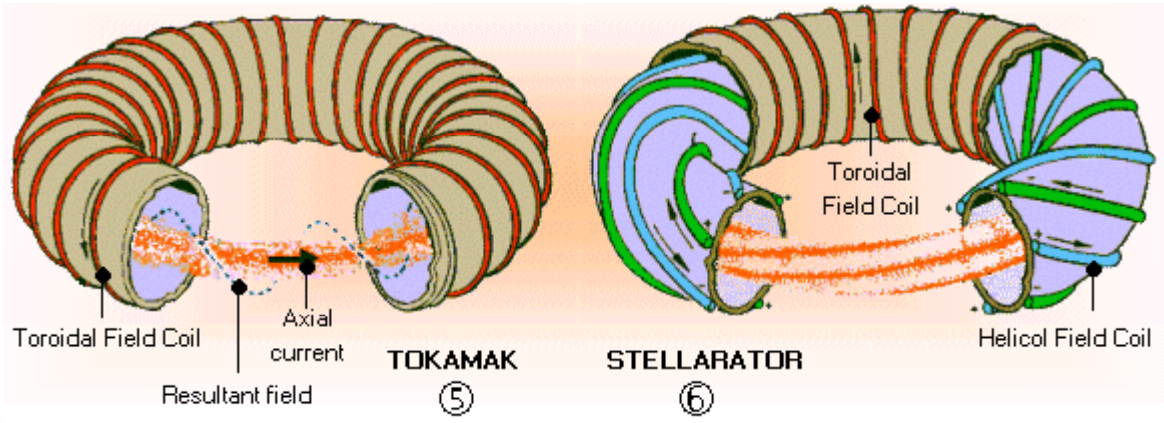




Basic Principle of Stable Motion of Ions in Magnetically confined Plasma

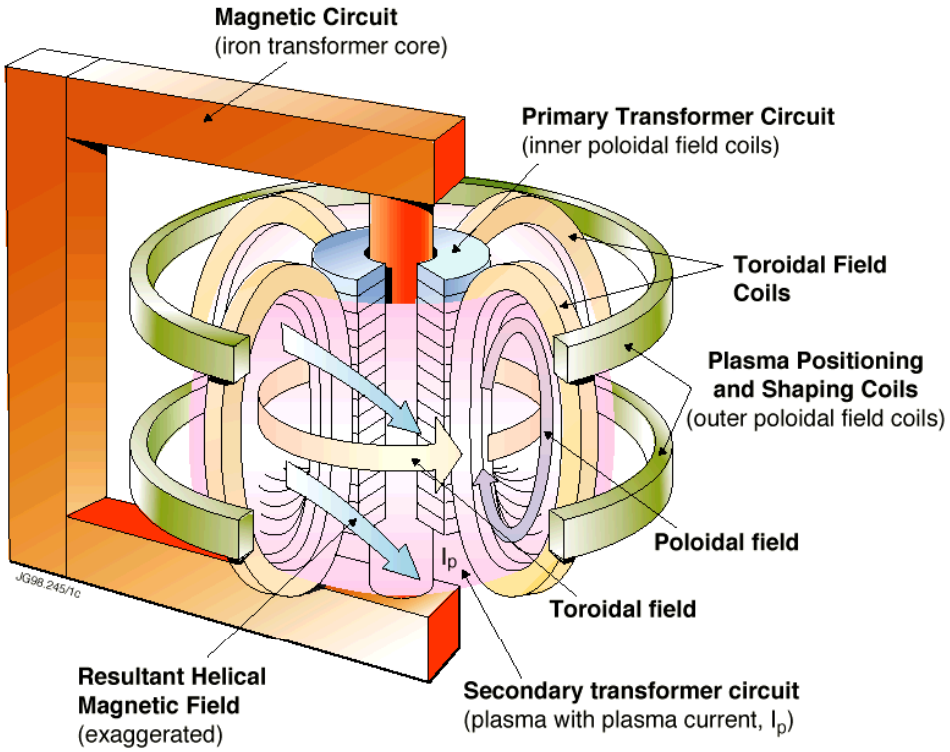


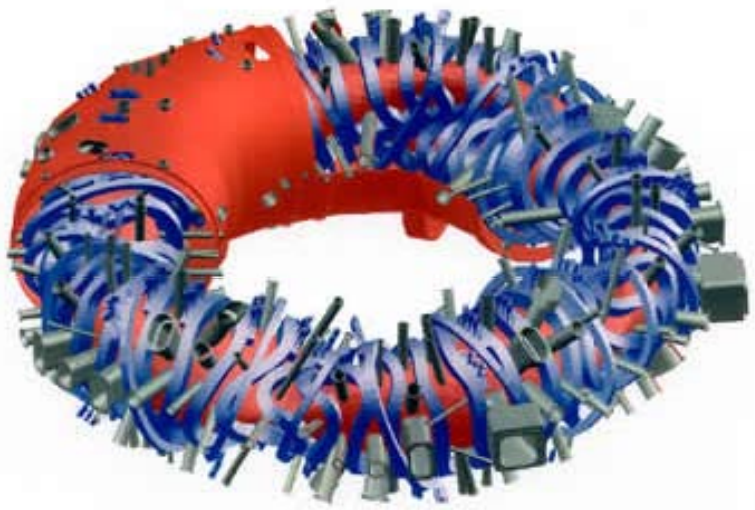


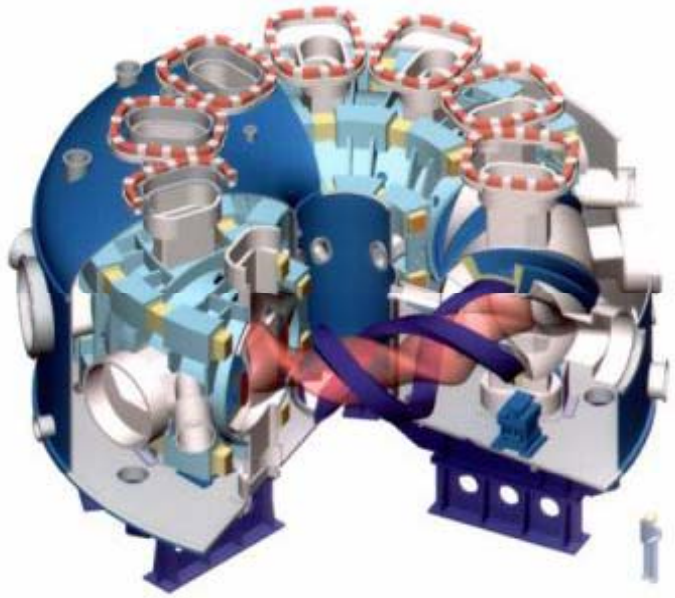


Tokamak and Stellarator

"тороидальная камера в магнитных катушках" (*toroidal'naya kamera v magnitnykh katushkakh*) — toroidal chamber in magnetic coils (Tochamac)).



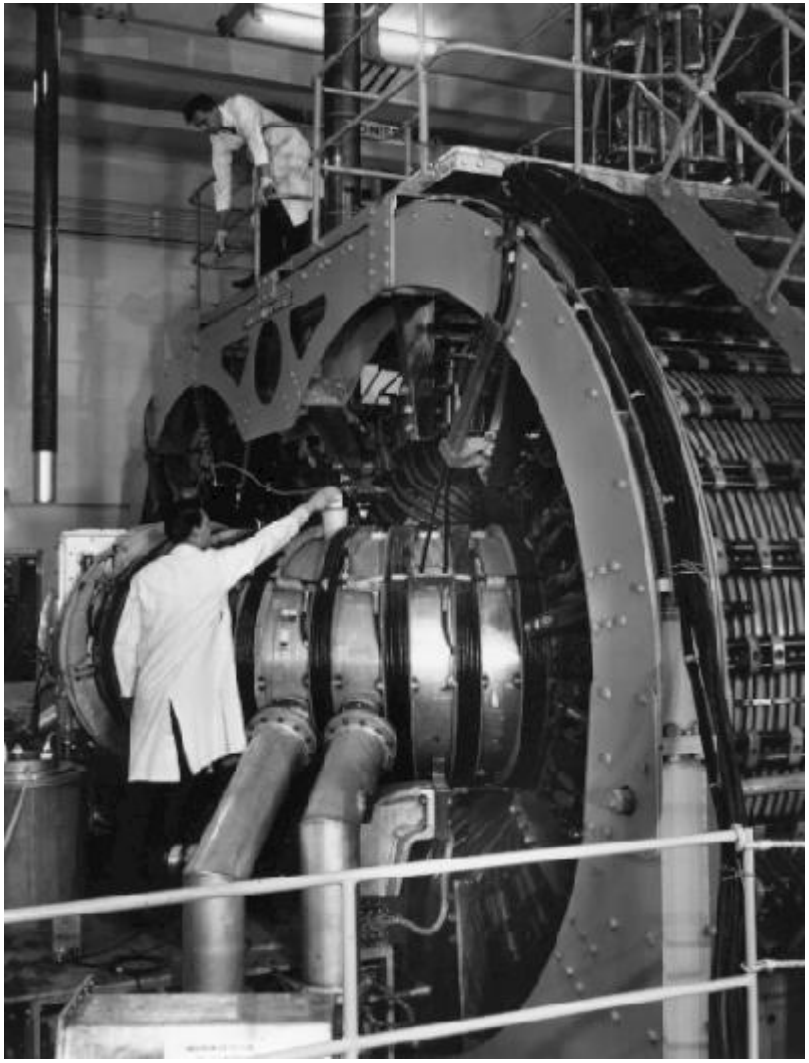




The First Devices

IAEA: 1958 First Geneva Conference

The 40’s-50’s: ZETA



- 1946 J.Tompson,M.Blecman - DD, 9MW thermal,torus , 500 kA.
- 1944-46 Los Alamos: E.Fermi, E. Teller, J.Tac, C.Ulam
- 1948 P.Tonemann exp.J=27 kA.
- 1951 X.Peron (March 21)
- 1951 L.Spitzer Stellarator B=2T, beta=50% (april)
- 1951 Stalin sign Order for MTR (May 5)
- 1955 first Tokamak TMP
- 1957 ZETA

1956

For the first time in the world at the International Conference (Harwell, UK) I.V. Kurchatov openly declared on behalf of the Soviet Government that the Soviet Union has it's own fusion research program. The final objective of which is to obtain the controlled fusion reaction and to create on it's basis an inexhaustible energy source to the benefit of the mankind.

Академик Курчатов И.В.
(1902-1960 гг.)
Academician I.V. Kurchatov

Впервые в мире на международной конференции (г. Харуэл, Англия) И.В. Курчатов открыто объявил от имени Советского Правительства о том, что Советский Союз имеет собственную программу термоядерных исследований, конечной целью которых является осуществление управляемой термоядерной реакции и создание на этой основе неиссякаемого источника энергии на благо всего человечества.

Plasma Fusion Performance

Fusion power amplification: $Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$

⇒ Present devices: Q ≤ 1

⇒ "Controlled ignition": Q ≥ 30

Predicted parameters in ITER (Q=10):

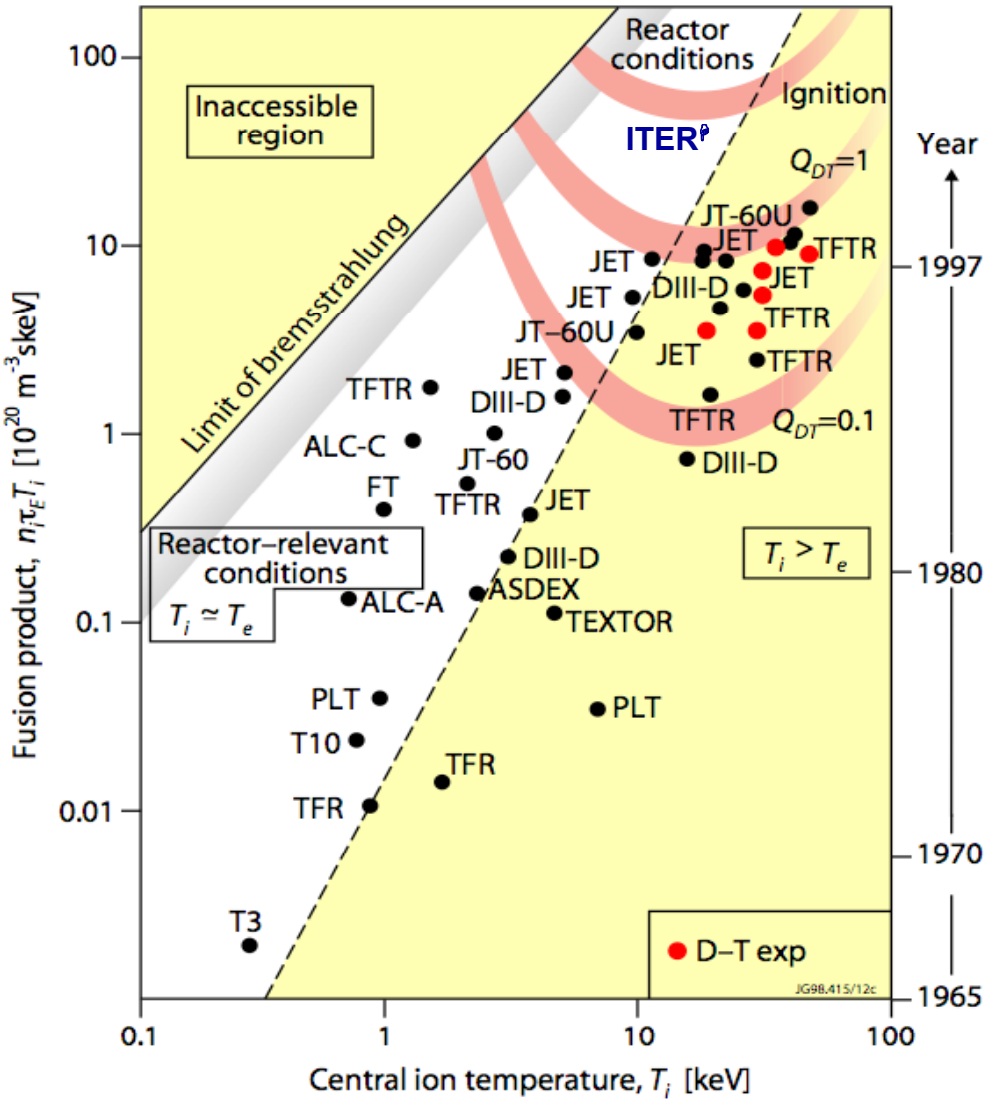
$n_i(0) \sim 10^{20}$ m^{-3}

Ti(0) ~ 25 keV

$\tau_E \sim 3.5$ s

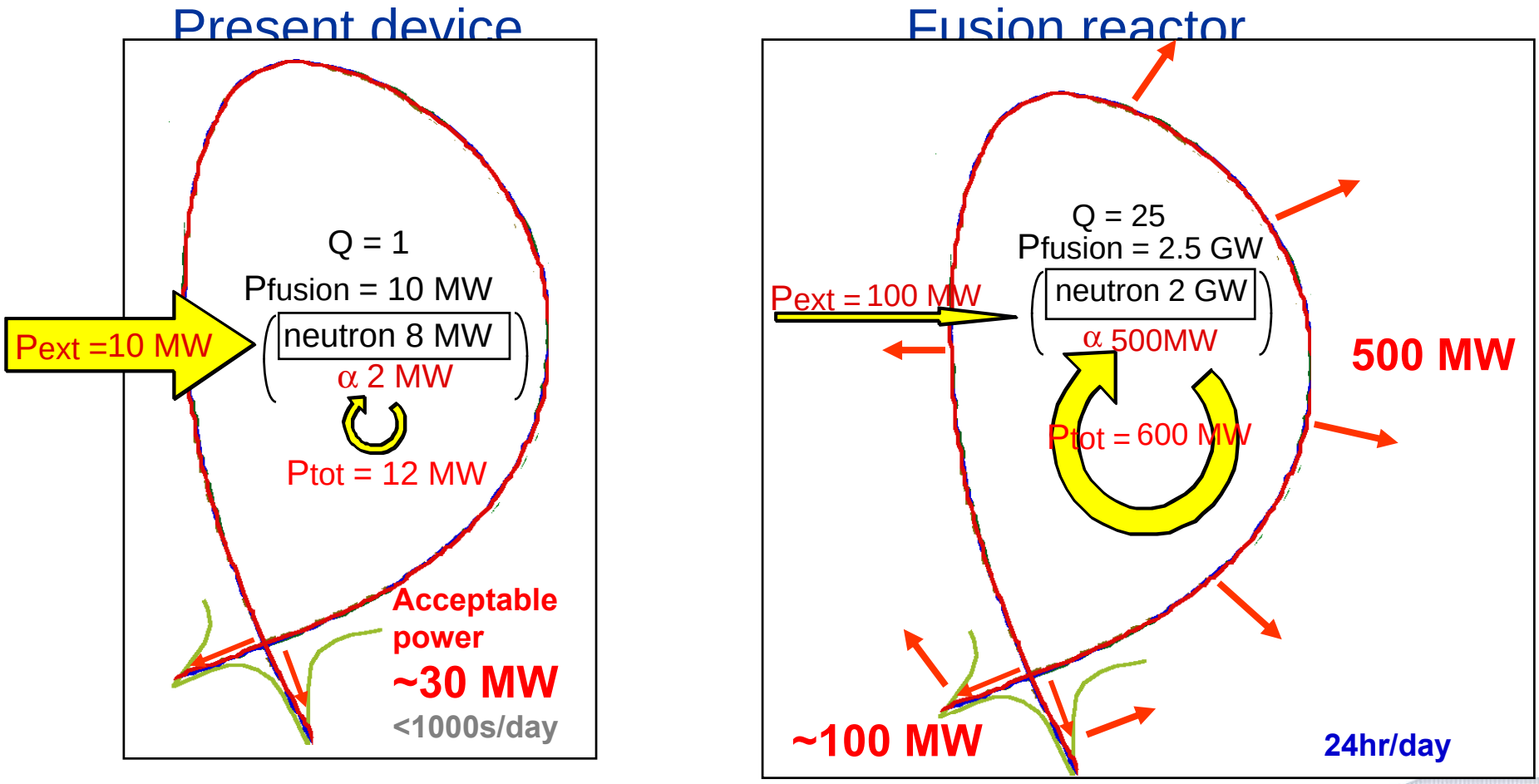
Fusion Triple Product

- Existing experiments have achieved nτT values
  ~ 1×10^{21} $m^{-3}s^{-1}keV$
  ~ $Q_{DT} = 1$
- JET and TFTR have produced DT fusion powers of >10MW for ~1s
- ITER is designed to a scale which should yield
  $Q_{DT} > 10$ at a fusion power of 400 - 500MW for ~400s

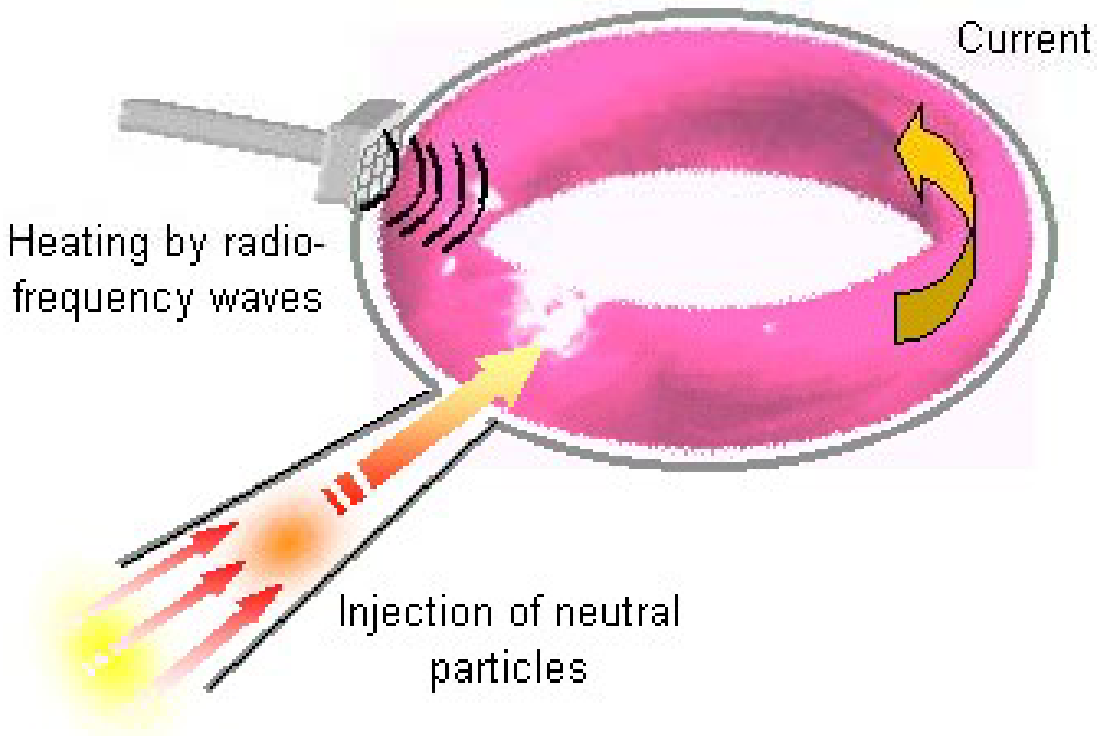


In reactor, alpha heating power is dominant

- The plasma determines its own profile.
- The major power must be widely distributed on the first wall.



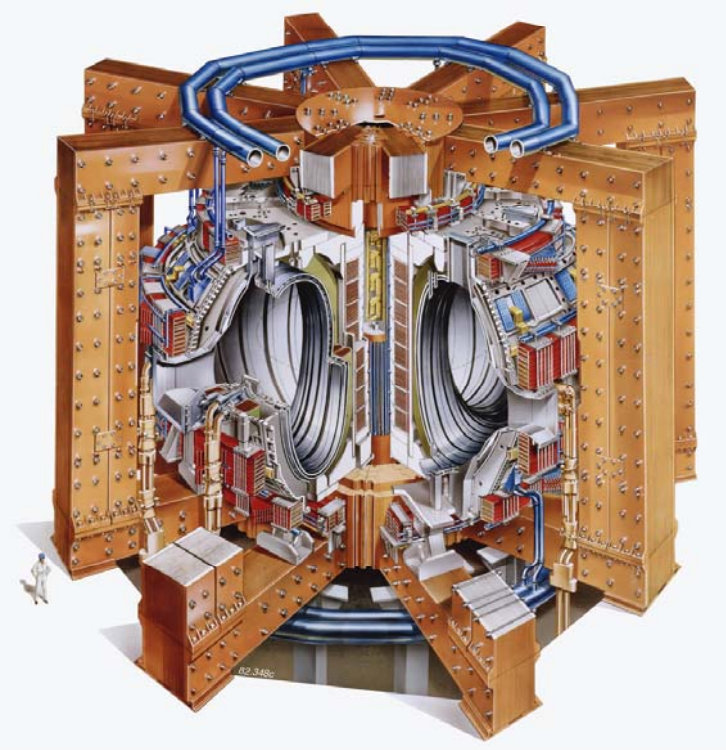
Plasma Heating

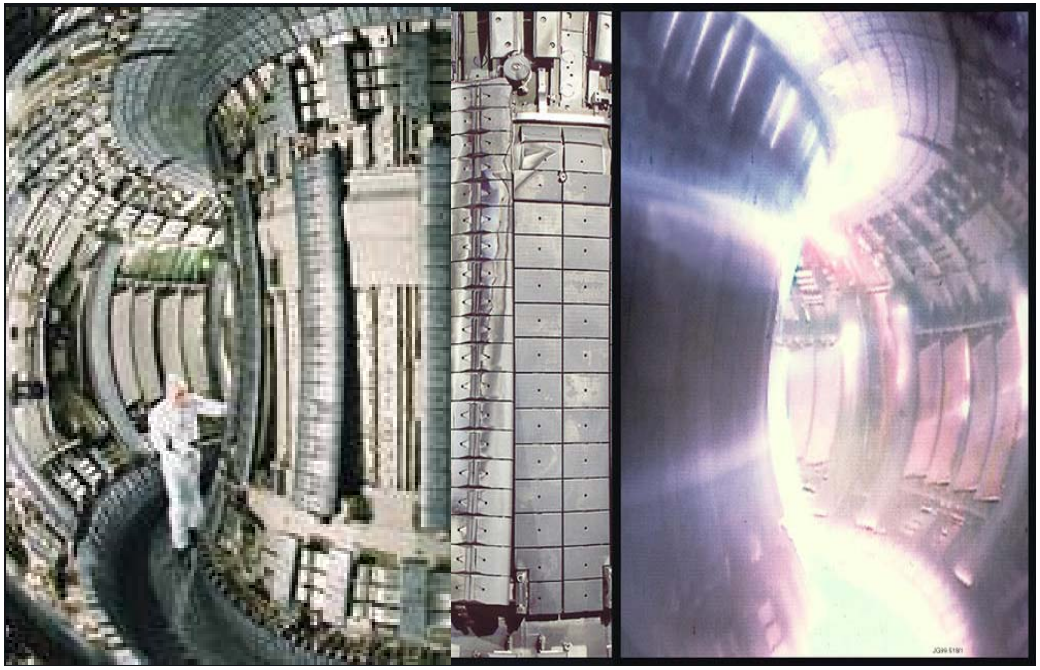


Joint European Torus (JET)

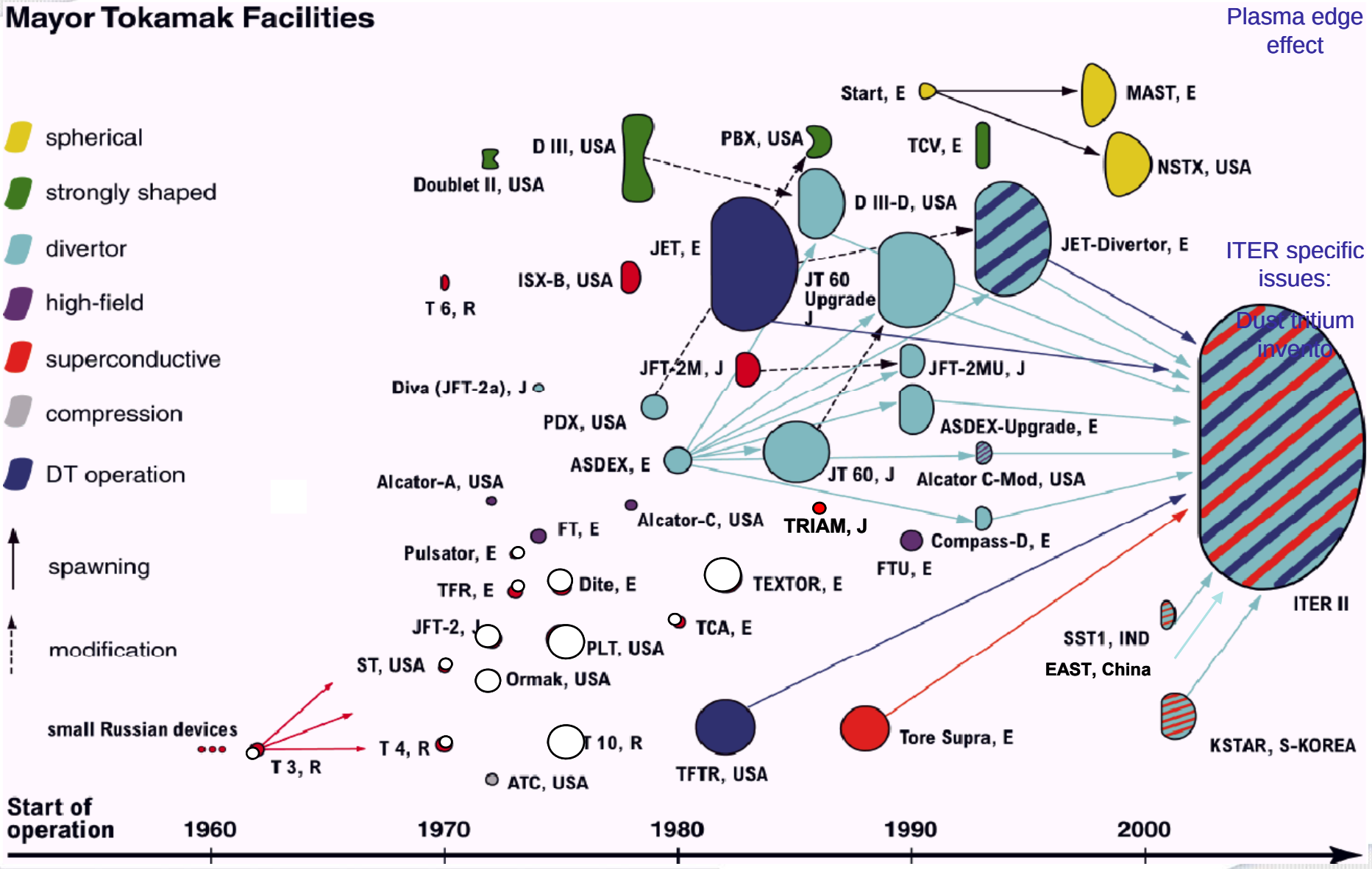
Currently the world's largest fusion research facility

Operated by UKAEA as a facility for European scientists



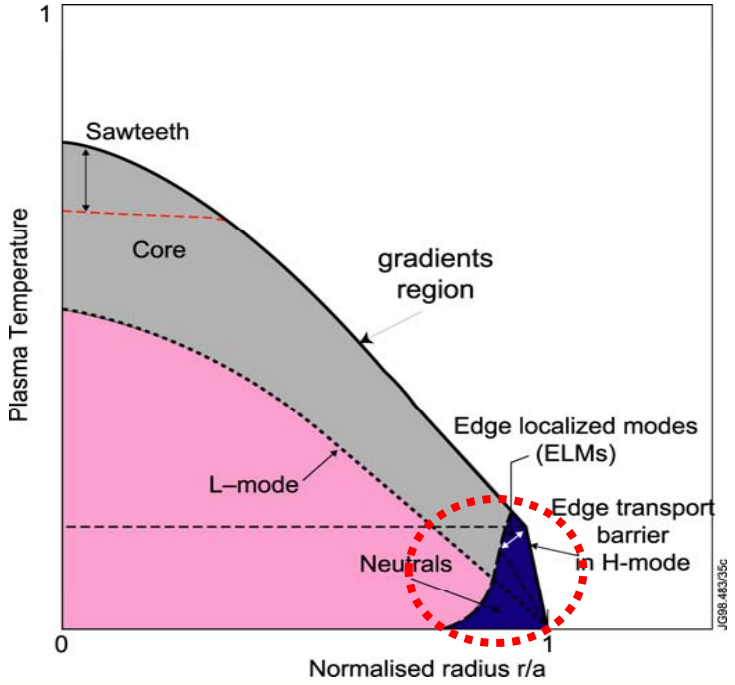


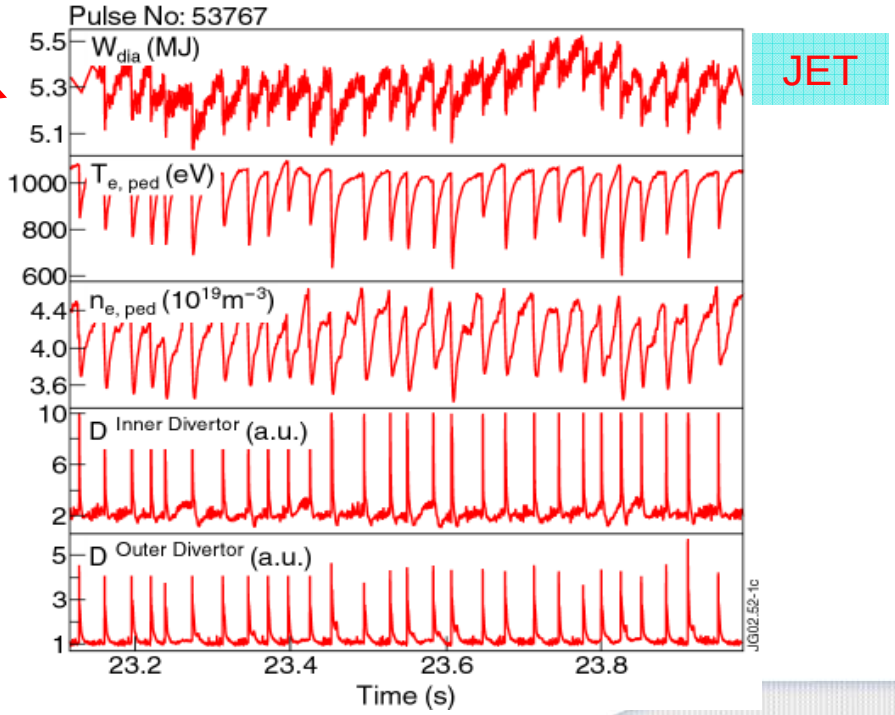
ITER, one of a kind, but not the first fusion facilitiy



ITER Plasma Scenario - ELMy H-mode

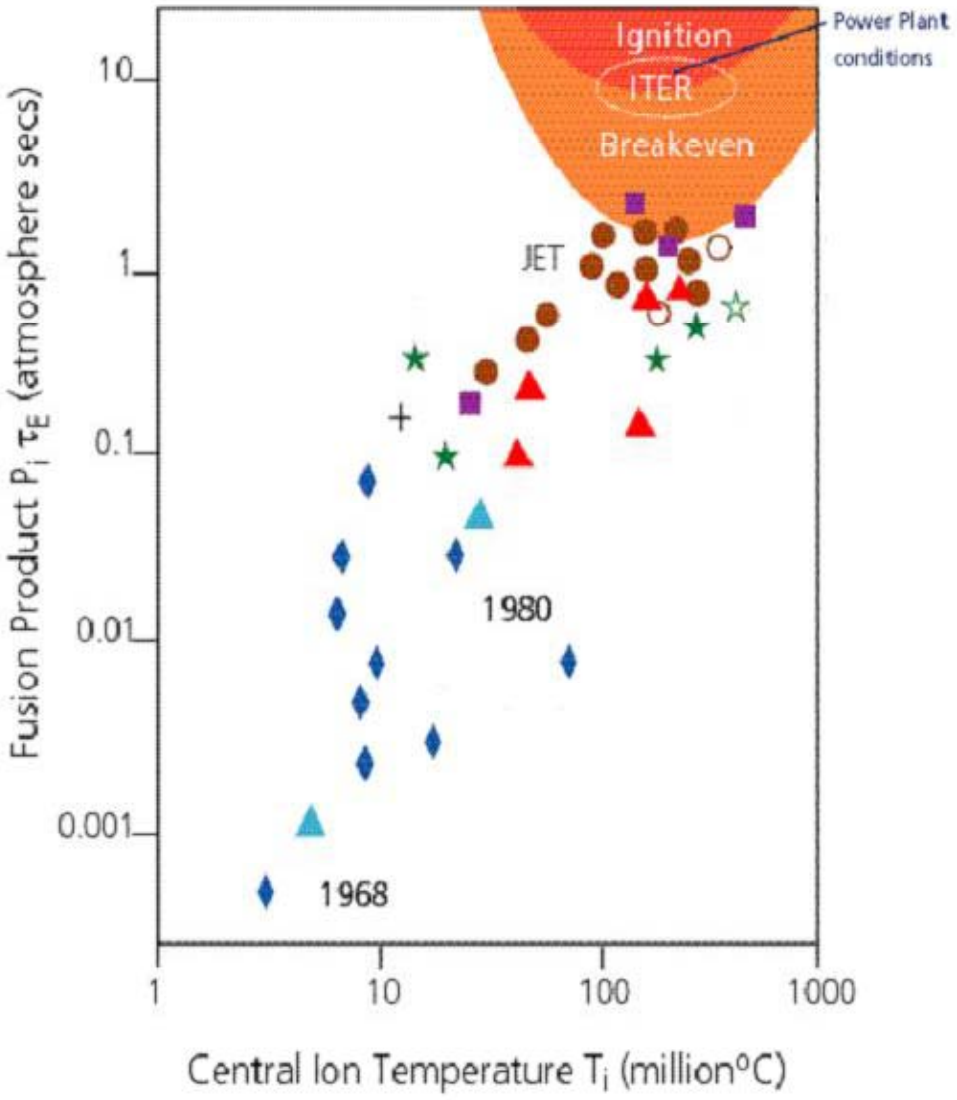
- Conventionally, plasma confinement regimes denoted L-mode and H-mode
  - The difference between these modes is caused by the formation of an edge pedestal in which transport is significantly reduced - edge transport barrier
  - edge localized modes maintain plasma in quasi-stationary state



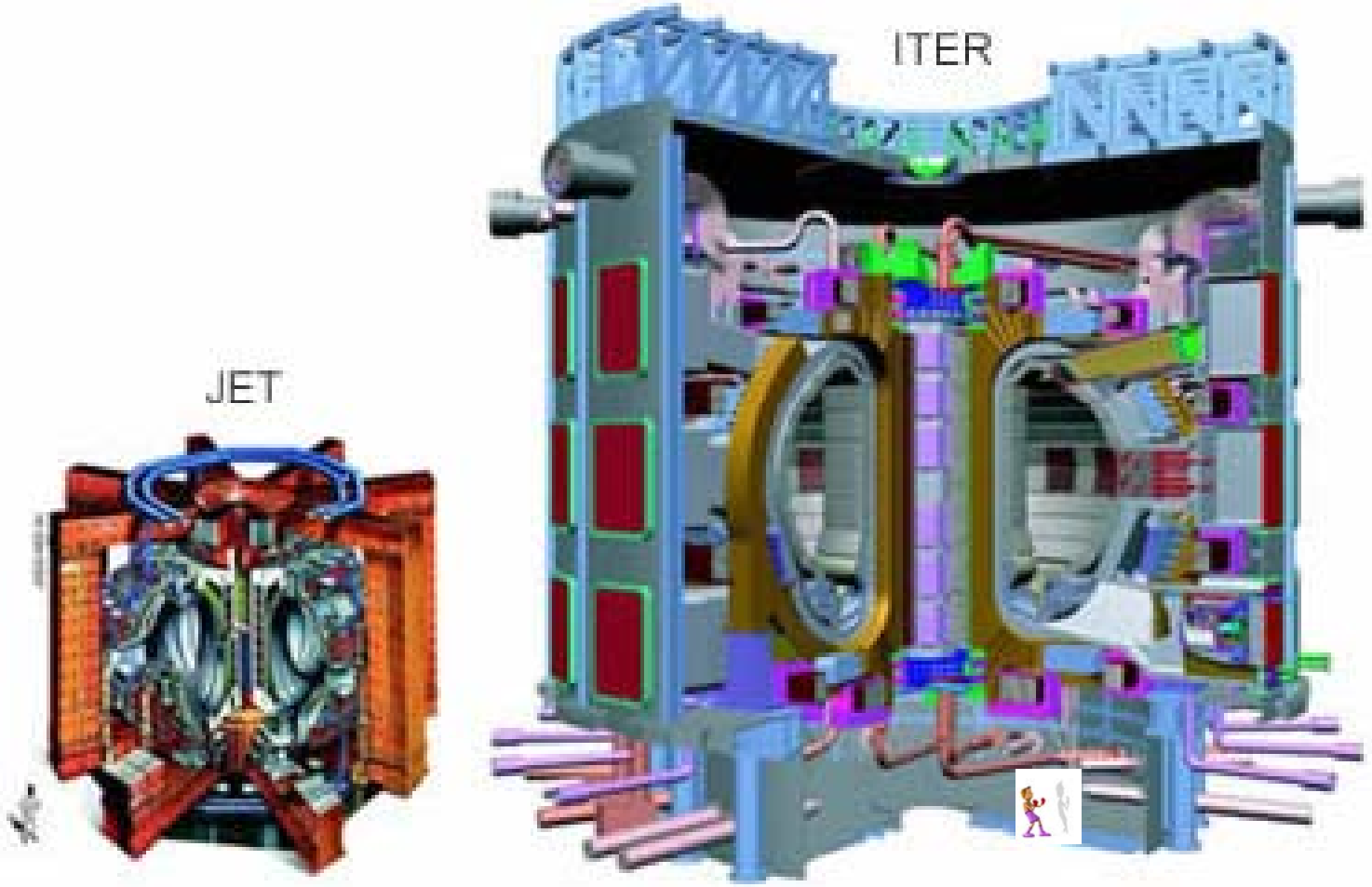


JET: The Key Facility

- JET: 16 MW of fusion power ~ equal to heating power.
- Ready to build a Giga Watt-scale tokamak: ITER



JET/JT-60/TFTR → ITER



Summary

- Basic of Fusion
- Fusion History
- Confinement
- Stability
- Tokamaks and Stellerators
- TFTR-JT 60 and JET: The state of the art
- ITER…. The next lecture!