Fusion Principles

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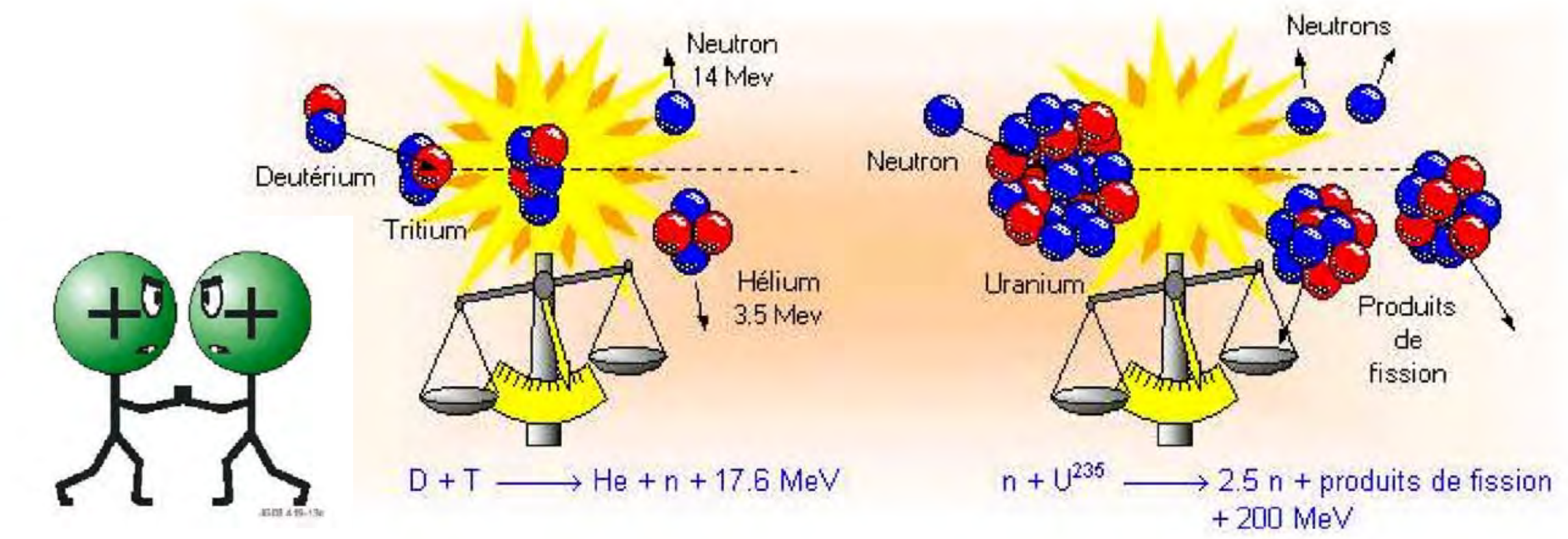
Fusion: energy source of the universe

Slide: A.J.H. Donné, SPIG 2020

Energy gain in fusion reactions



- ***$E = mc^2$*** : the reaction products are lighter than the fusing elements
- The mass is released as the energy
- To accomplish fusion the Coulomb repulsion has to be overcome

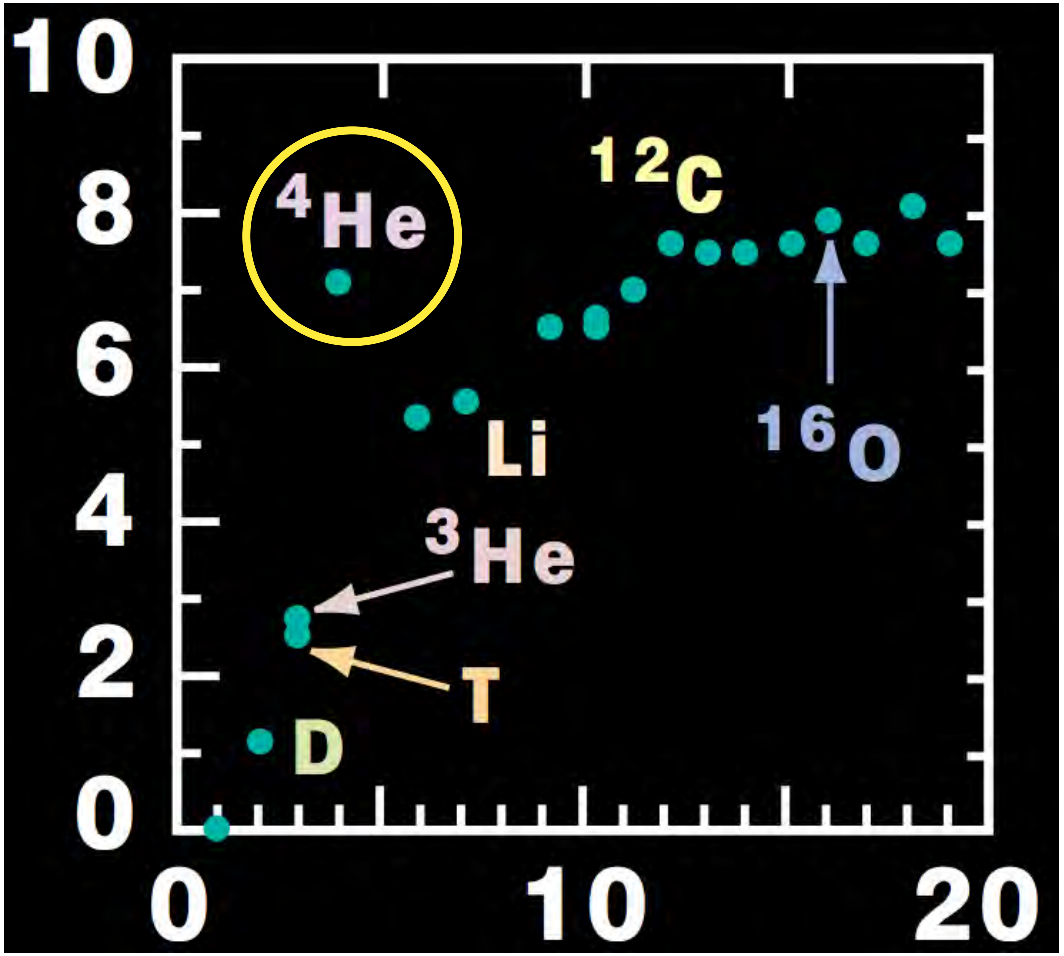
→ the nuclei must have very high energy, i.e. high temperature → plasma

- Main problem: confine the plasma until the rate of fusion reactions is large enough to generate the necessary power

Energy gain in fusion reactions

^4He has a particularly large binding energy

Binding energy per nucleon (MeV)



Nucleon mass number A

Nucleus	Total Binding Energy (MeV)
D = ^2H	2.22457
T = ^3H	8.48182
^3He	7.71806
^4He	28.29567

Large gain in energy when ^4He is one of the reaction products

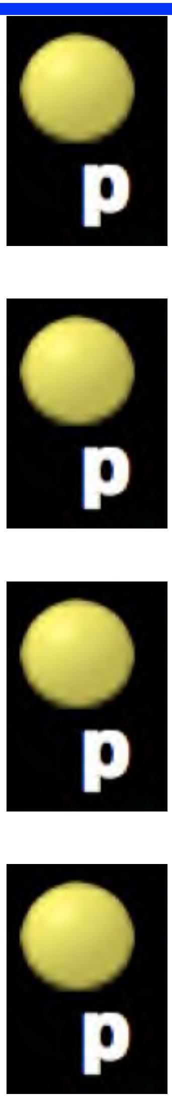
Fusion from hydrogen to helium

Fusion →

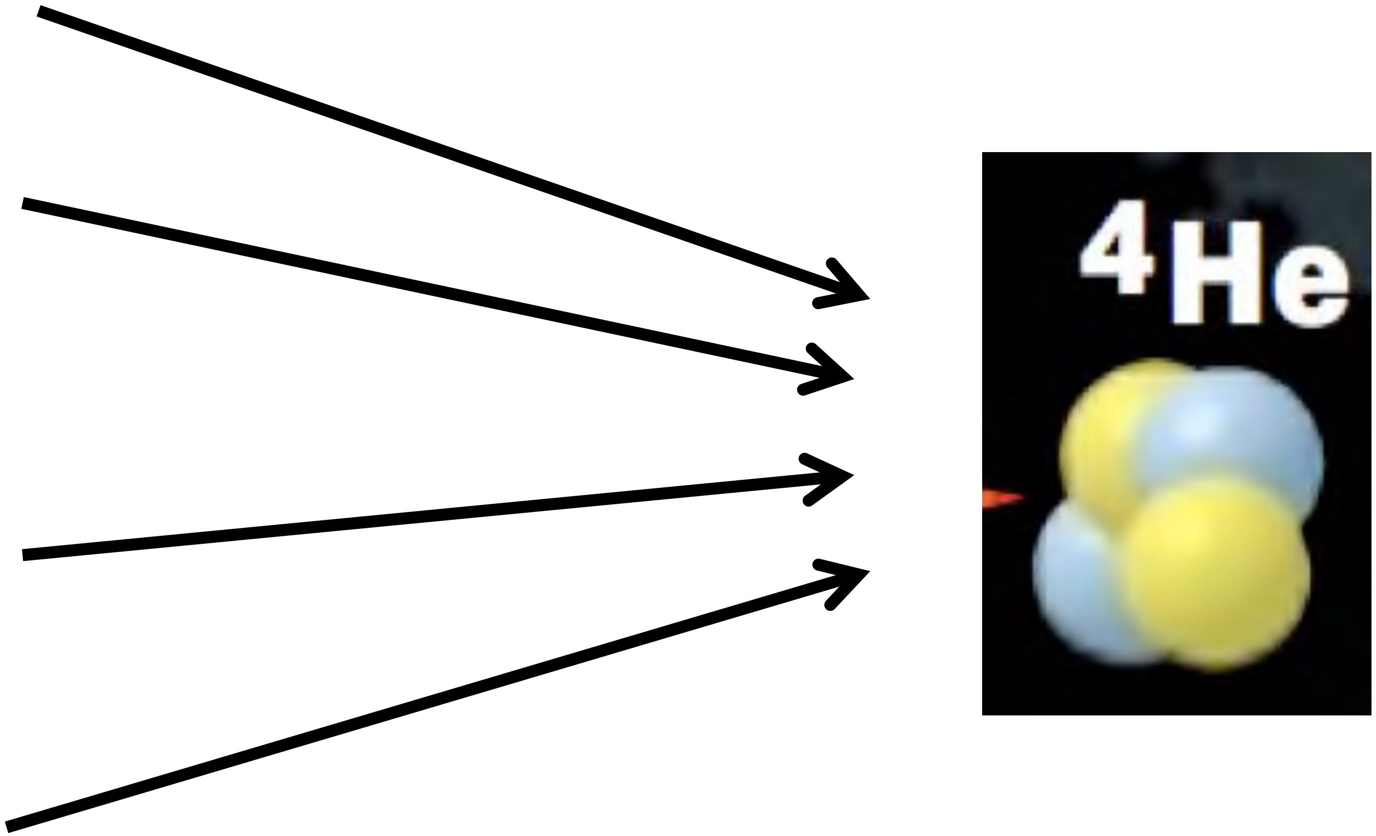
Group #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period																		
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	(117) (Uus)	118 Uuo

* Lanthanoids	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinoids	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Helium from protons only as in our sun ?



+4 → +2 ???

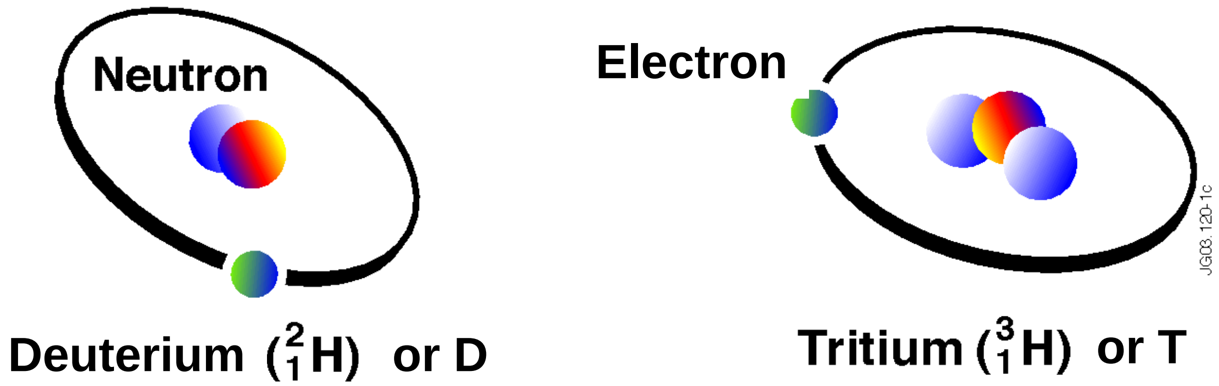


Involves conversion proton to neutron

Very difficult and slow reaction (which is good for us....)

Sun : Every second : 4 million tonnes transformed → Energy

On earth: use deuterium and tritium



Stable
Isotope

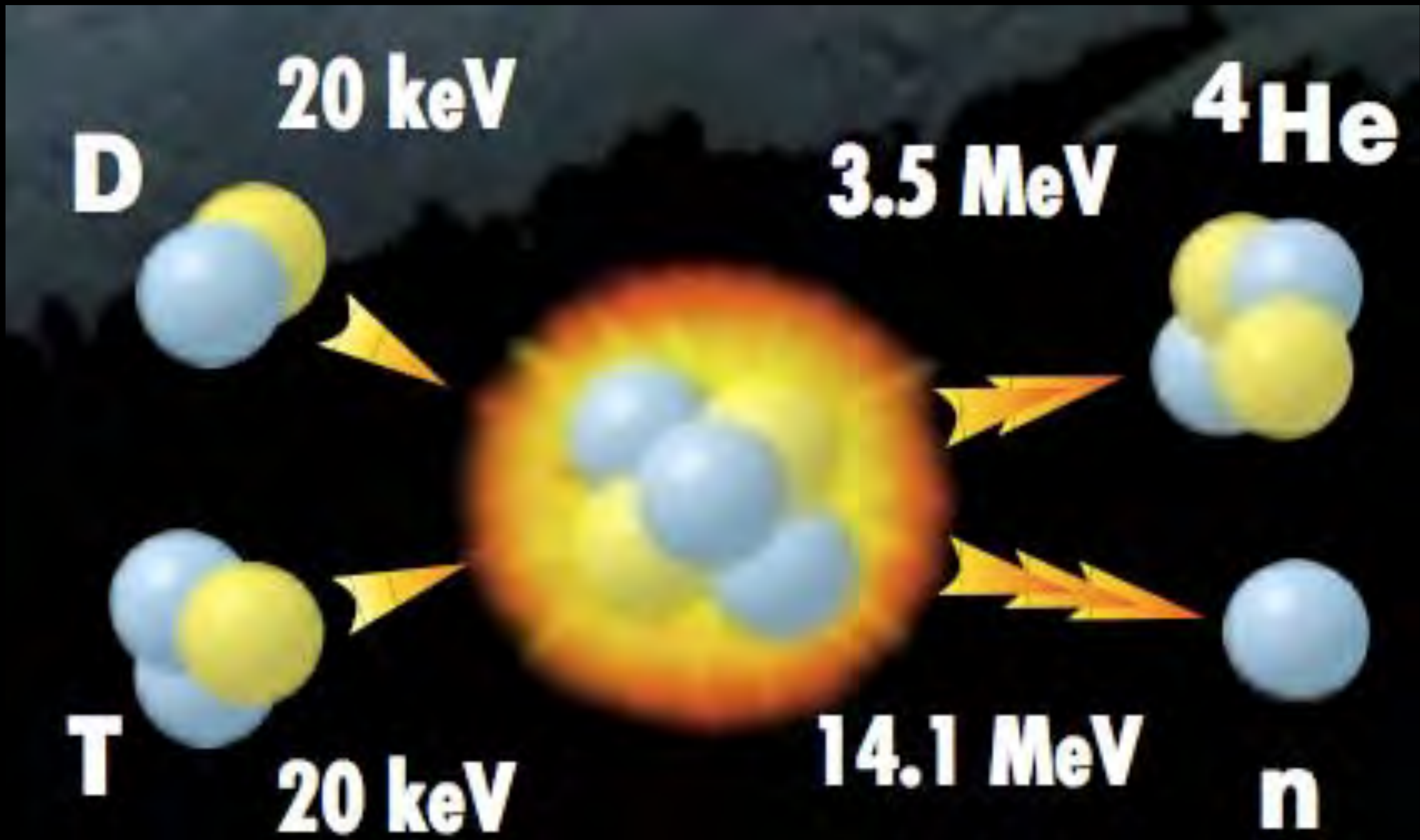
Artificial
Isotope
Half life
12.3 years

‘Easiest’ fusion reactions

Fusion Reaction		Temperature Needed (in Million Degrees)	Reaction Energy (in keV)
D + T	^{4}He + n	100-200	17,600
D + ^{3}He	^{4}He + p	~700	18,300
D + D	^{3}He + n	~400	~4,000
	T + p	~400	~4,000

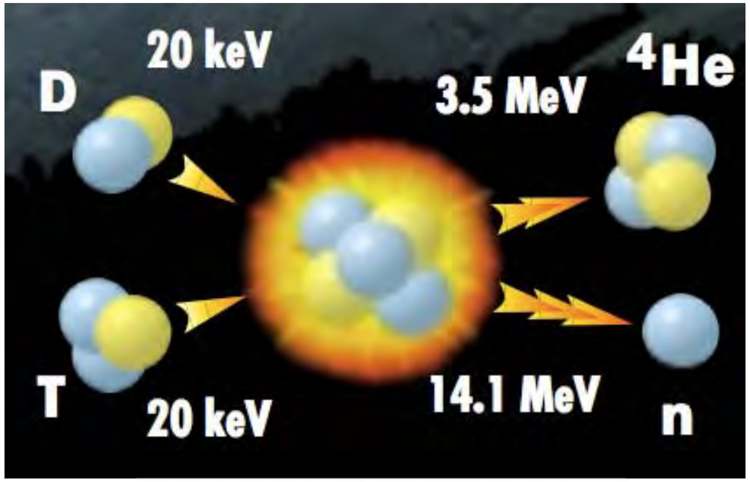
Extensive database on fusion reactions : http://pntpm3.ulb.ac.be/Nacre/barre_database.htm

The 'simplest' fusion reaction on earth

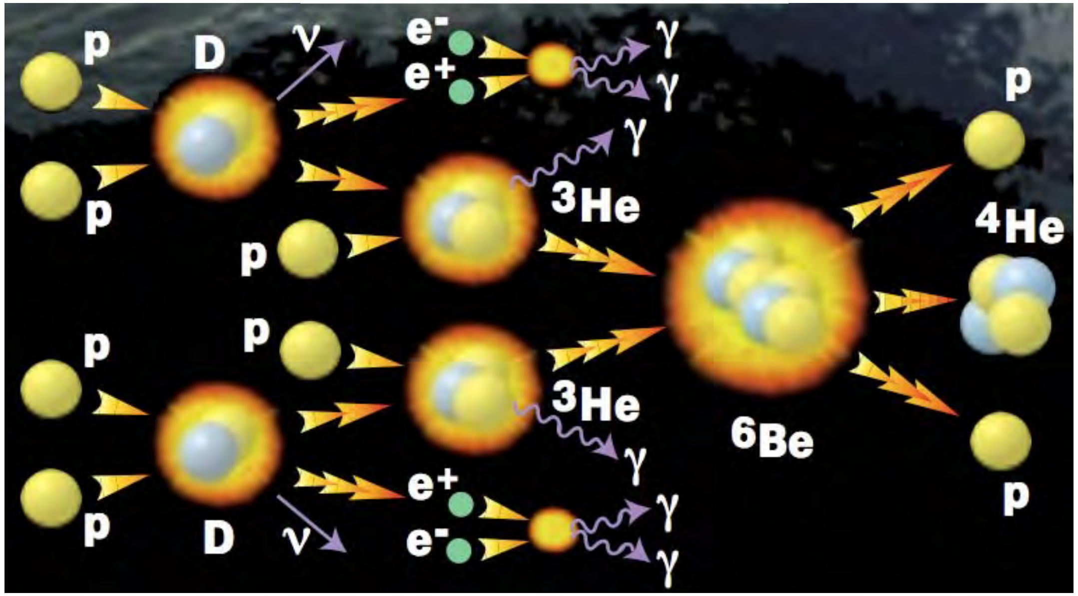


Comparison: fusion reaction on earth and in the sun

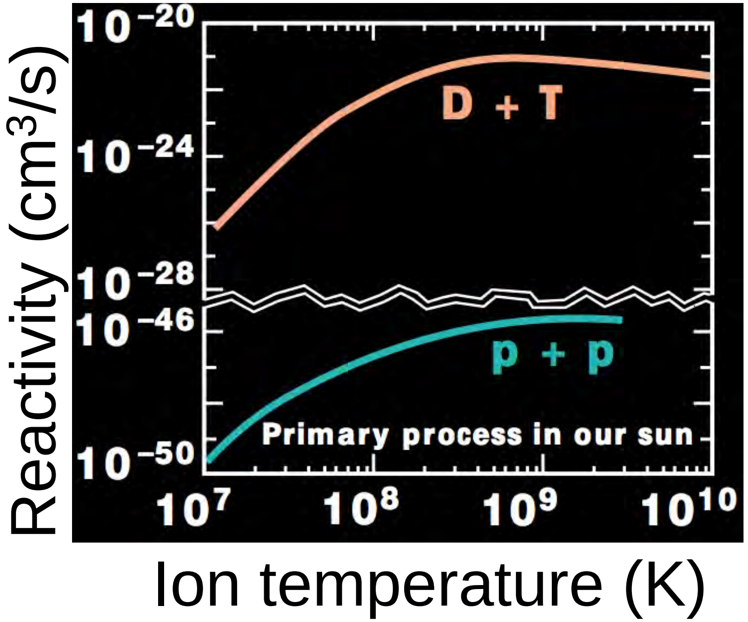
On earth (D-T)



In the sun (p-p)



D-T reaction has
10^{25} times larger
reactivity (cm^3/s)
than the p-p reaction



Fusion on earth: deuterium and tritium supply

Deuterium: from sea-water (30 gr/ton) → virtually unlimited source

Tritium is radioactive ($T_{1/2}$ ~ 12 years) → has to be produced

Breeding of Tritium from Lithium:

$$\boldsymbol{n} + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + \mathrm{T}$$

$$\boldsymbol{n} + {}^{7}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + \mathrm{T} + \mathrm{n}$$

The walls of a fusion-reactor are covered with Lithium

In-situ production of T, closed circuit → safety aspect

Lithium: deposited in earth-crust and sea-water

In summary:
fusion fuel – D and Li – is practically unlimited

The D in 3 bottles and the Li in 3 stones can supply a family with 2 kids with electricity for a year!

Advantages of fusion

- Ash is ^4He
  - — no radioactivity
  - — chemically inert : no ozone depletion, no acid rain,...
  - — no greenhouse effect
  - ⇒ Excellent environmental compatibility

- Does not imply long term storage of radioactive waste
  - — part of fuel is active (tritium), but consumed in reaction
  - — choice of structural materials to reduce long lived activity
  - ⇒ Offers prospect to recycle radioactive waste in 1-2 generations

- Inherently safe
  - — malfunction of control system does not lead to runaway
  - — 'gas burner' : shutting down gas supply stops reactor
  - ⇒ Tchernobyl like accident EXCLUDED

- Inexhaustible
  - — fuel consumption is minimal, reaction releases lots of energy
  - ⇒ Energy source for thousands/millions of years

- Energy independence
  - — no geographical dependence for fuel
  - ⇒ Avoid geopolitical difficulties

Energy needed to initiate fusion reaction

Height of the Coulomb barrier V_C

$$V_C = \frac{q^2 Z_x Z_y}{4\pi\varepsilon_0 (R_x + R_y)} \quad \text{Joule}$$

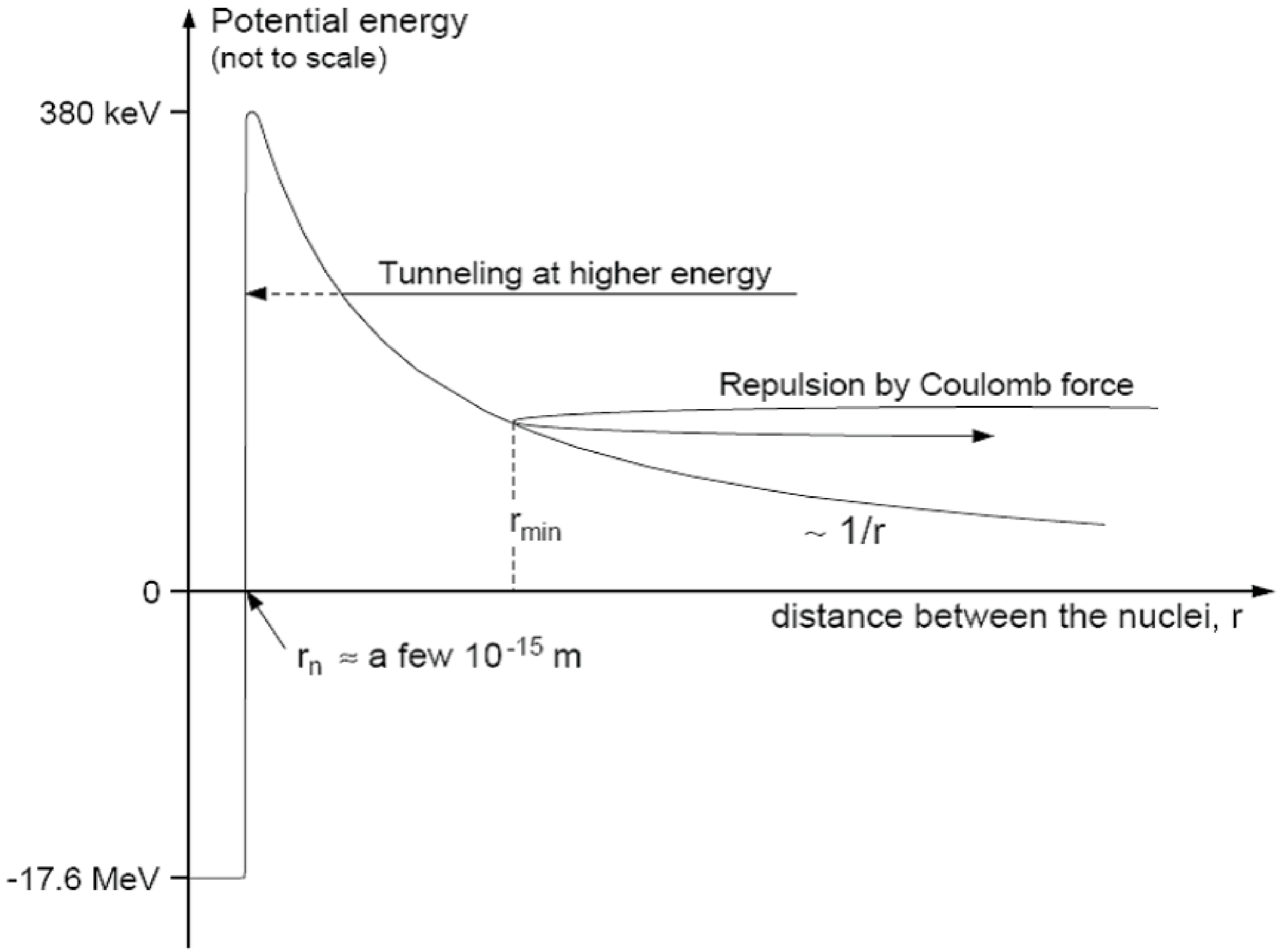
$$(R = 1.4 A^{1/3} fm)$$

$$= 1.44 \frac{Z_x Z_y}{1.4(A_x^{1/3} + A_y^{1/3})} \quad \text{MeV}$$

D-T reaction ➢ V_c = 0.38MeV = 380 keV.
The corresponding gas temperature is ~ 4.4 10^9 K

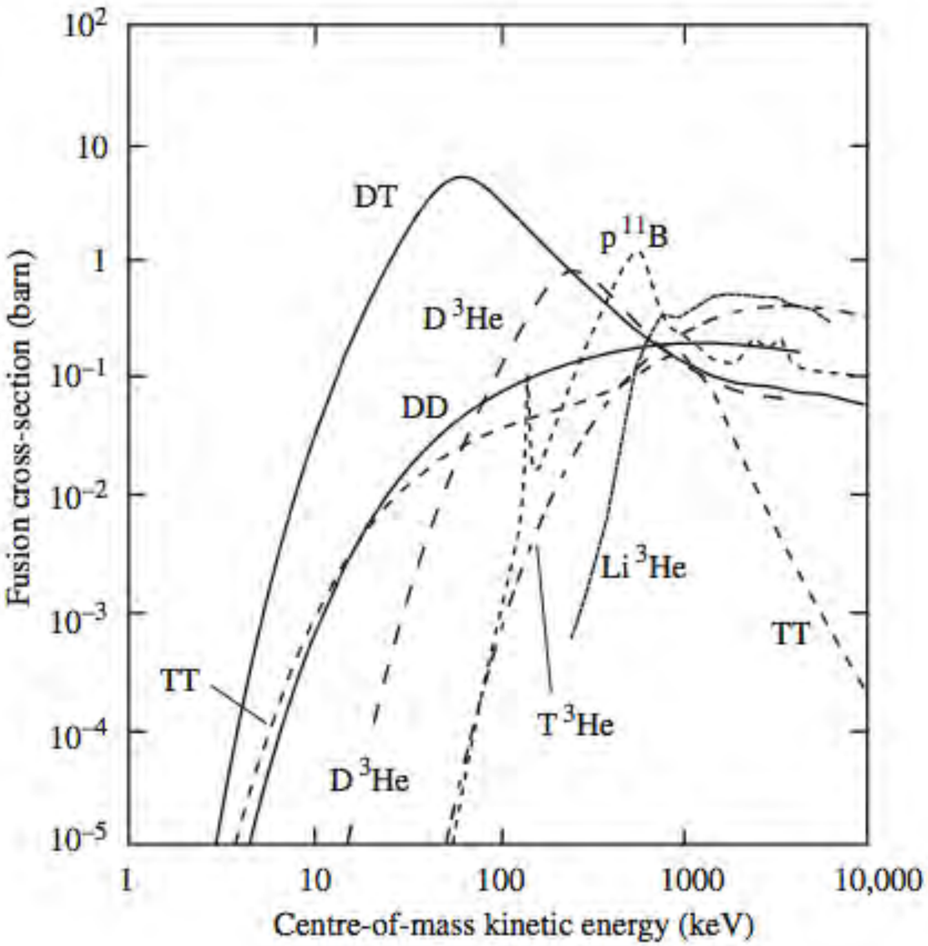
However the maximum reactivity
is reached at 10-15 keV or 110-160 million K…

Most fusion reactions occur through tunneling

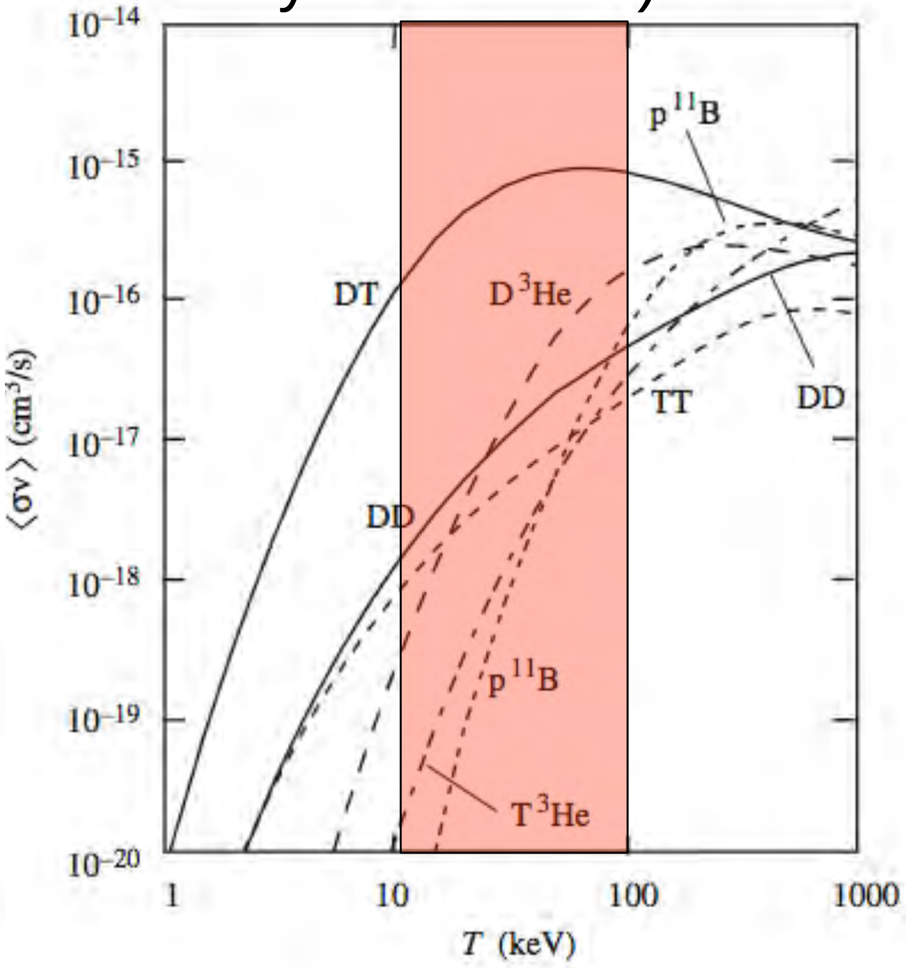


Fusion Cross-Sections and Reactivities

Fusion cross-section (in barn = 10^{-28} m^2)



Fusion Reactivity in cm^{3}s^{-1} (averaged over Maxwellian velocity distribution)



Optimal temperature for fusion

D-T reaction : Maximum for T ~ 10-15 keV

Fusion power:

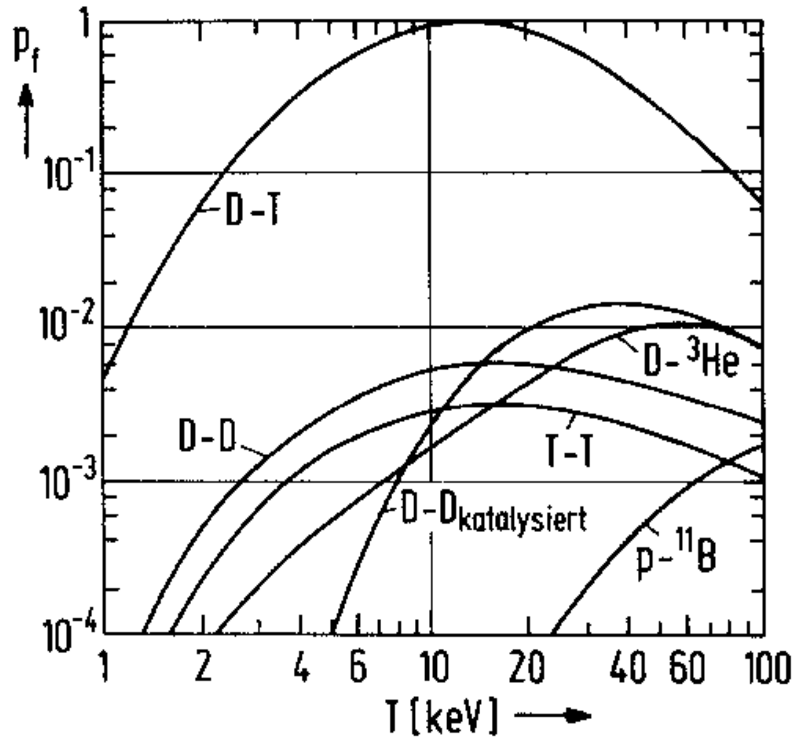
$P_{fusion} \sim n^2 \langle \sigma v \rangle E_{fus}$

At fixed pressure

$p = cte = nkT \;\; \text{-- >} \; n \propto 1/T$

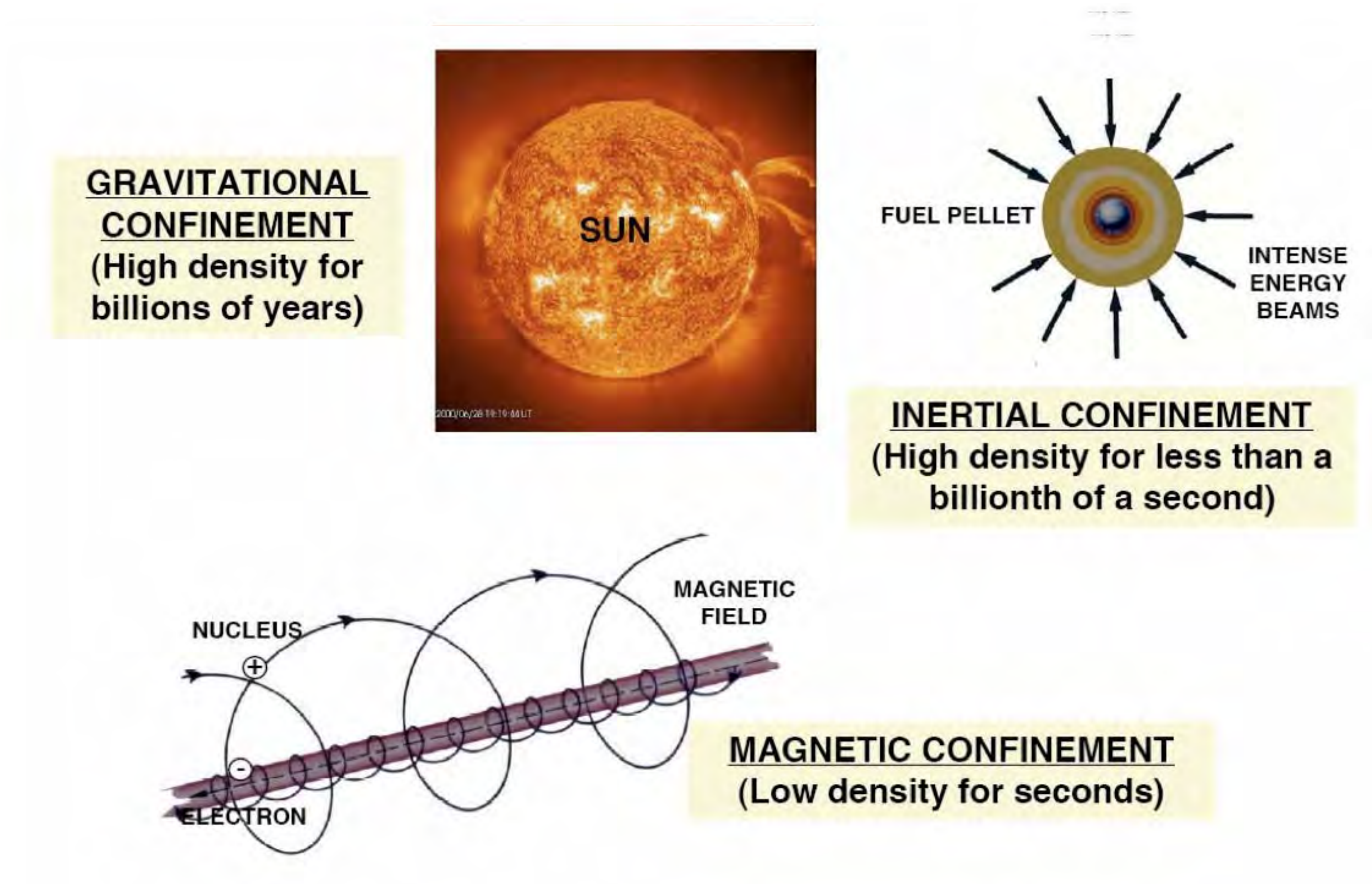
Thus :

$P_{fusion} \sim \langle \sigma v \rangle E_{fus} / T^2$



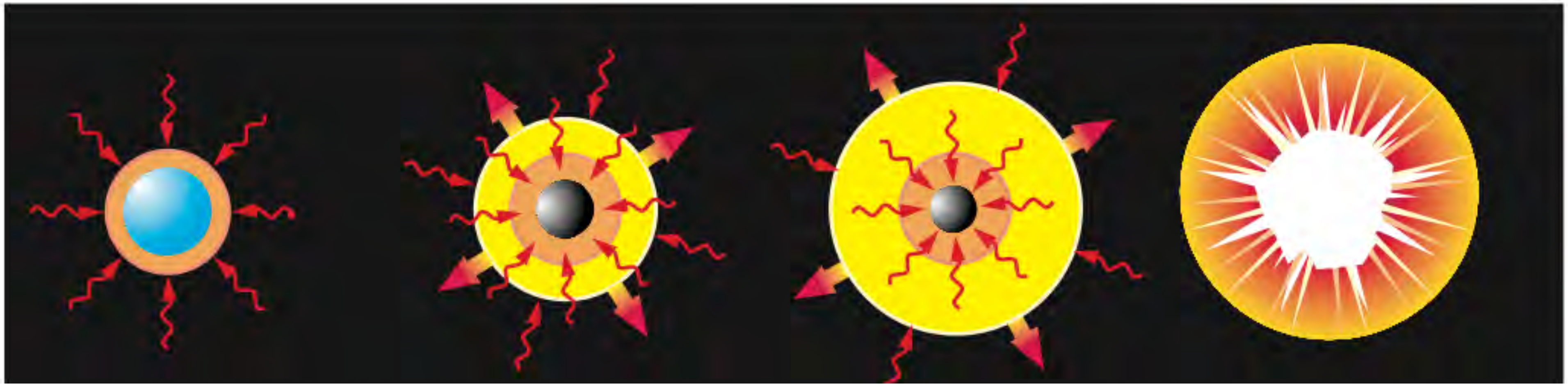
P_{fusion} normalized to max of D-T

How to confine matter at very high temperatures ?



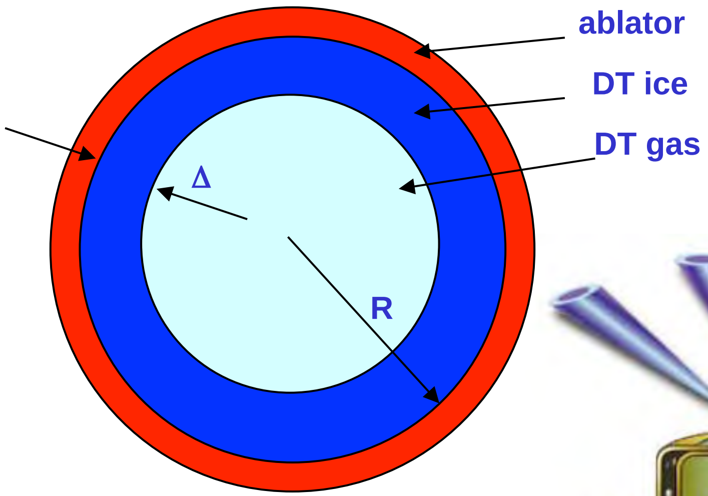
Realizing Fusion
A. Inertial Fusion

Using powerful laser or particle beams to compress a tiny pellet

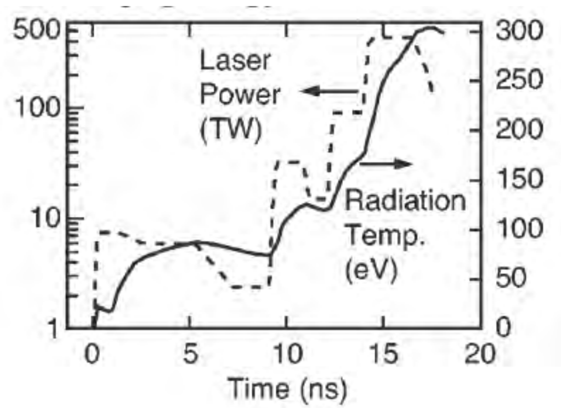


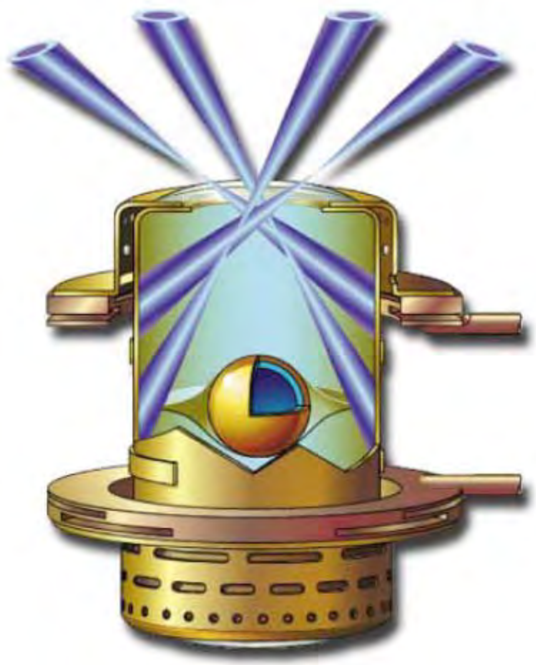
Surface Heating | **Compression** | **Ignition** | **Fusion**

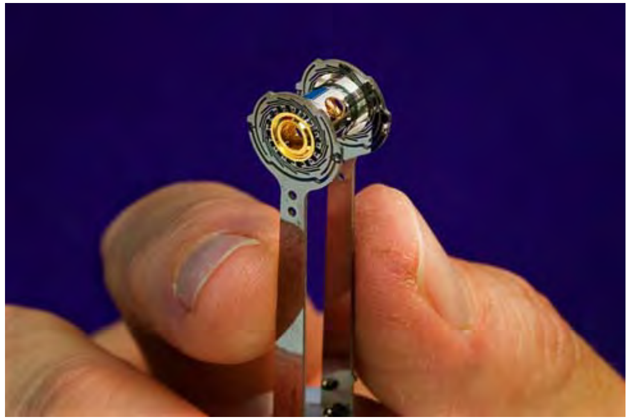
Targets for Inertial Fusion



R ~ 1 mm
Δ ~ 0.2 mm







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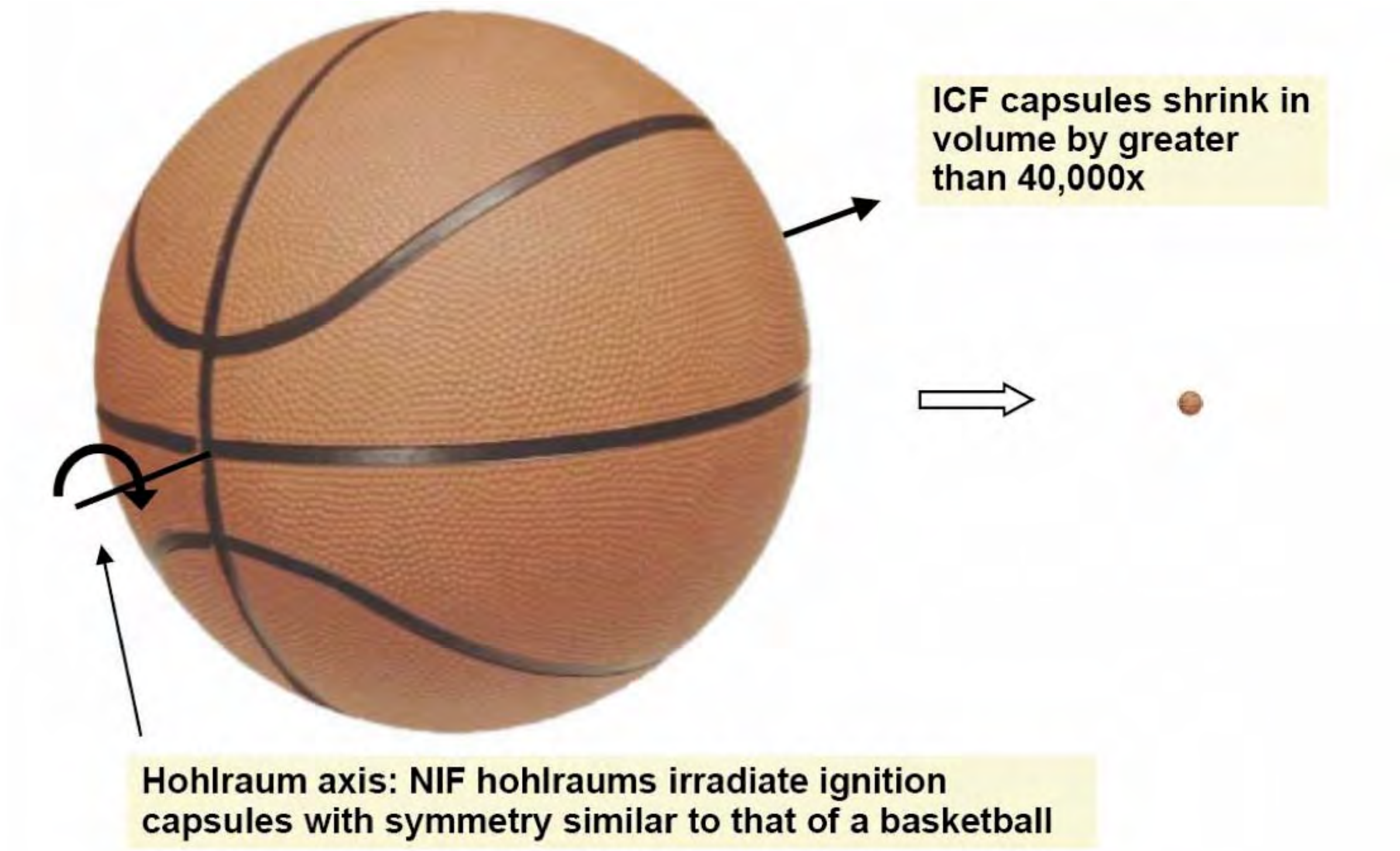
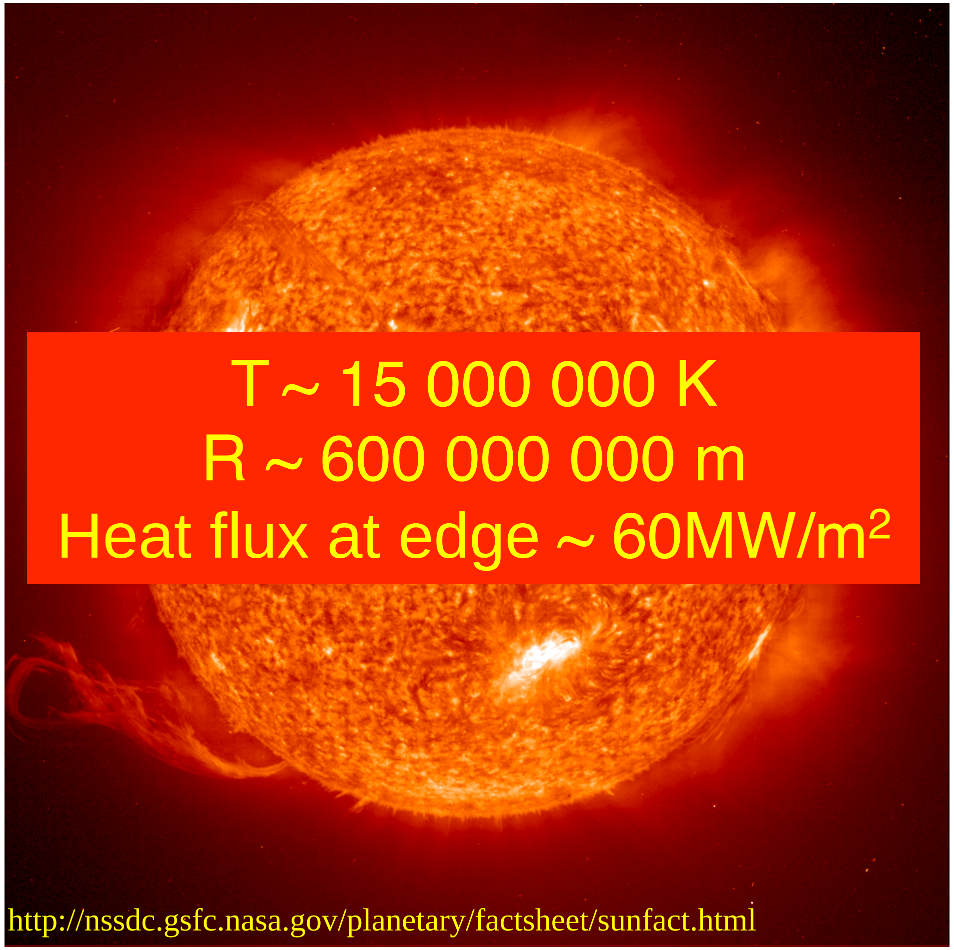


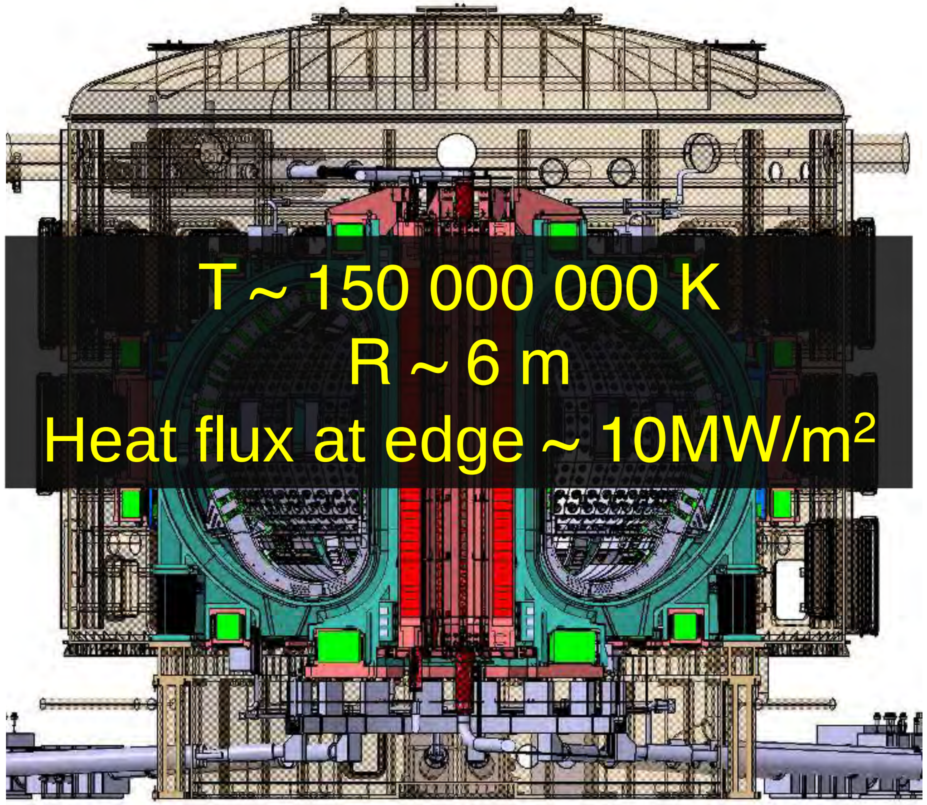
Very powerful laser systems needed
High requirements for isotropic illumination of target

Realizing Fusion:
B. Magnetic Fusion – a real challenge

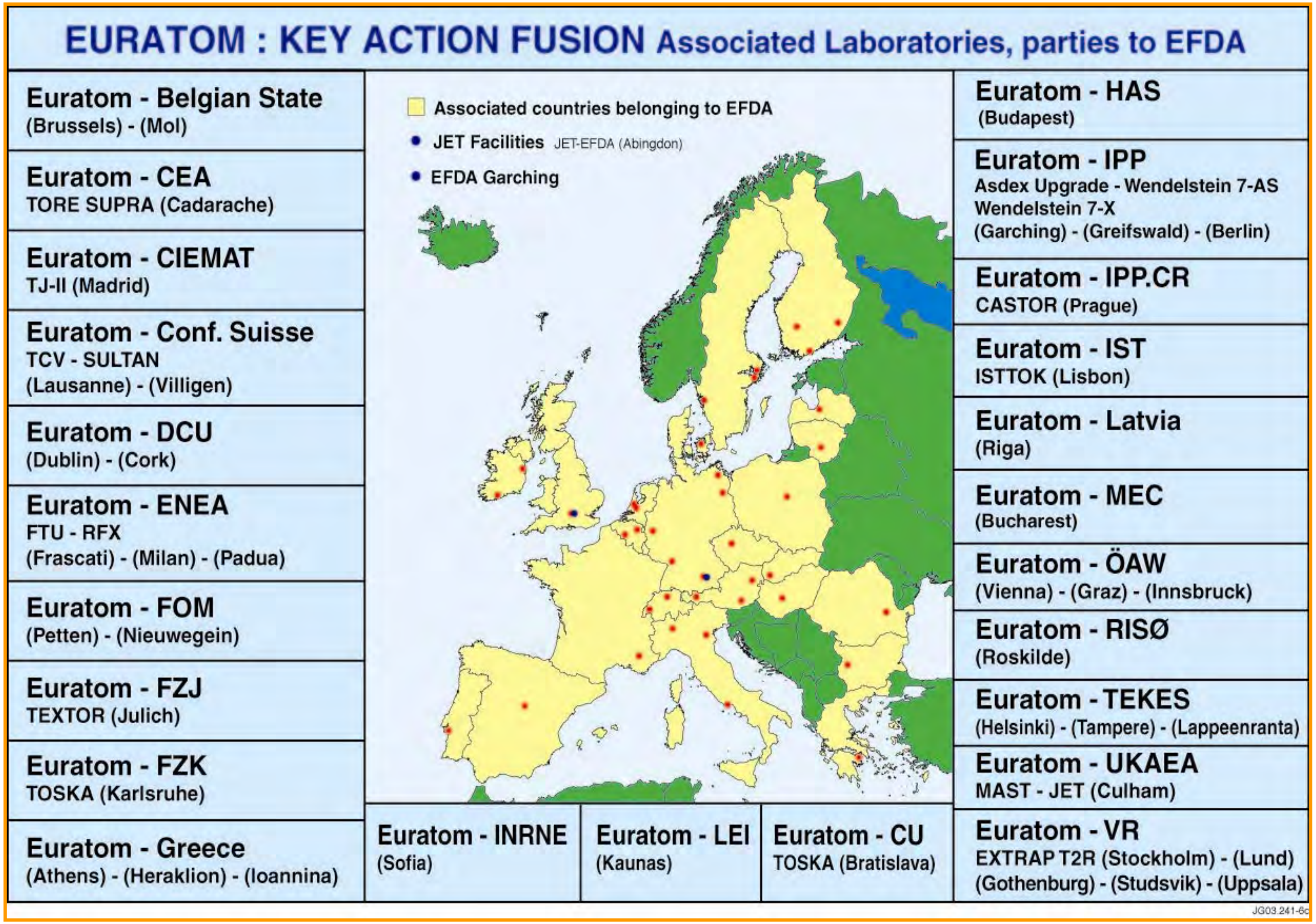
Sun



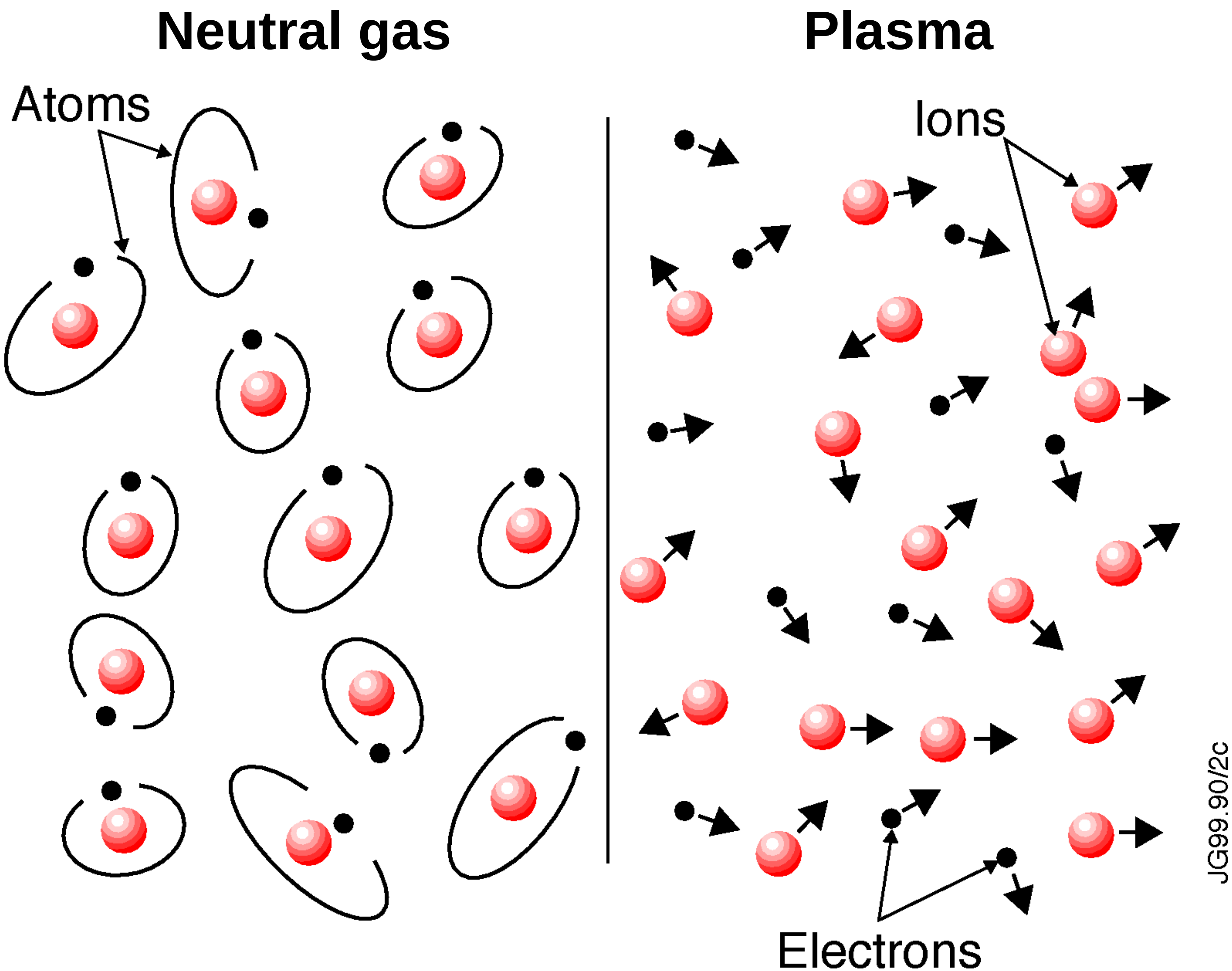
ITER (France, in construction)



Fusion research in Europe



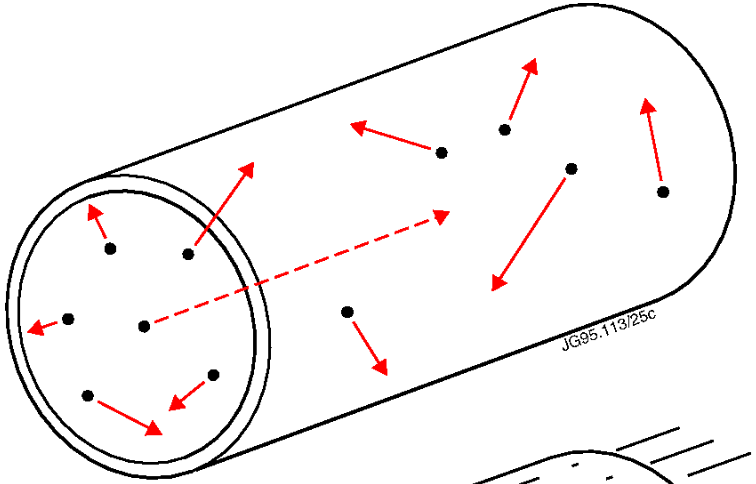
Principle of magnetic fusion



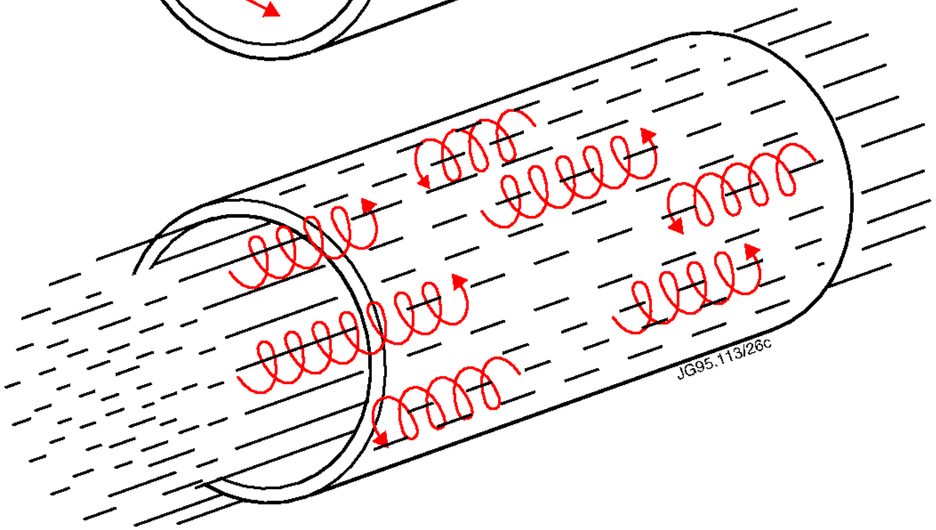
Low temperature / High temperature

Principle of magnetic fusion

Charged particles 'stick' to magnetic field lines (Lorentz force)



No magnetic field

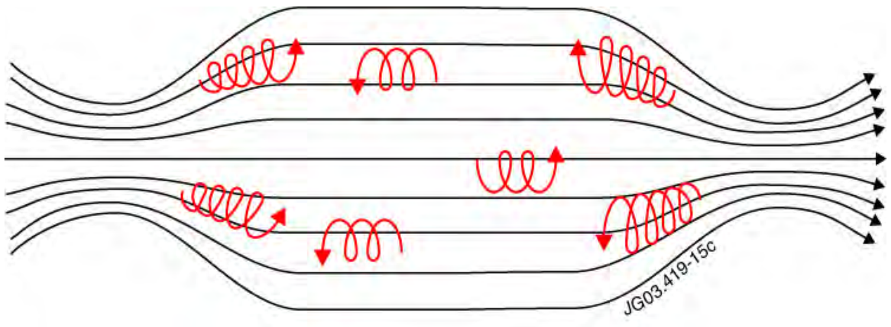


With magnetic field

Principle of magnetic fusion

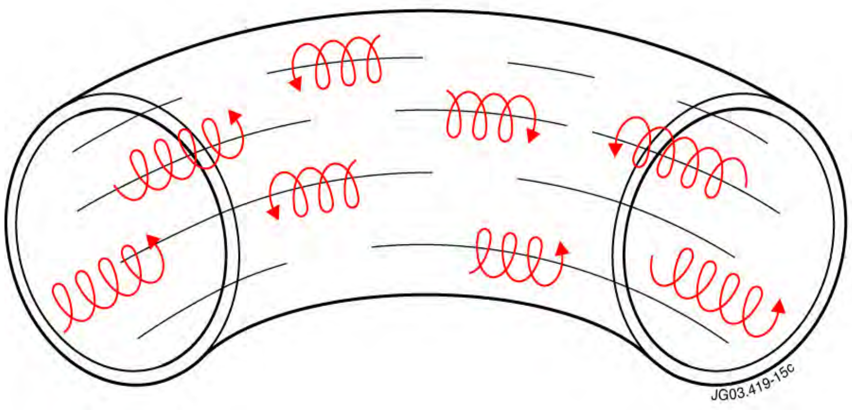
Particles follow magnetic fields
how to limit losses at the end of cylinder?

Two possible solutions



- ‘close' magnetic field at ends

  BUT : too high losses at ends



- 'close' magnetic fields on themselves

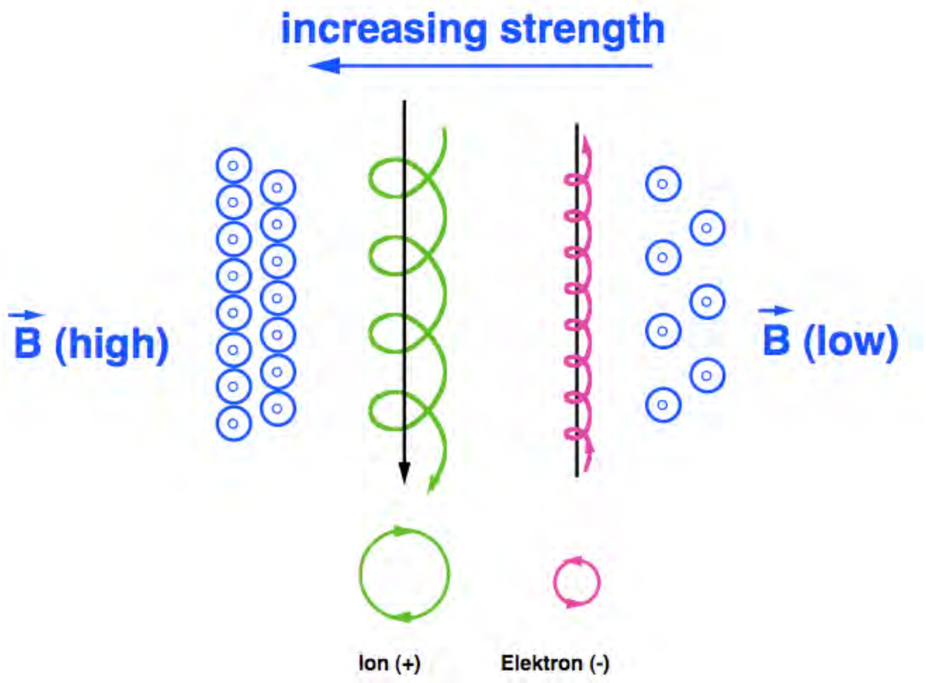
  ⇒ toroidal configuration, BUT…..

Pure Toroidal field does not work : Charge Separation !

Fundamental Reason:
Gyroradius varies with magnetic field and particle speed

$$\rho_L = \frac{m v_\perp}{qB}$$

Pure toroidal magnetic field
Charges Separate → Electric Field



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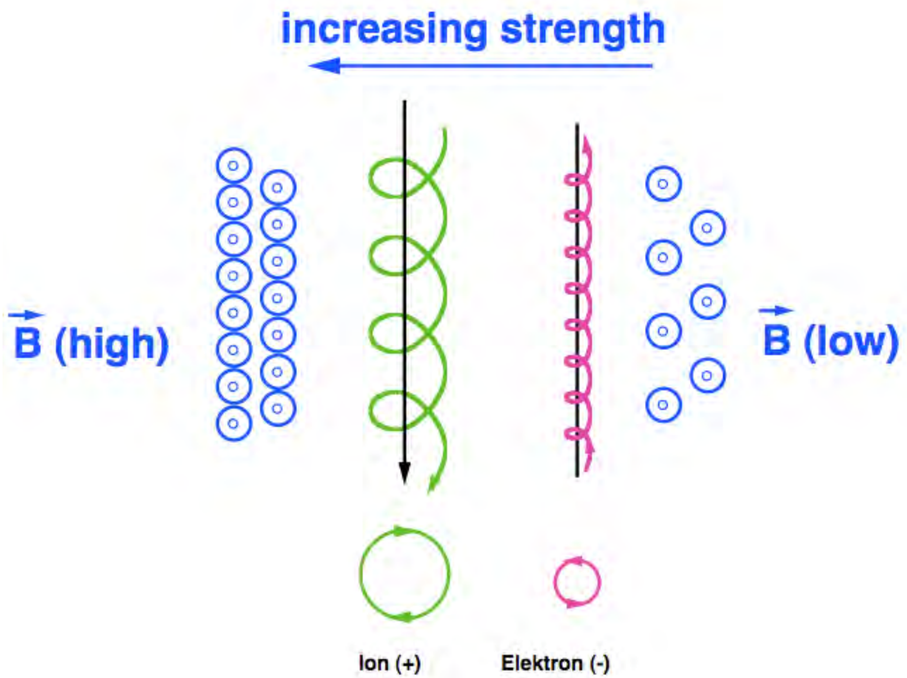
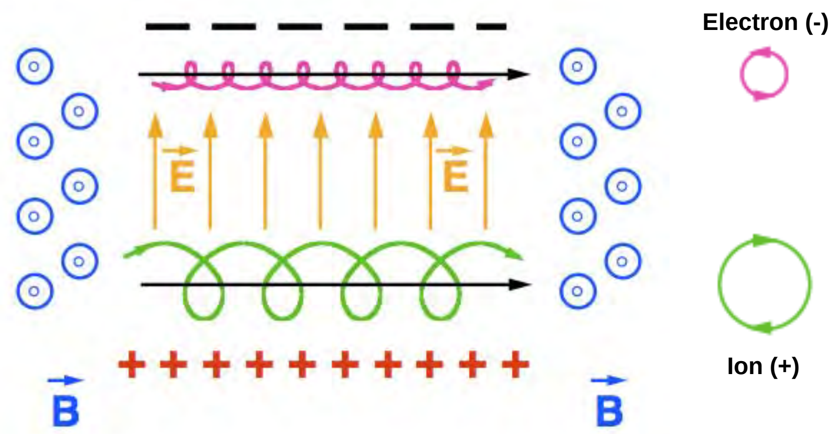


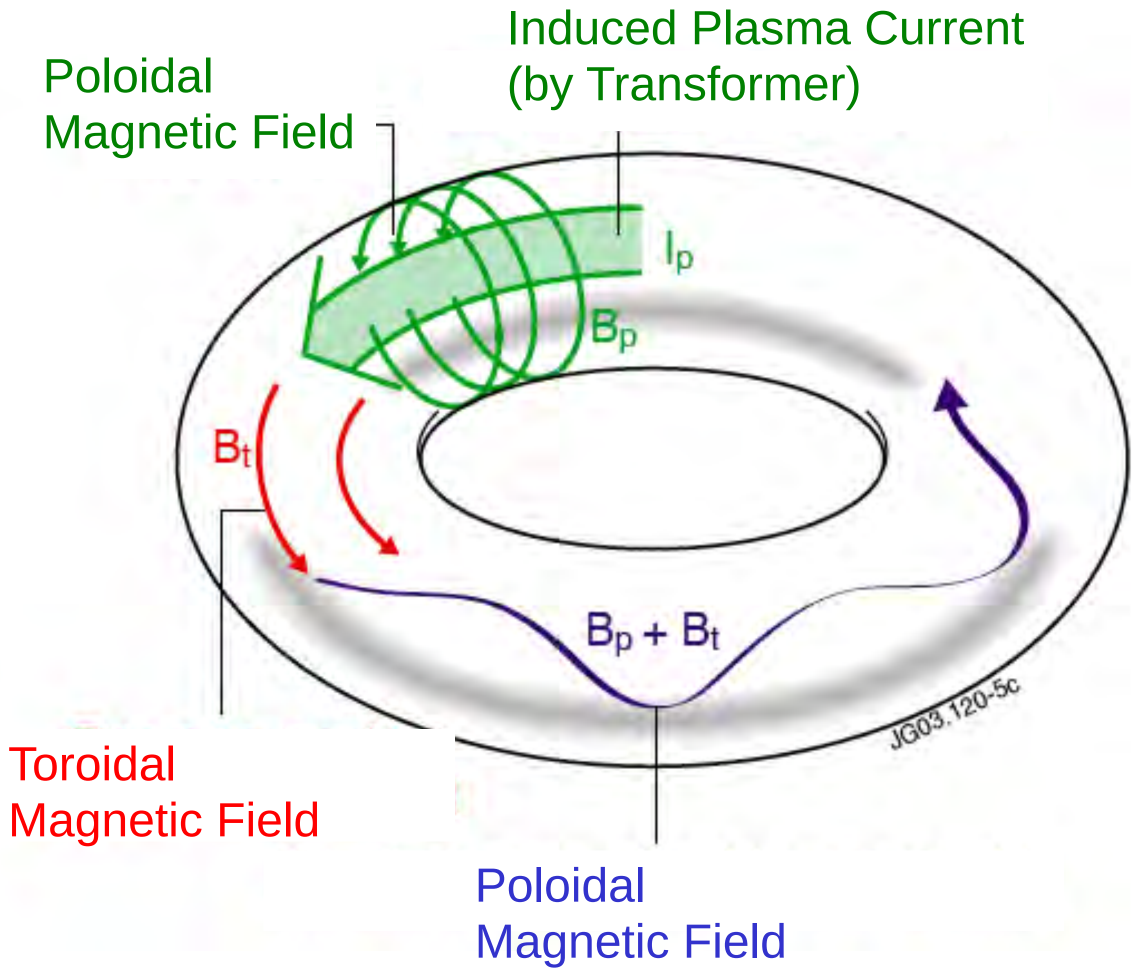
Magnetic field + Electric Field
ALL particles move outward !



Realizing a helicoidal magnetic field : Option 1

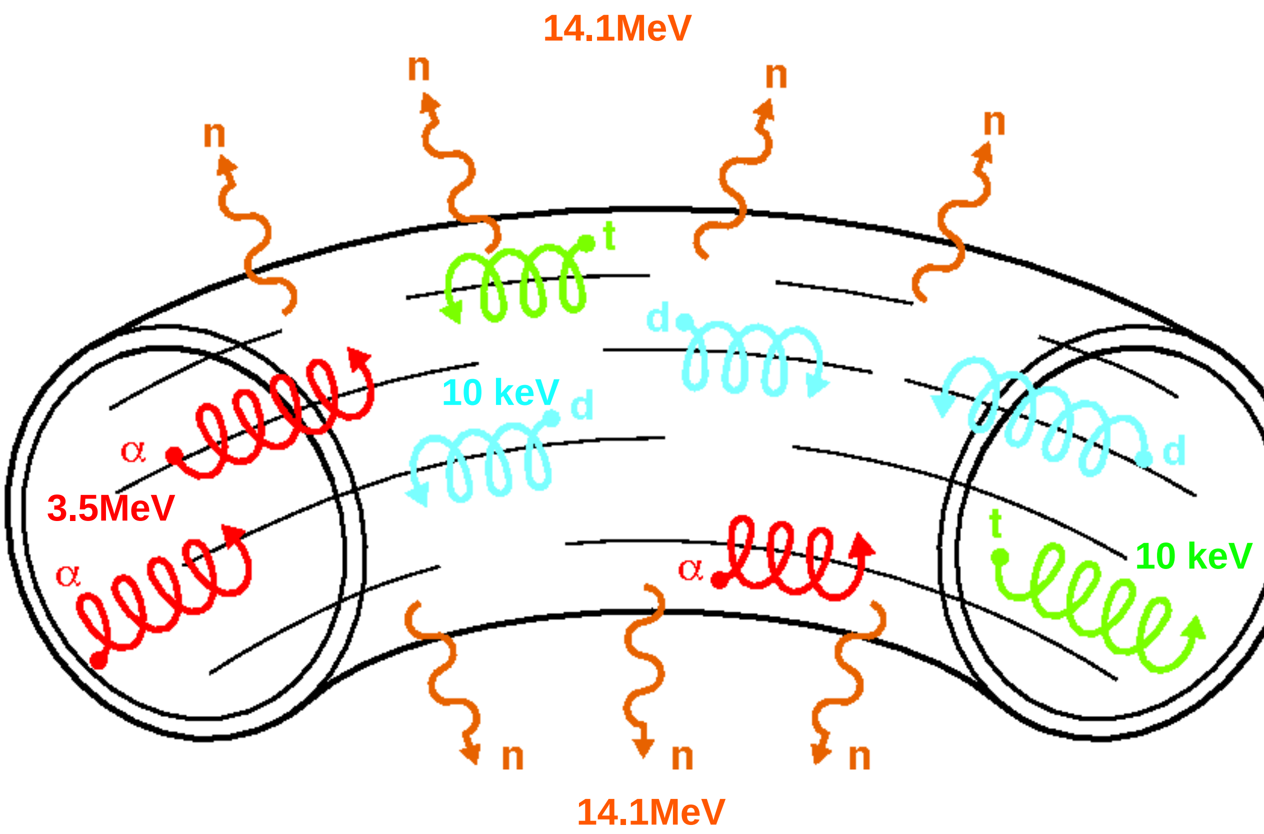
Tokamak

Large current induced in plasma (~100kA - 10MA)



Tokamak – Final Configuration

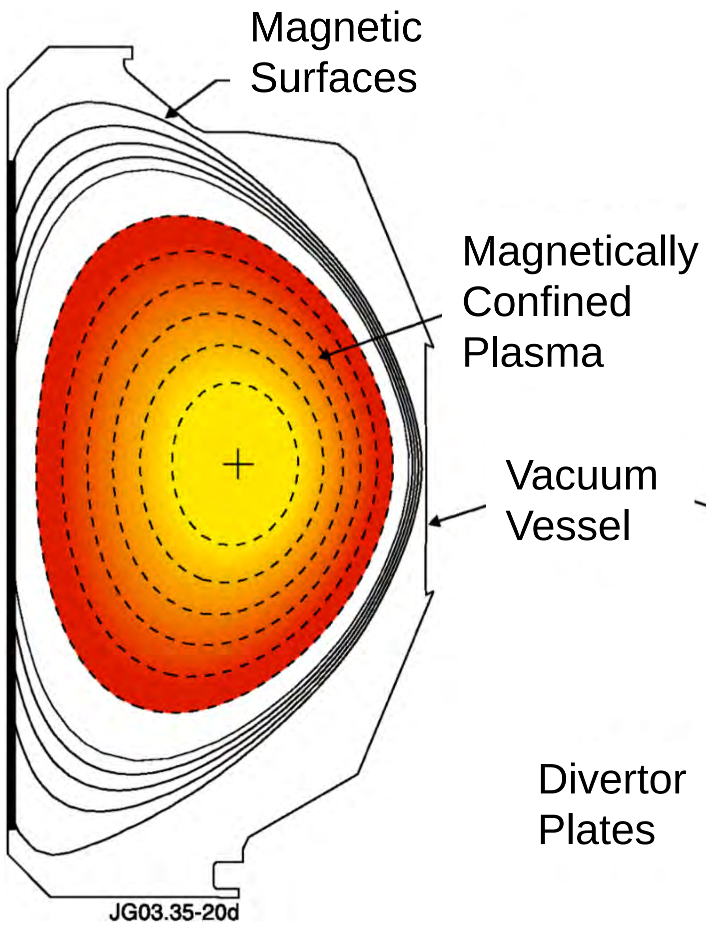
A torus with a large flux of high energetic neutrons



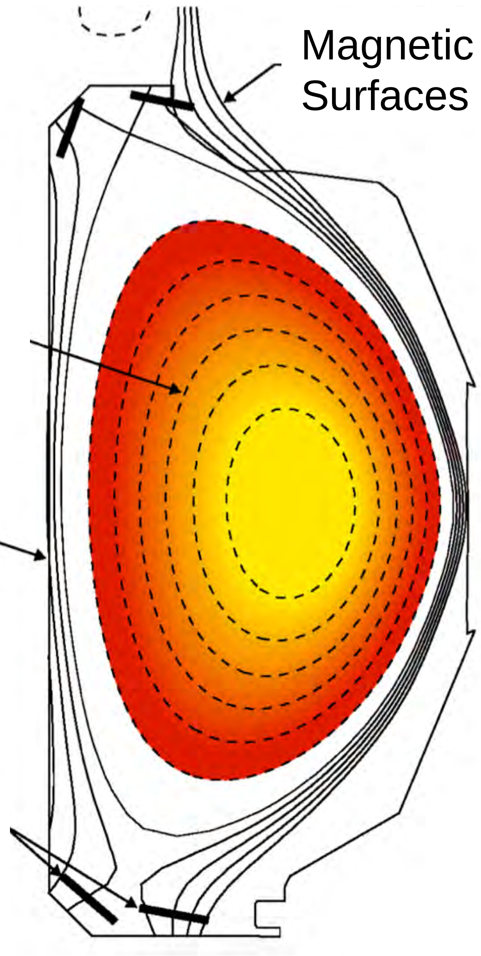
Nota :
1 keV = 11 600 000 °C

Two tokamak configurations in use

Limiter Configuration

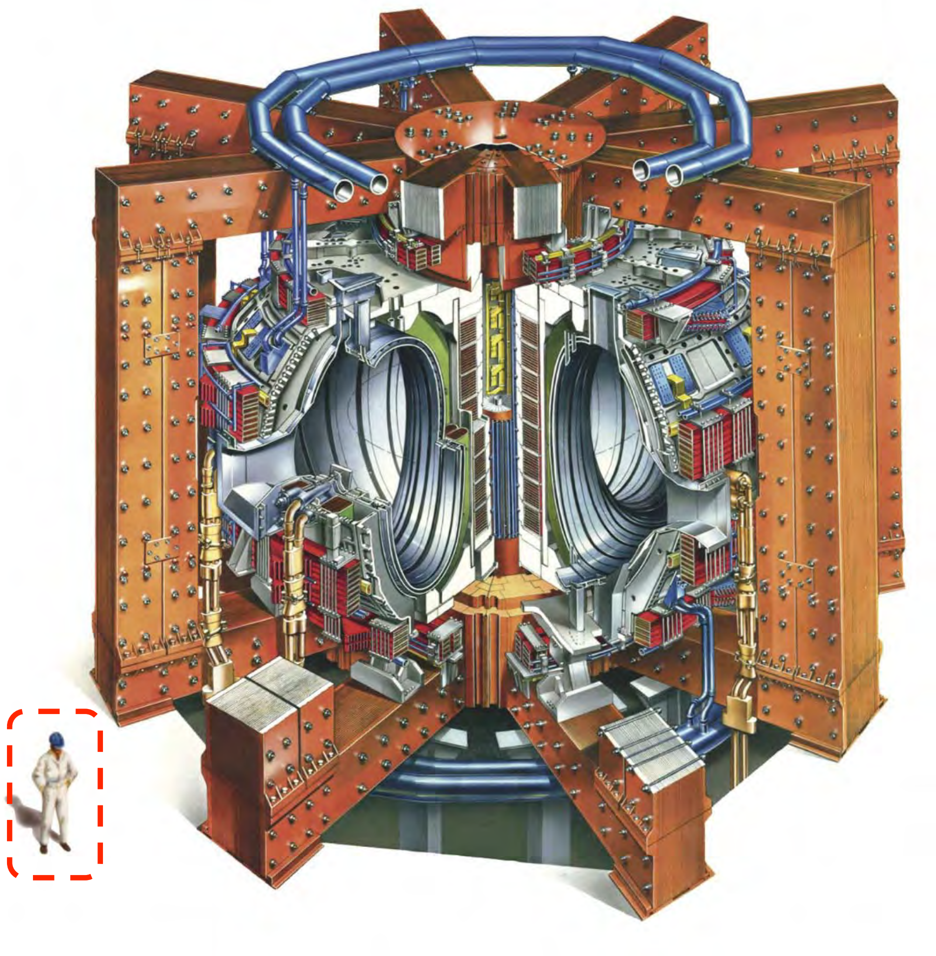


Divertor Configuration

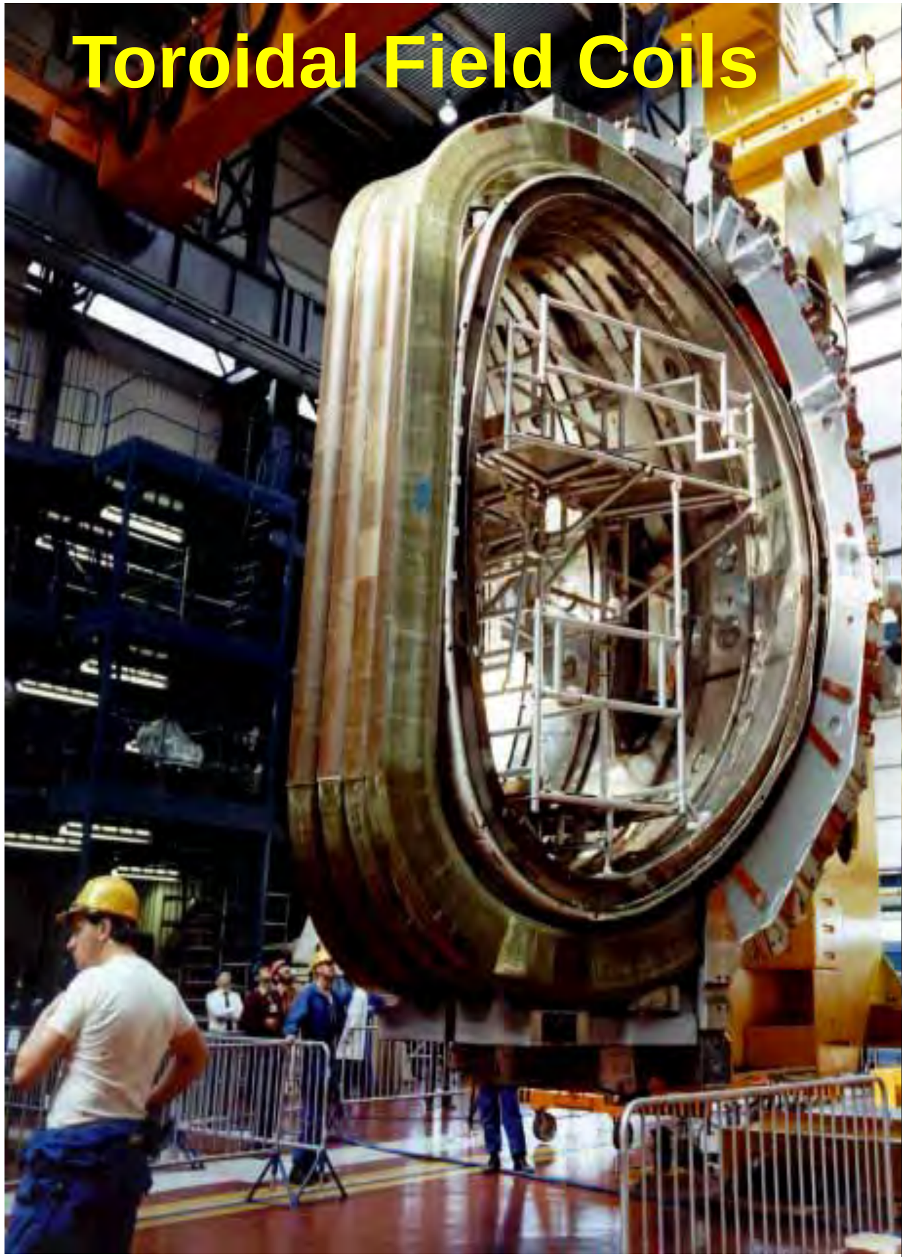


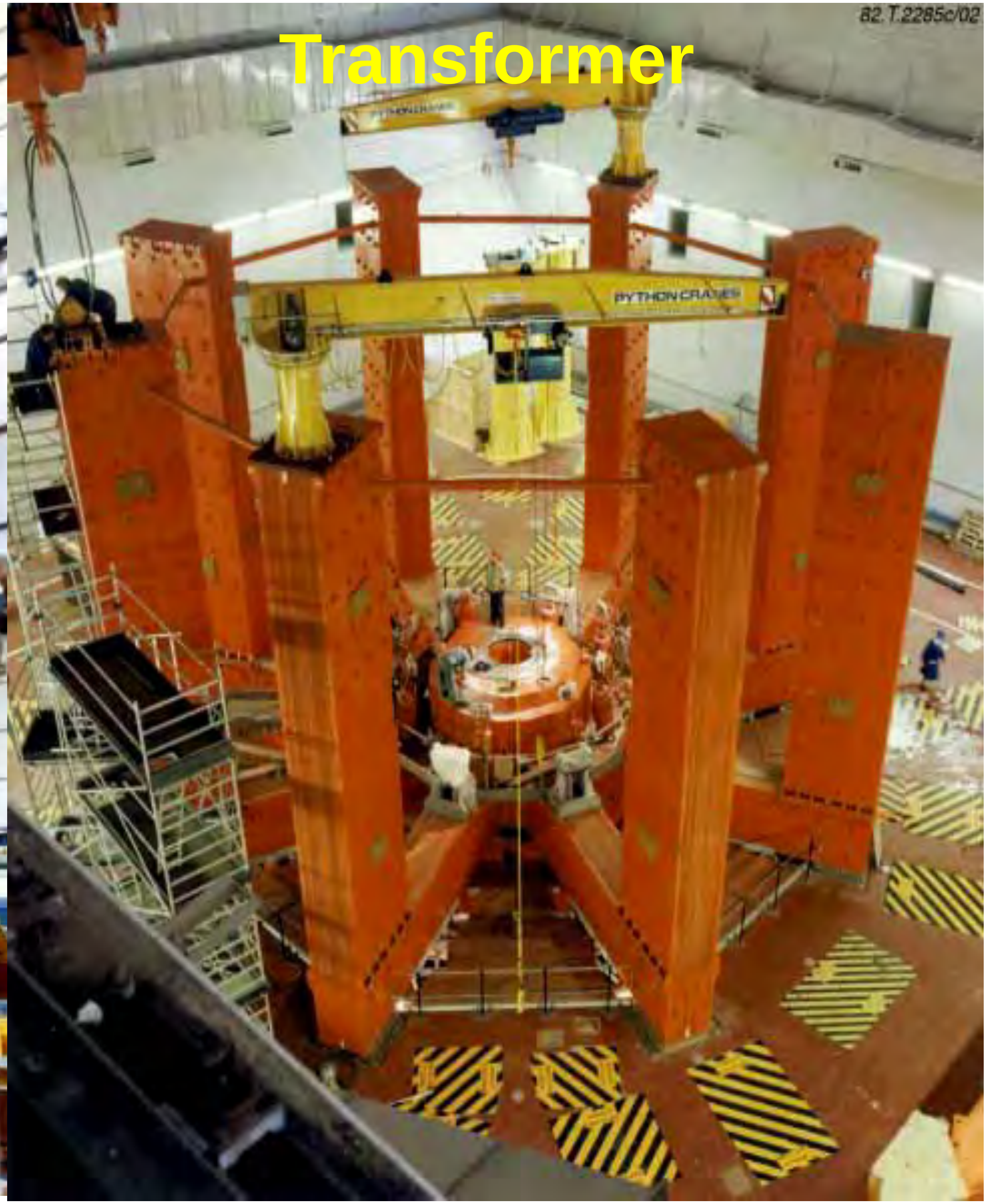
Largest operating tokamak: Joint European Torus (JET)

- Start of operation in 1983
- Major radius: ~ 3 m
- Plasma radius: ~ 1 m
- Plasma volume: ~ 80–100 m^3
- Plasma current: ~ 3 MA
- Magnetic field: ~ 3 T
- World record in fusion power: 16 MW
- $Q = P_{out} / P_{in} = 0.66$

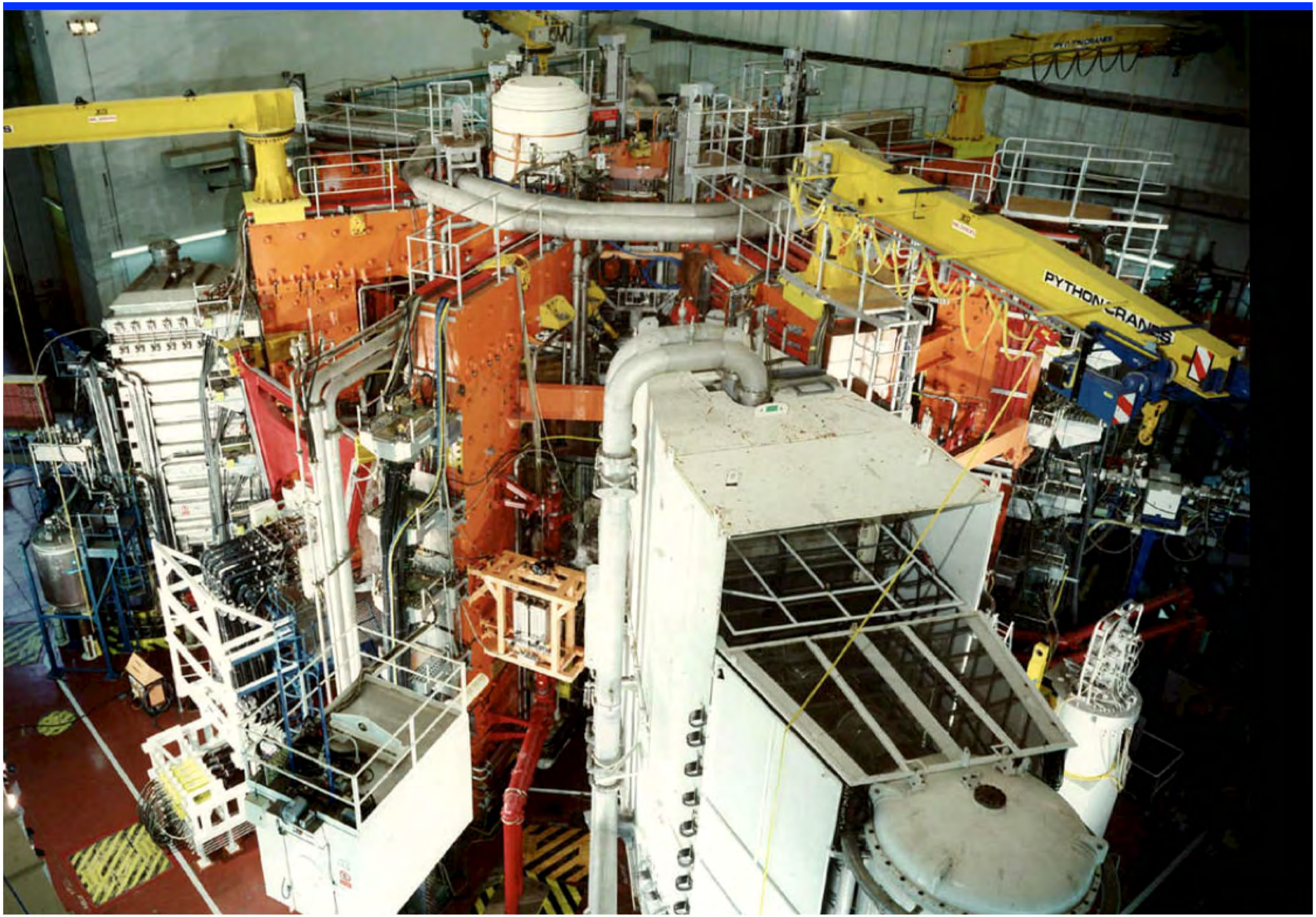


Dimensions of JET

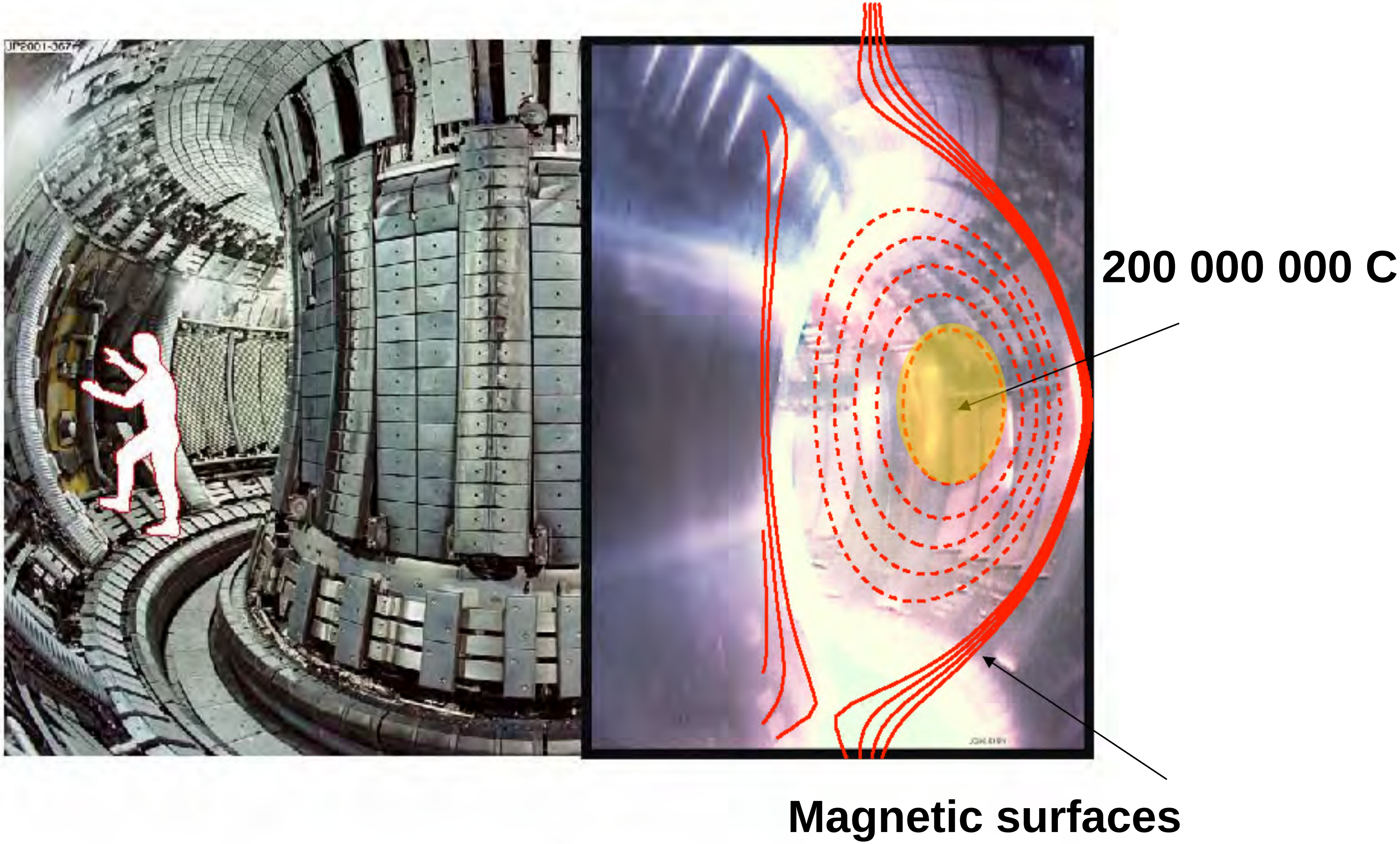




Joint European Torus (JET)



Inside of JET with and without plasma



Characterizing progress – Power multiplication Q

$$Q = \frac{P_{fusion}}{P_{external\ heating}}$$

Breakeven Q=1

when $P_{fusion} = P_{external\ heating}$

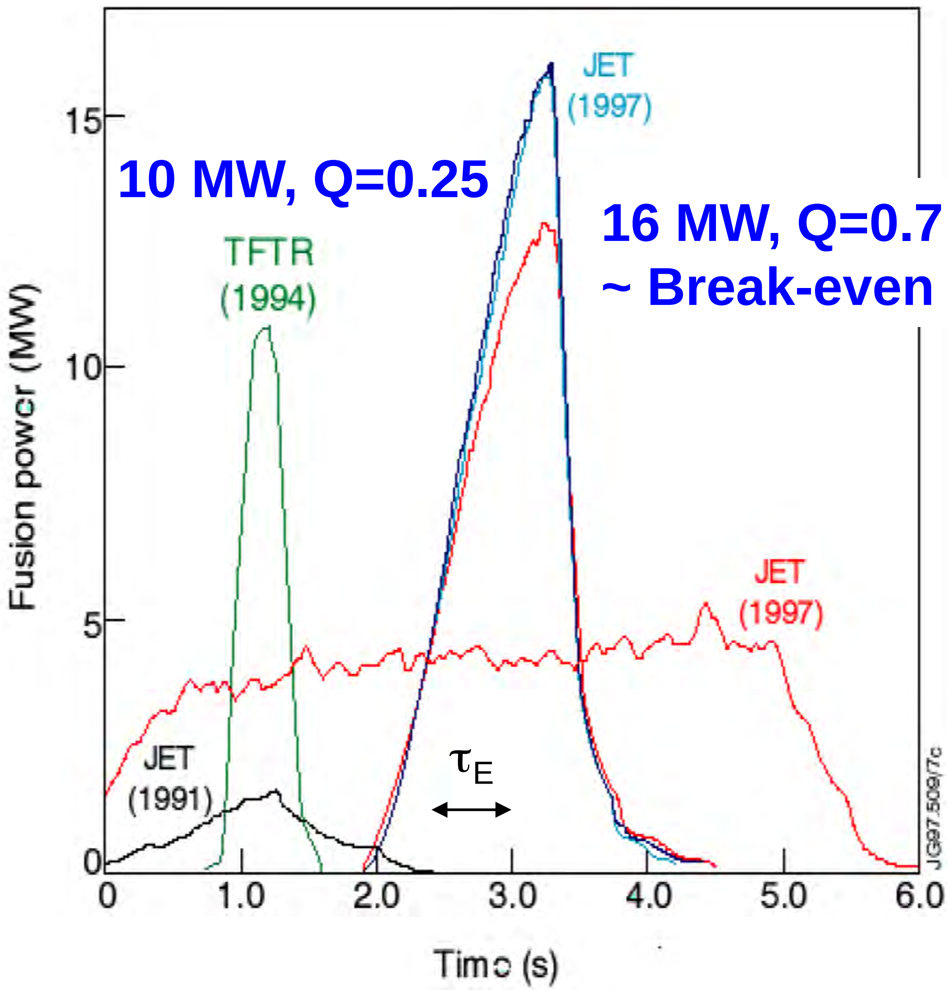
Ignition Q = ∞

when $P_{external\ heating} = 0$
No external heating needed
Self-sustained fusion reaction

Note:

Q characterizes the balance between fusion and external heating power **only**

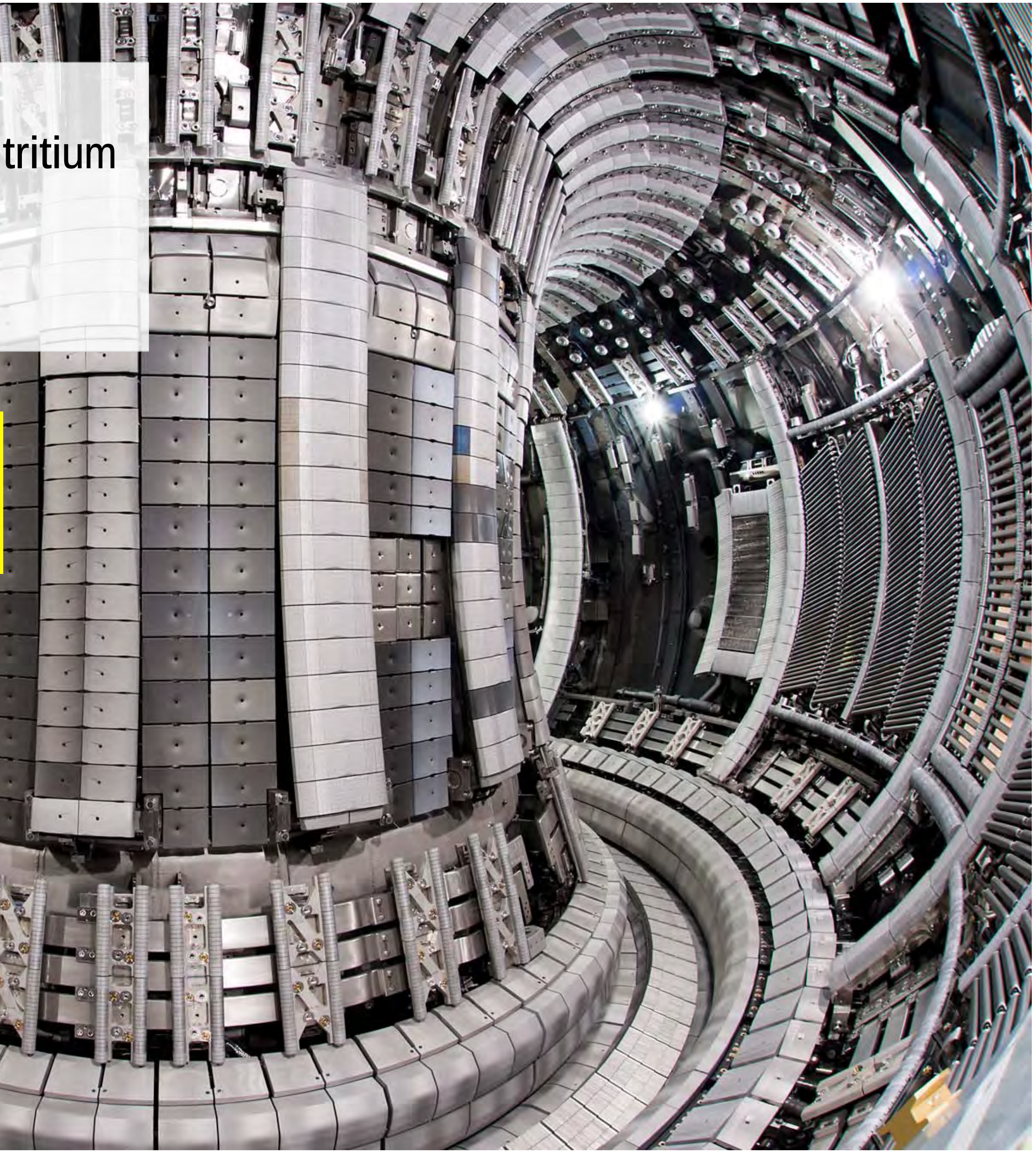
It is **not** representative for the balance between total power consumption (magnetic fields, additional systems) and fusion power output



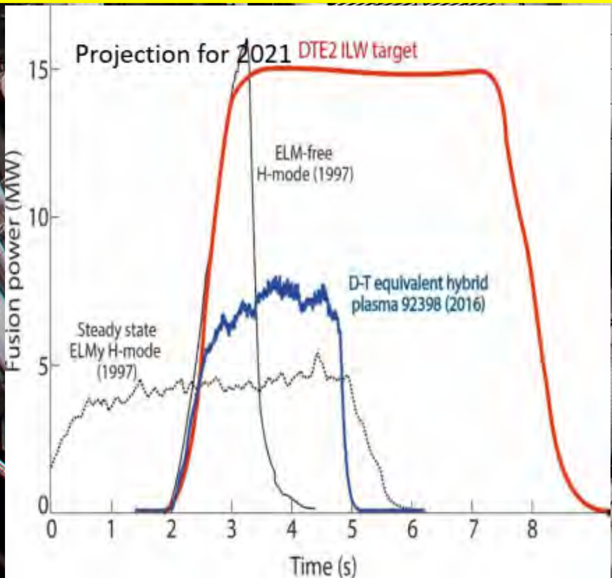
TFTR : Tokamak Fusion Test Reactor, Princeton, USA
JET : Joint European Torus, Culham, UK

Inside of JET with Be wall

- Be-wall, W-divertor
- Only device currently able to use tritium
- Remote handling
- Closest in performance to ITER
- DTE2 campaign: Aug.-Oct. 2021



Fusion power projections for JET D-T plasmas (2021)

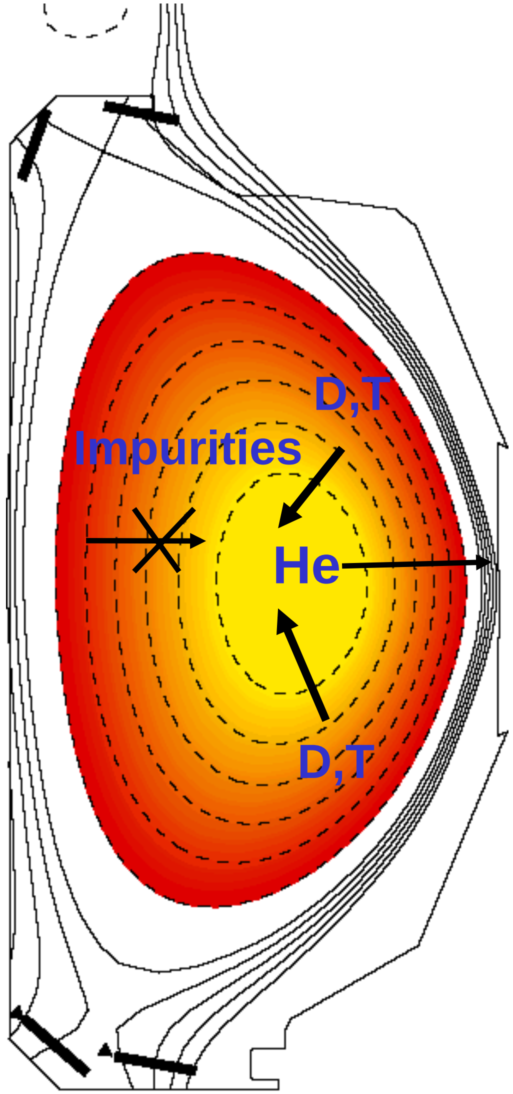


From JET to ITER

*ITER = International Thermonuclear Experimental Reactor

ITER should show us how to maintain the fusion 'fire' !

Important questions waiting for an answer



Physics

- Clean plasma centre needed
  — He must disappear quickly (…but not too quickly…)
  — Low level of other impurities

- High fusion reactivity :
  — Ensure a good flow of D and T to the plasma center

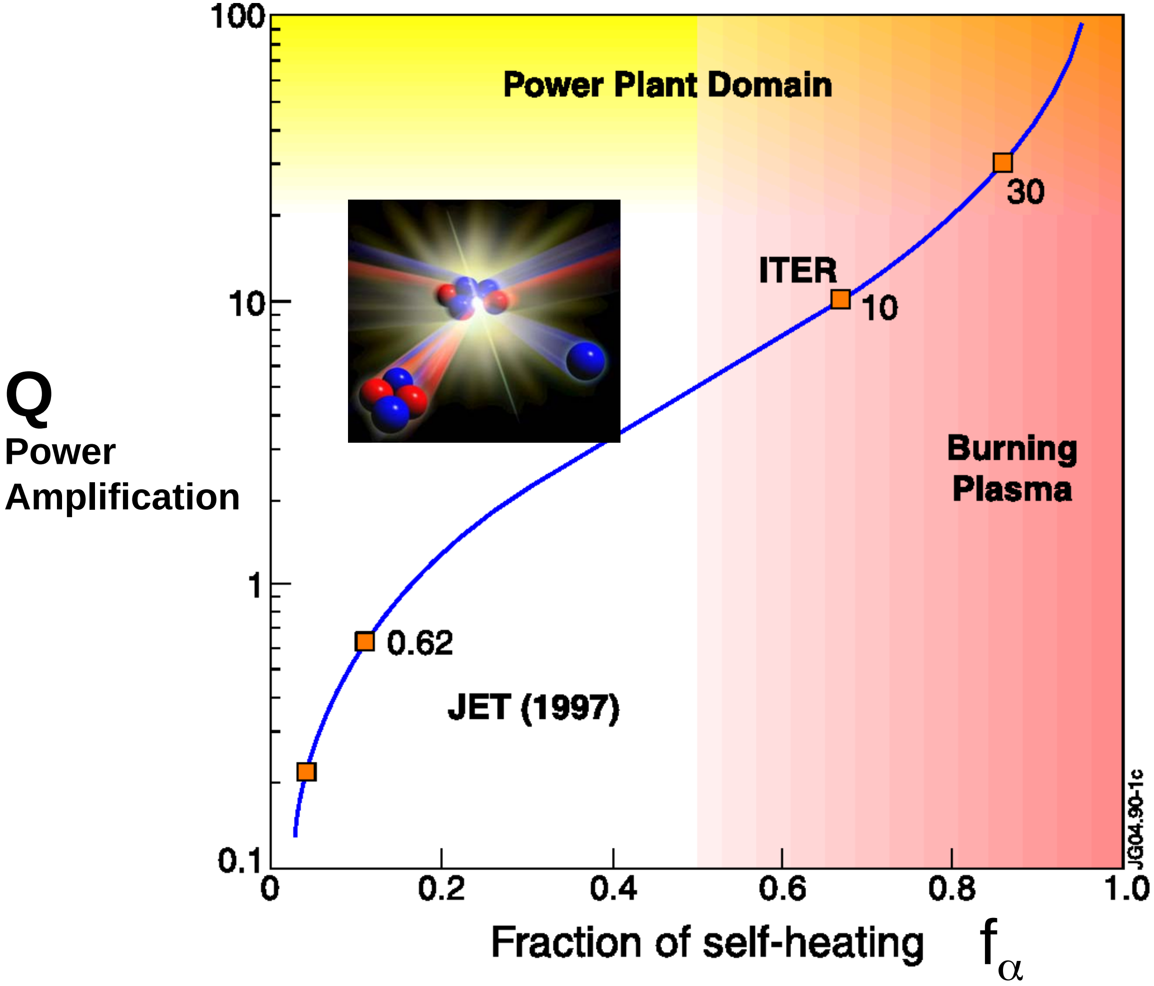
- Stable plasma:
  — Suppress instabilities

Technological

- Check first wall properties
- Check T breeding techniques

ITER is not just 'big science'

BUT crucial for scientific progress



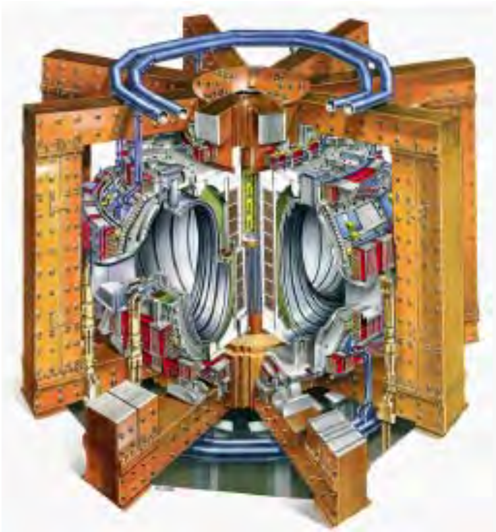
$f_\alpha = Q / (Q+5)$

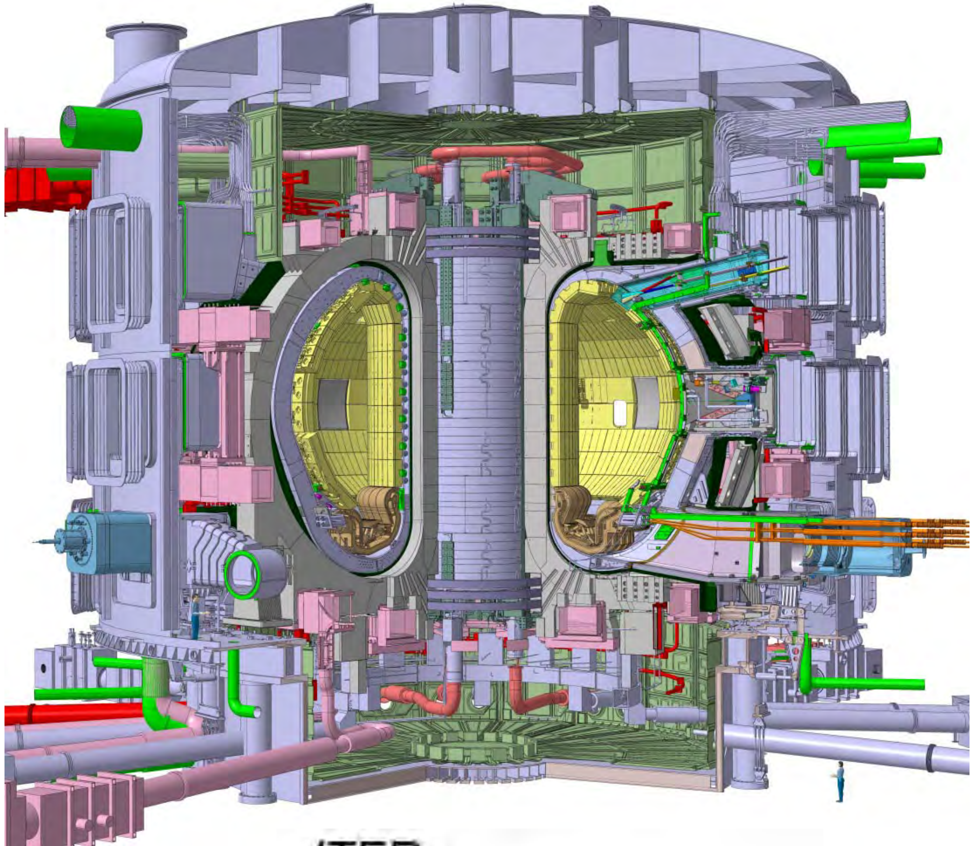
Fraction of plasma self-heating by fusion born α-particles

$Q > 10 \;\; \rightarrow \;\; f_\alpha > 2/3$

With ITER, for the first time:
fraction of alpha particles similar to fusion reactor plasma

ITER : ~ 2x larger than JET





JET

V_{plasma} 80 m^3

P_{fusion} ~16 MW 2s

t_{plasma} ~30 s

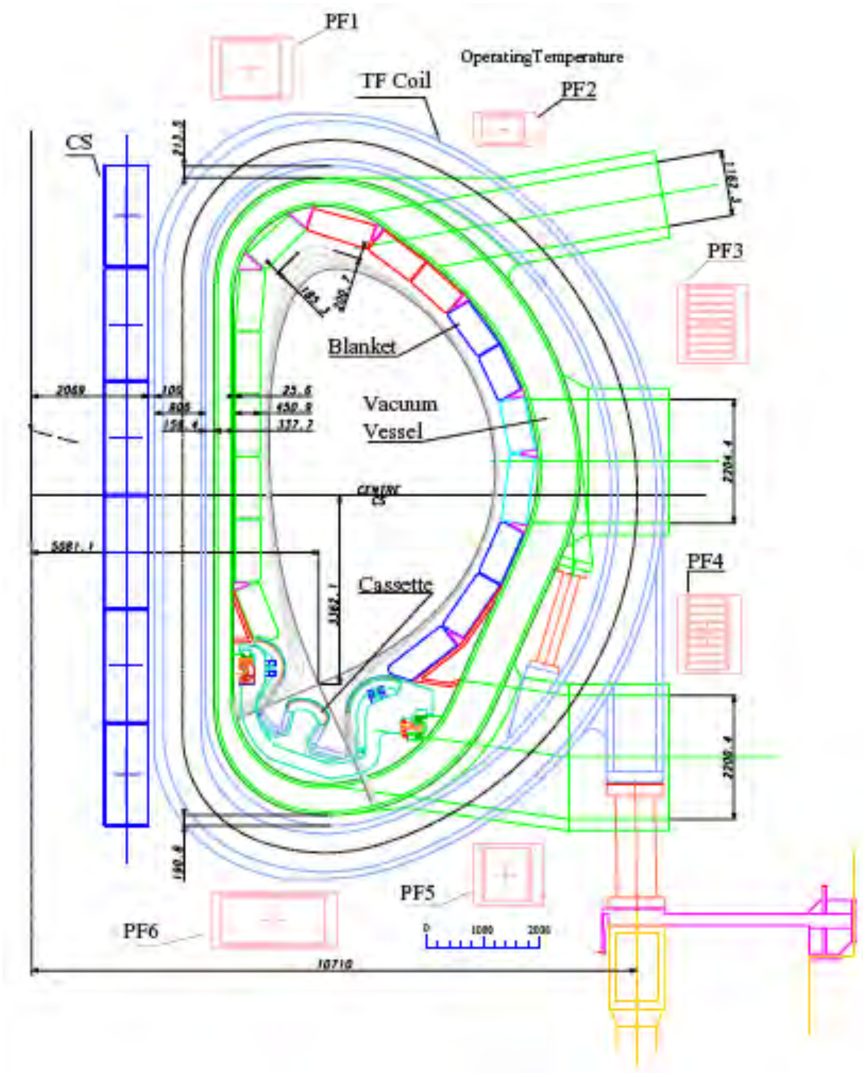
ITER

V_{plasma} 830 m^3

P_{fusion} ~500 MW 500s

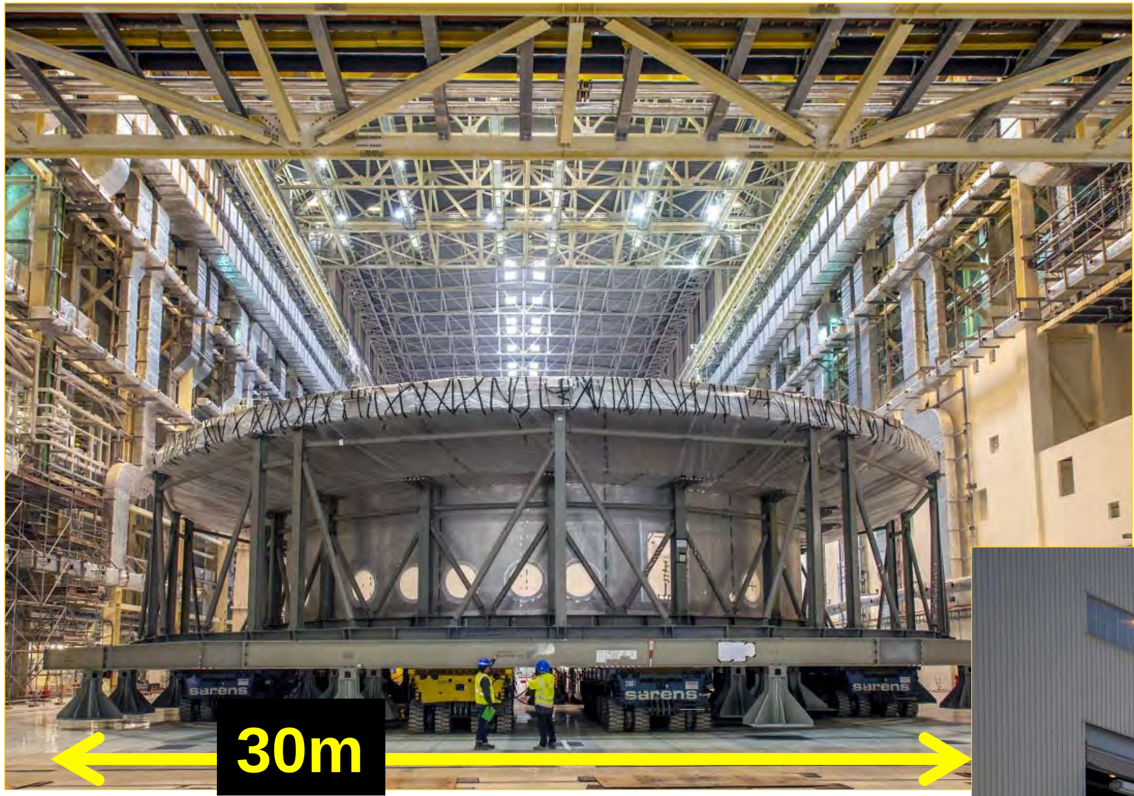
t_{plasma} ~400 s

ITER Design Parameters



	ITER
Major radius	6.2 m
Minor radius	2.0 m
Plasma current	15 MA
Toroidal magnetic field	5.3T
Elongation / triangularity	1.85 / 0.49
Fusion power amplification	≥ 10
Fusion power	~500 MW
Plasma burn duration	300-500 s

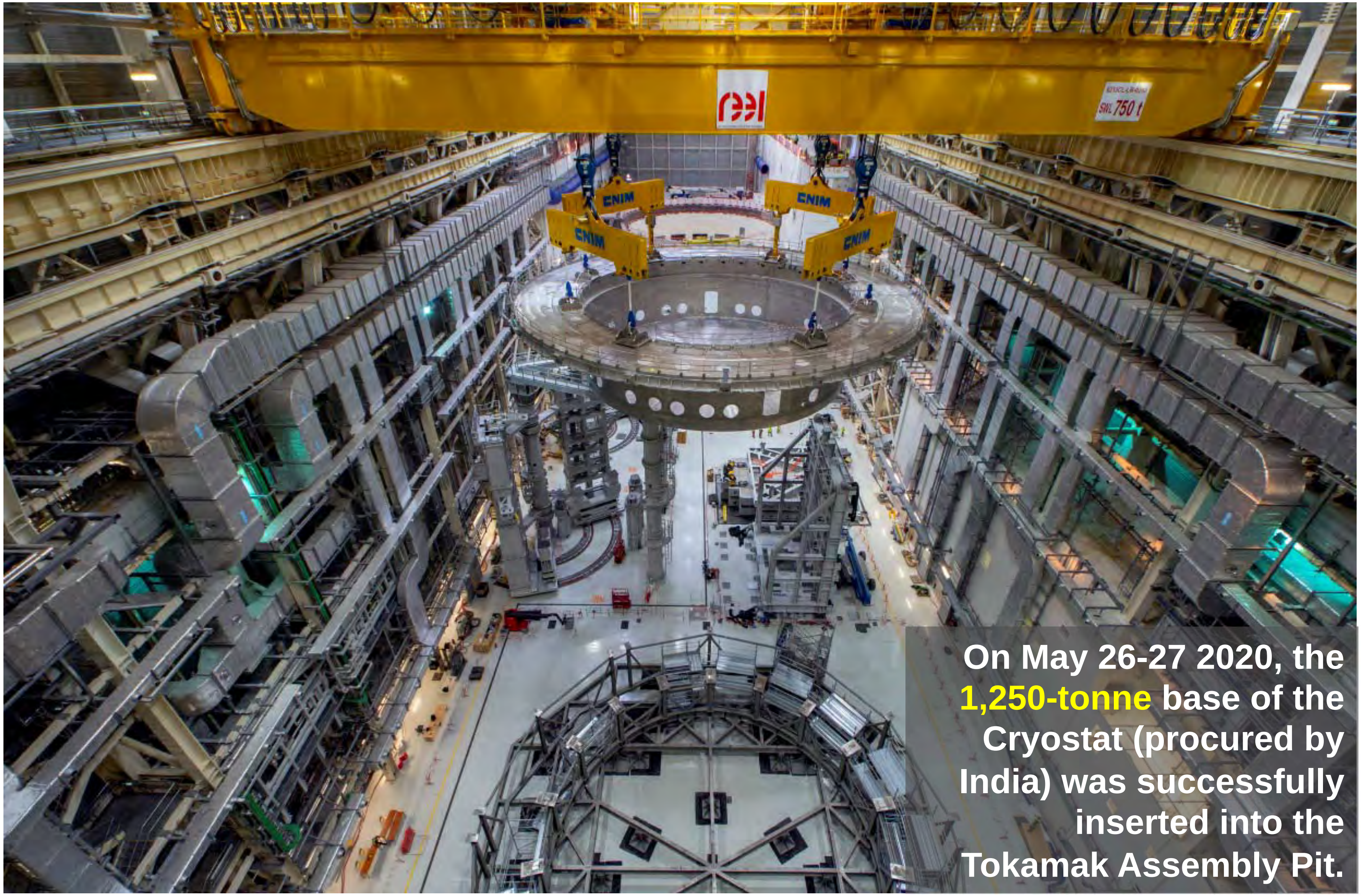
ITER's construction progress (2020)



Cryostat Base in Assembly Hall, April 2020

Cryostat Upper Cylinder emerging to
go into storage, April 2020

A very important milestone (May 2020)



On May 26-27 2020, the **1,250-tonne** base of the Cryostat (procured by India) was successfully inserted into the Tokamak Assembly Pit.

On-site fabrication of poloidal field coils (up to 24m diameter)

PF Coil #5 ready for cold testing, June 2020

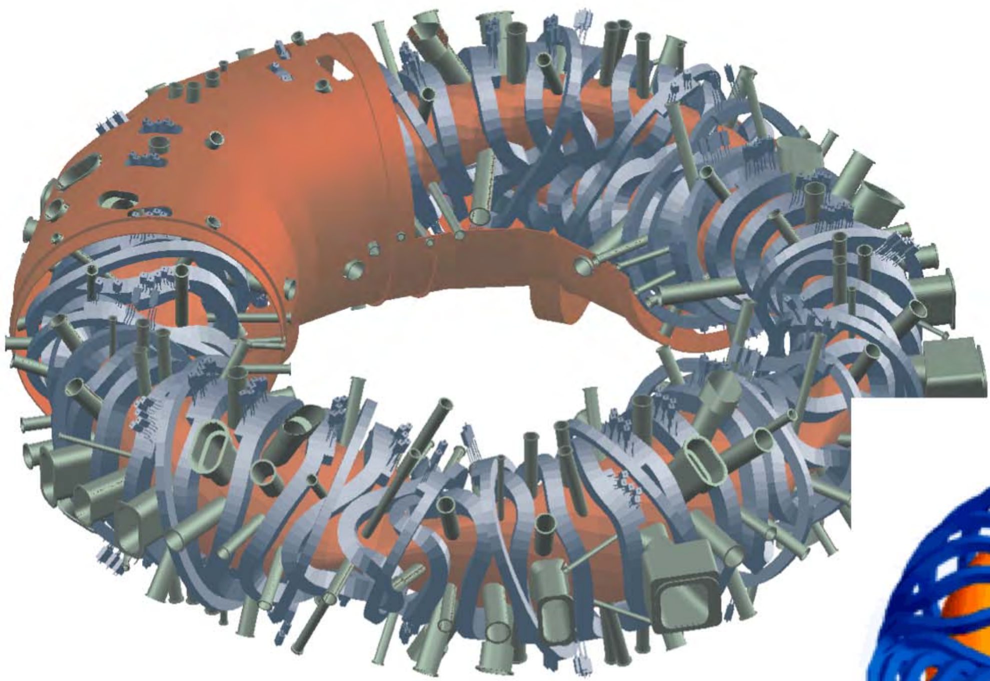
PF Coil #2 ready for resin impregnation, June 2020

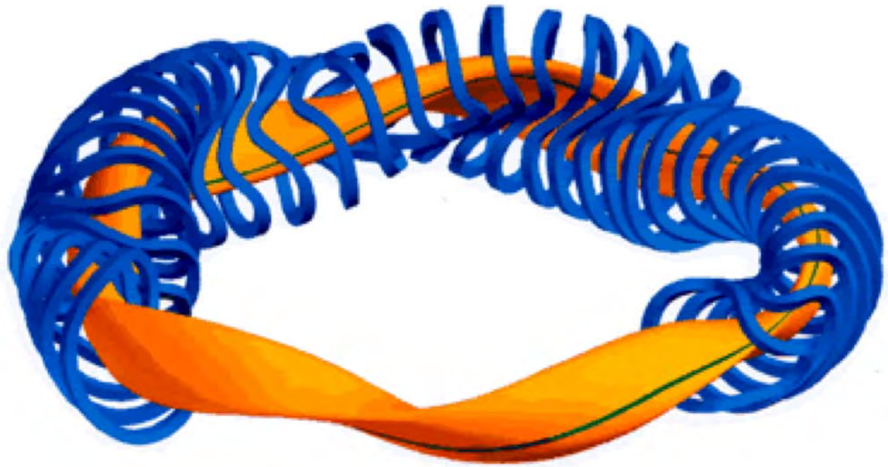
Start of ITER experiments : ~ 2026

Realizing a helicoidal magnetic field : Option 2

Stellarator

Complex 3D coils create directly a helical field





No plasma current

⇒ no transformer

⇒ continuous operation

Wendelstein 7-X: Overview

Physics goals

Fusion product should be about 1/50 of a fusion reactor

Major, average minor radius:	*R=5.5 m, <a>=0.53 m*
Magnetic field on plasma axis:	*B=2.5 T*

Test magnetic field optimization

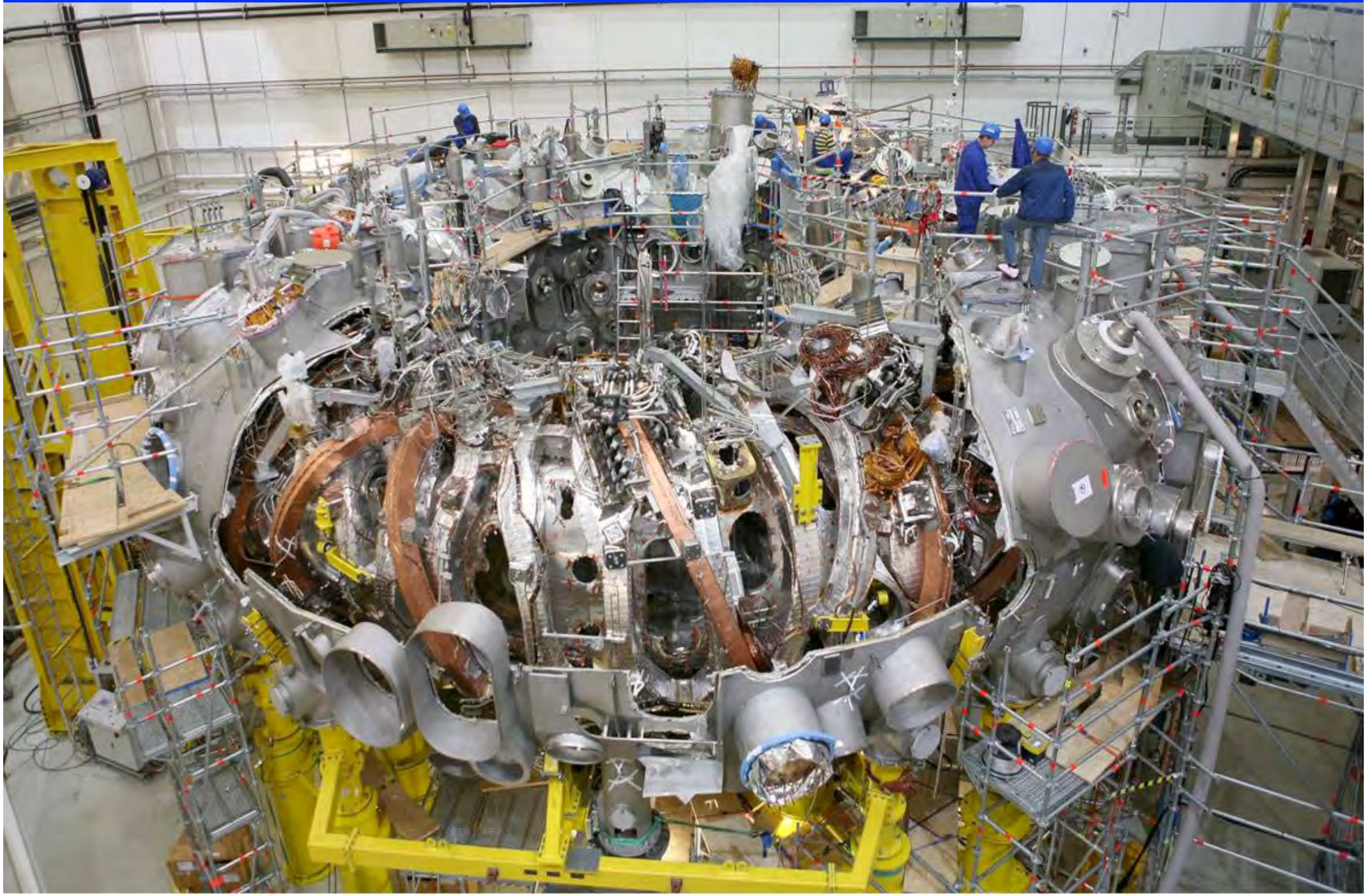
physics experiment:	*H, D plasmas only, additional planar coils*
heating systems	10*MW ECRH, 20 MW NBI, ICRH*
mimic α-particle heating:	ICRH, *NBI*
low impurity content, heat removal	*divertor*

Technological goals

Reactor feasability of stellarators

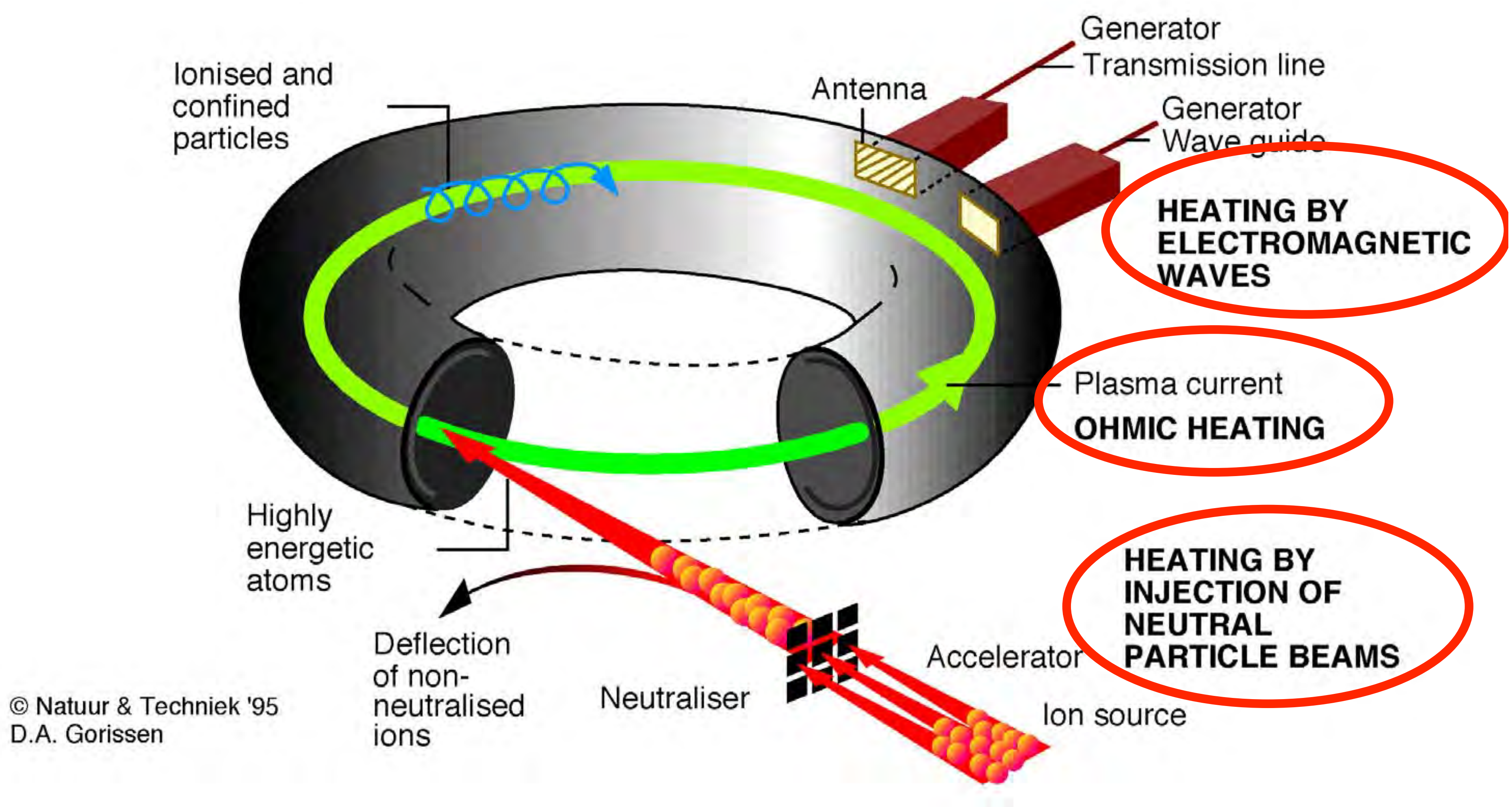
steady-state operation	*30 minute plasma heating with ECRH*
	superconducting coils
	active cooling of plasma facing components

Wendelstein 7-X : November 2011

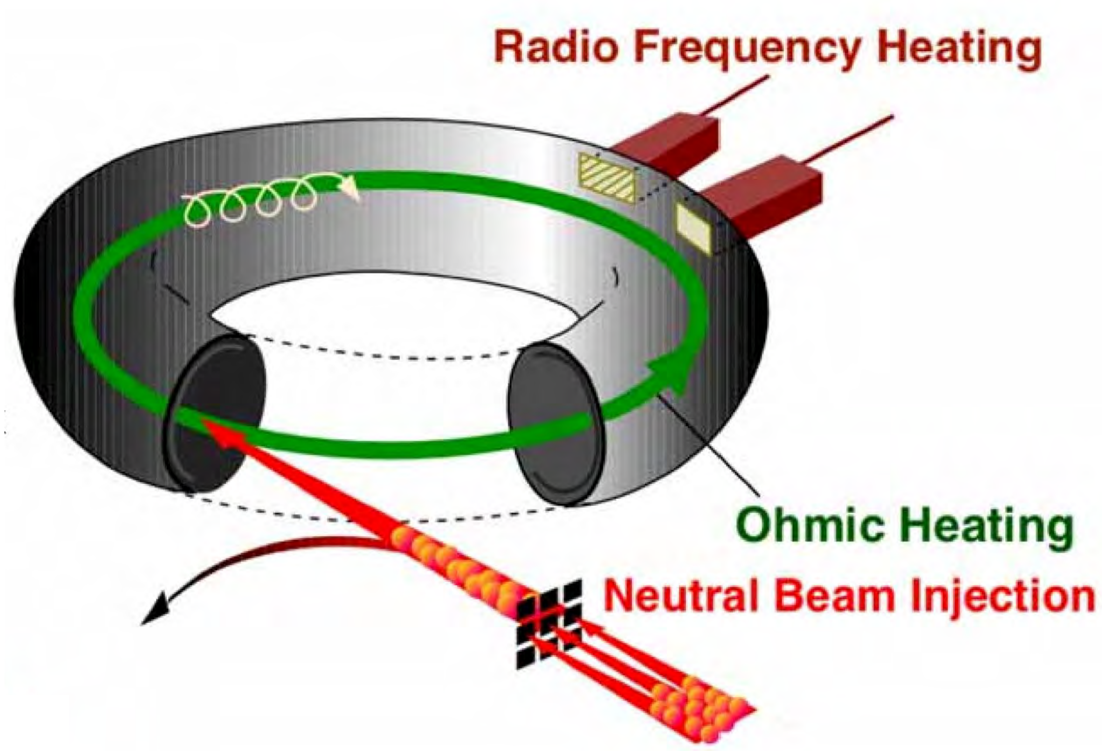


How to create the ultra high temperatures needed ?

In a future fusion reactor: α-particle heating



How to create the ultra high temperatures needed ?



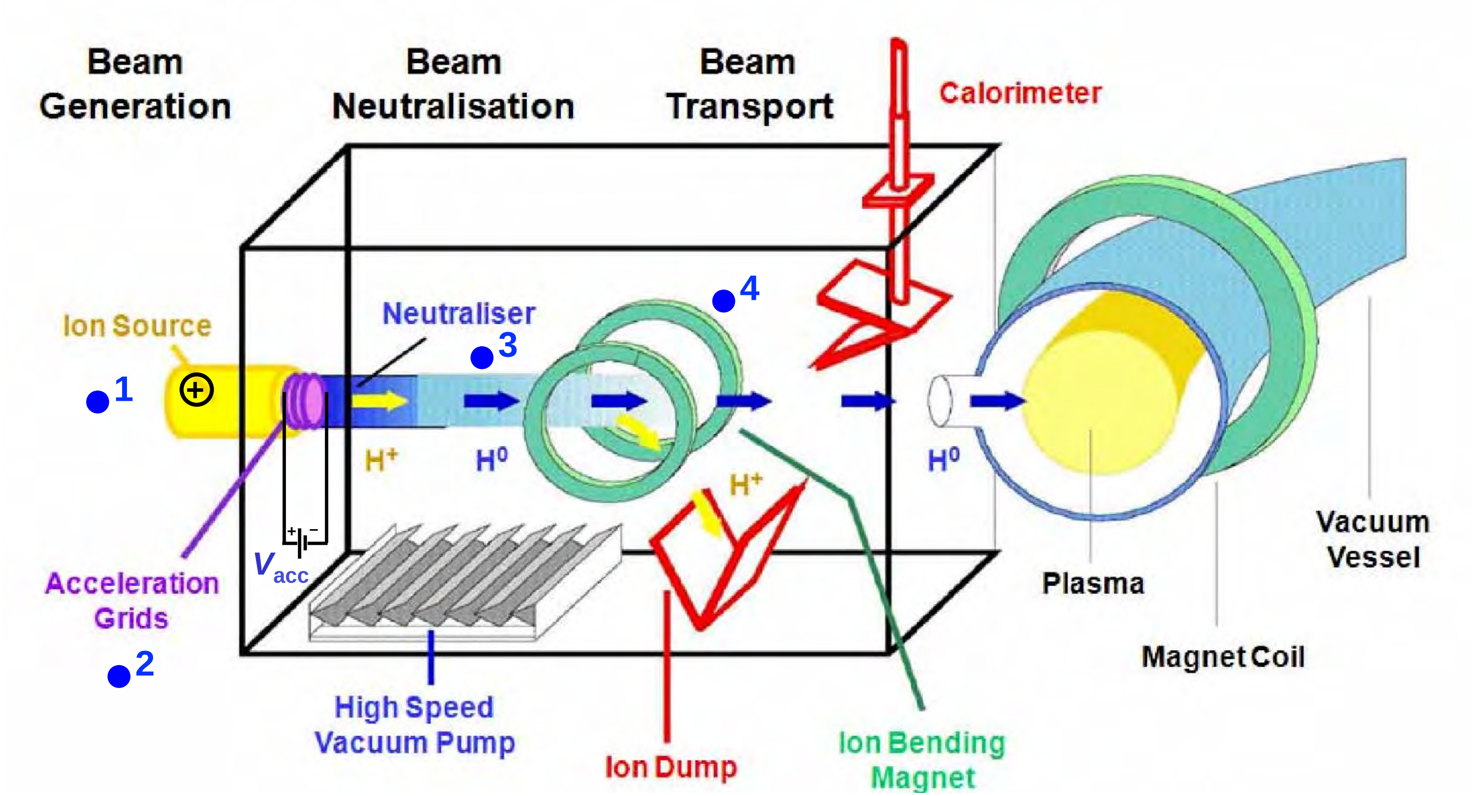
Analogy for NBI heating

Method 1: neutral beam injection (NBI)

inject high-energy neutral particles (~ 100keV – 1MeV) into the plasma

Neutral beam injection

- ●[1] Ion source (low temperature plasma)
- ●[2] Acceleration
- ●[3] Neutralization (passing through a cold neutral gas)
- ●[4] Separate neutrals and ions



Neutral beam injection: a technological challenge

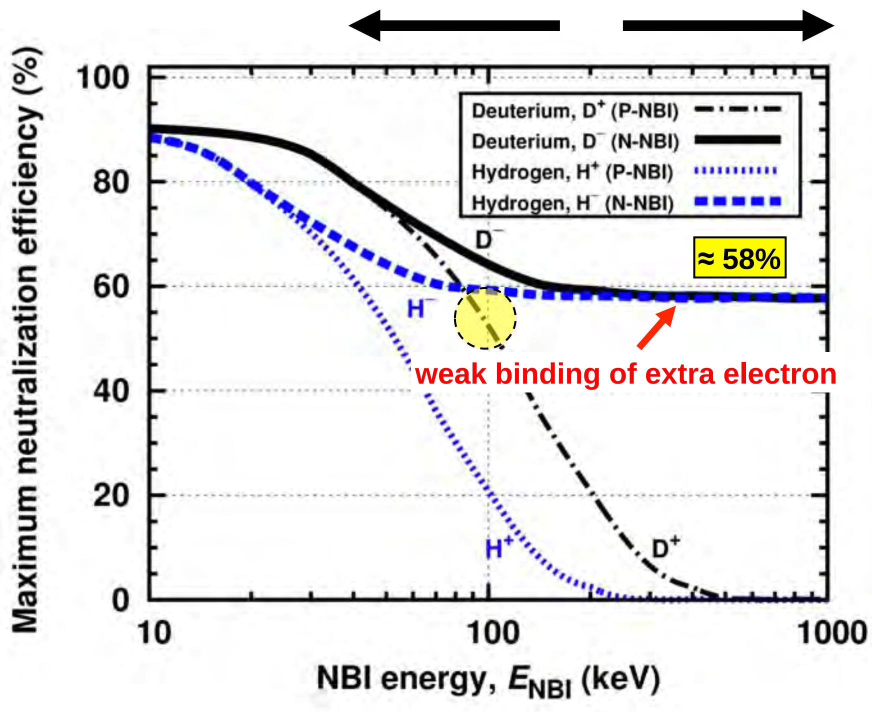
- Today most NBI systems use positive ion sources (e.g., D^+, H^+, T^+): best choice when the injection energy $E < 150$ keV

- For $E > 150$ keV: NBI system has to rely on using negative ions (neutralization efficiency ~ 60%)

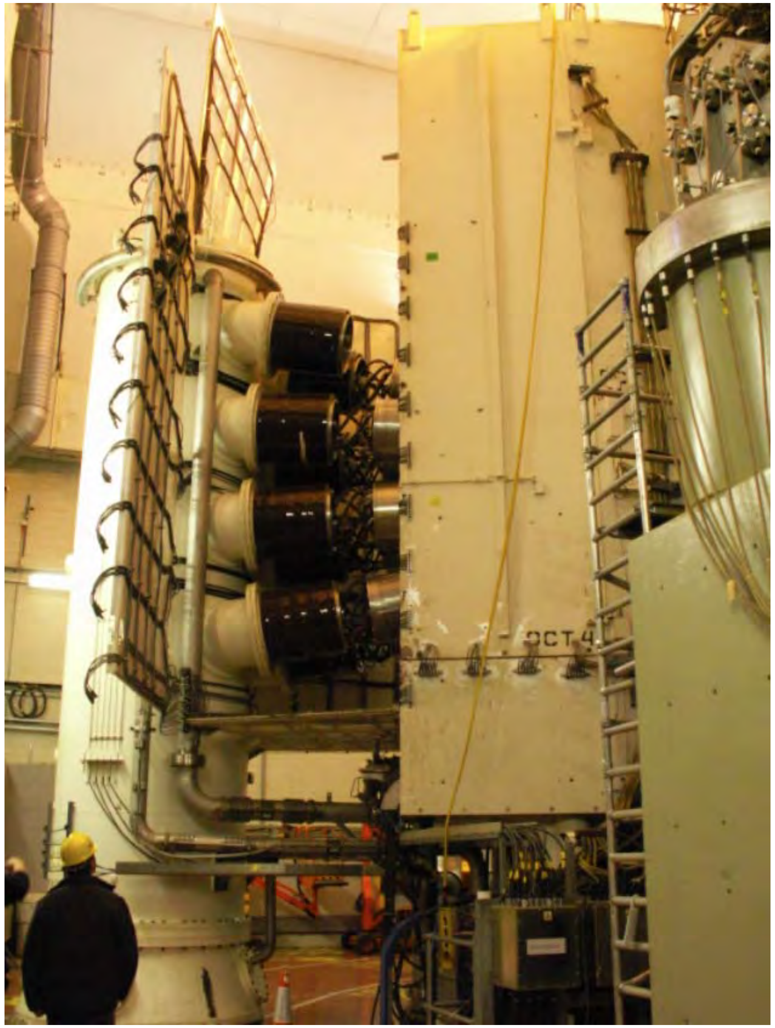
- The technology has been tested and further developed (e.g., 400 keV beam at JT-60U)

- Technology for 1 MeV NBI system for ITER is much more challenging! (being developed in Padua)

NBI systems based on *positive* vs. *negative* ions



Example of Neutral beam injection (in JET)

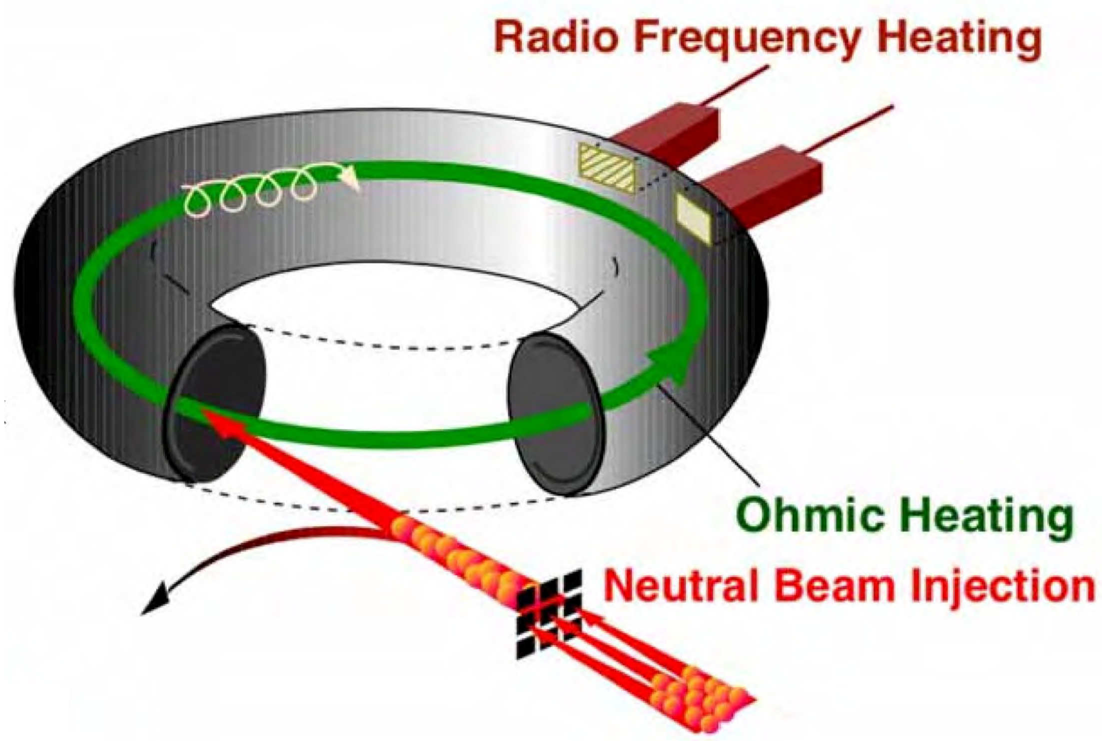


- One of the neutral beam injectors in JET

- Four of the 8 PINIs (Positive Ion Neutral Injector) are visible:
  - ✓ 120keV
  - ✓ 2MW D^0 beam

- Total power available From NBI in JET: max. ~ 36MW

How to create the ultra high temperatures needed ?

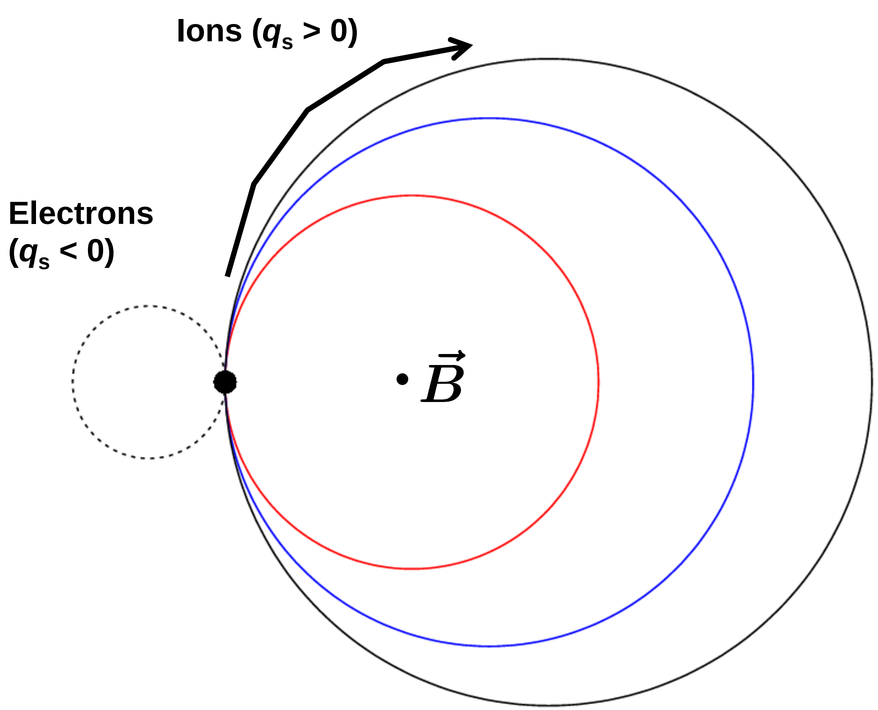


Analogy for RF heating

Method 2: radiofrequency heating (RF)

resonant transfer of RF power from waves to plasma particles (ions or electrons)

How do radiowaves heat plasmas ?



- Hydrogen ions ($A = 1$, $Z = 1$)
- Deuterium ions ($A = 2$, $Z = 1$)
- Tritium ions ($A = 3$, $Z = 1$)

Cyclotron frequency

$$\omega_{cs} = (q_s/m_s)\, B$$

- Depends on a particle's charge-to-mass ratio
- Rotation direction is different for ions and electrons

Example: Cyclotron frequencies in ITER

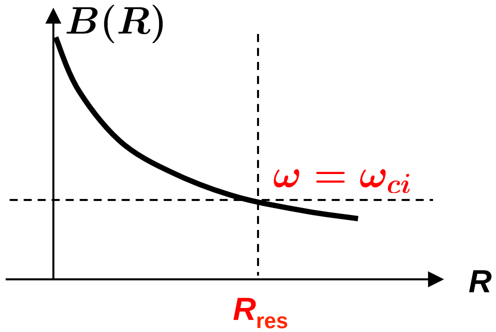
Particle in ITER (B_0 = 5.3T)	$(Z/A)_i$	Cyclotron frequency f_{ci}
D, $^4He^{2+}$	1/2	40MHz
T	1/3	27MHz
Electron (ECRH)		148GHz

How do radiowaves heat plasmas ?

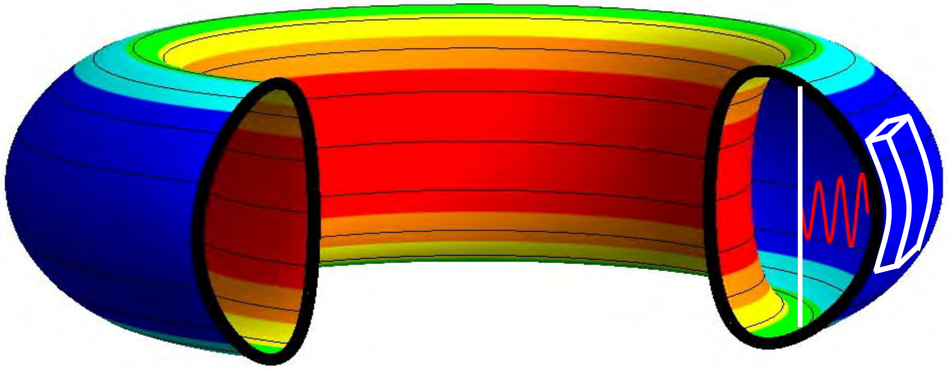
- **ICRF: cyclotron absorption by ions when $\omega = n\omega_{ci}$ (n = 1, 2, 3,…)**

  → **localized around the ion cyclotron (IC) resonance layers $\omega = n\omega_{ci}(R_{res})$**

  → **IC location externally controlled with ω**



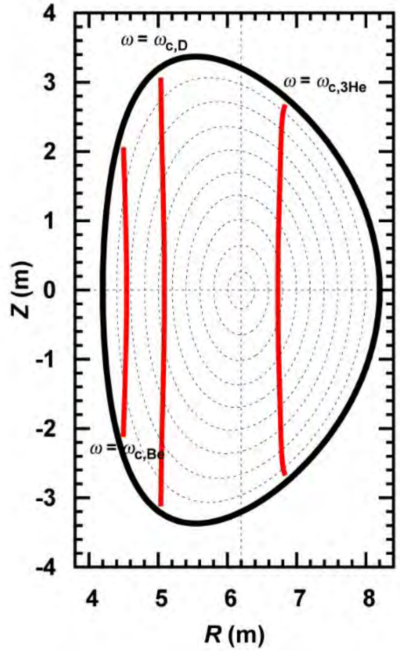
Color: magnetic field strength, $|B|$



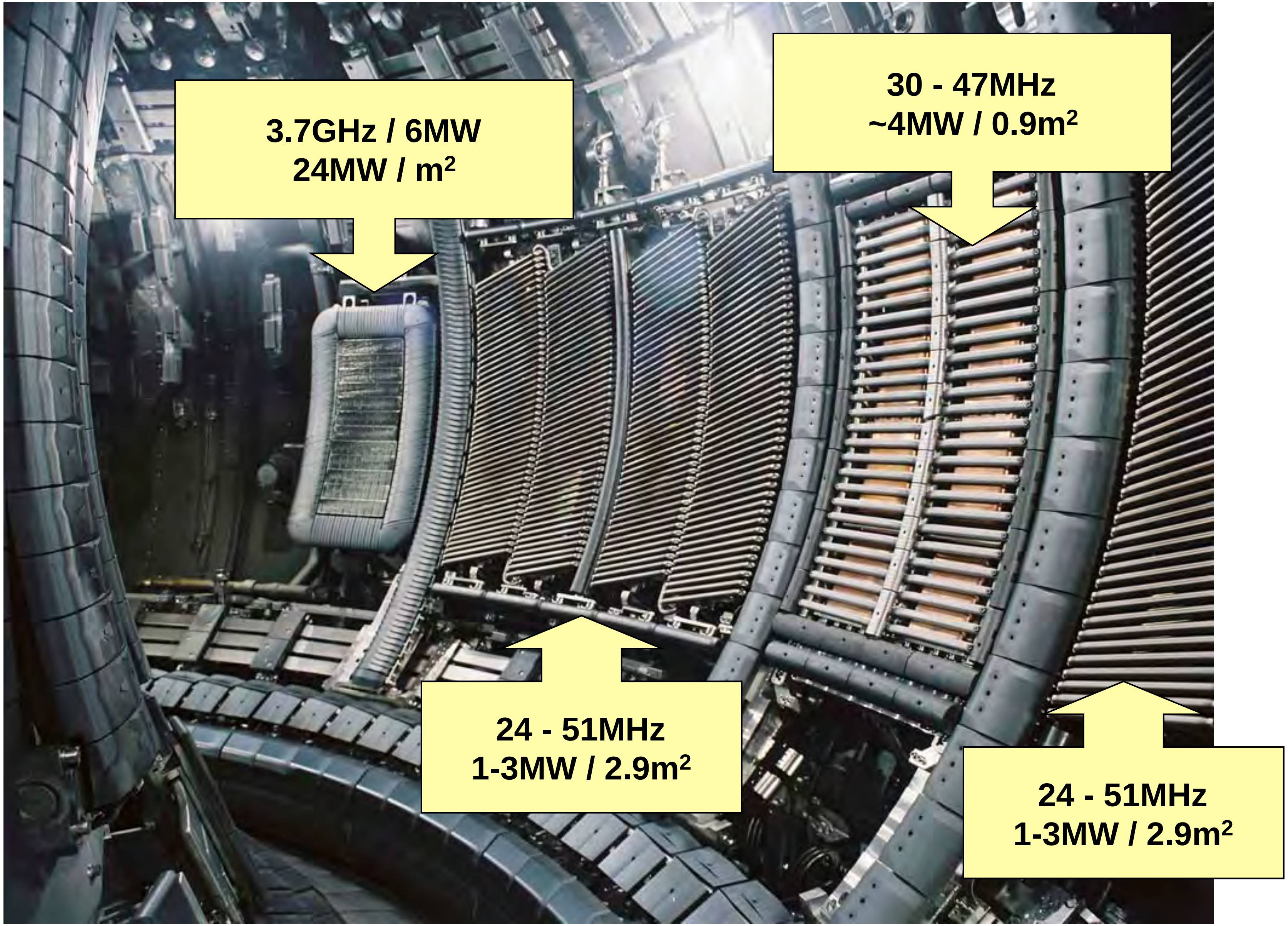
$$B(R) \approx B_0 R_0 / R$$

$$\Rightarrow R_{res}|_{\omega = n\omega_{ci}} = R_0 \frac{nZ_i}{A_i} \frac{15.25\, B_0(\mathrm{T})}{f(\mathrm{MHz})}$$

Example: IC layers in ITER at B_0 = 5.3T, f = 50MHz)



Example of RF heating systems (in JET)



Plasma Energy and Energy Confinement Time

$$W_p = 1.5 \int_V k\,[n_e(r)\,T_e(r) + n_i(r)\,T_i(r)]\,dV$$

$$\frac{dW_p}{dt} = P - \frac{W_p}{\tau_E}$$

If $P = 0 \Rightarrow W_p(t) = W_p(0)\,e^{-t/\tau_E}$

Transport losses by conduction and convection

τ_E measures how fast the plasma looses its energy

τ_E is a measure for the thermal insulation of the plasma

Under stationary conditions (dW/dt=0) : $\tau_E = \frac{W_p}{P}$

Lawson Criterium for D-T reaction

Heating power must be large enough to compensate for the losses

$$P_{heat} + P_{\alpha} \geq P_{transport} + P_{Bremsstrahlung}$$

Condition for Breakeven (Q=1)

$$n_e \tau_E \geq 10^{20} m^{-3} s$$

Condition for Ignition (Q=∞)

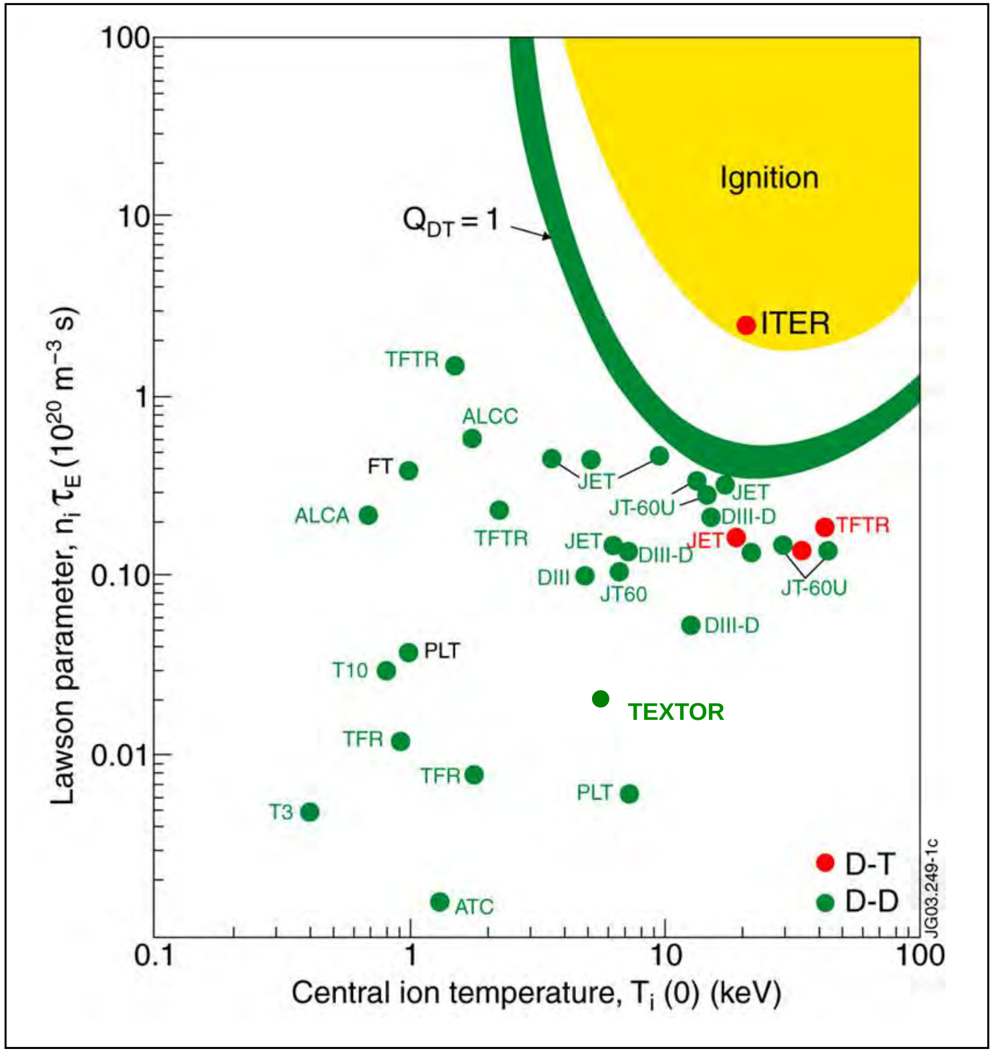
$$n_e \tau_E \geq 3 \times 10^{20} m^{-3} s$$

Charcterizing progress – Lawson Criterion

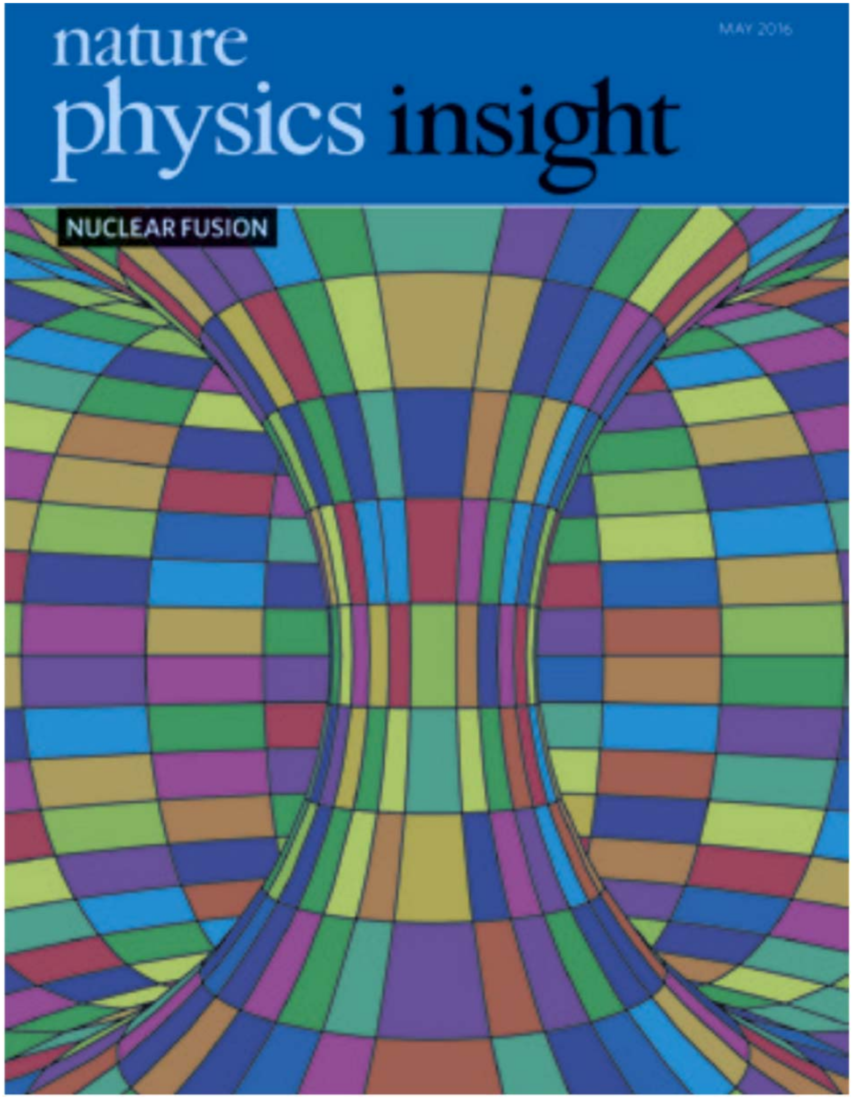
Positive power balance in a reactor → Condition on $n_i \tau_E$

Present machines are close to produce fusion energy comparable with the energy required to sustain the plasma (breakeven : Q=1)

Next step devices (ITER) are expected to produce significantly more fusion energy than the energy required to sustain the plasma (Q=10 or larger)



Latest status in fusion research



Nature Physics,
May 2016

“Insight Section”
On nuclear fusion

66 pages of
last minute info on:

- -Magnetic fusion
- -Inertial fusion
- -Fusion materials research
- -Computational advances

http://www.nature.com/nphys/journal/v12/n5/index.html

Fusion: energy source of the universe

Personal opinion for consideration by the audience

- Population explosion, especially in emerging economies
- The lion's share of world energy production is of fossil origin (80 - 90%)
  - Finite resources
  - Need a replacement: but only two classes left - nuclear and renewable
  - Climate effects due to CO_2
- Renewable energy (hydro, wind, solar, ...) must contribute, but:
  - Large fluctuations: day / night, summer / winter, storm / windless, ..
  - Low energy density: large installations and costs
  - Need for backup, storage and large interconnections
- Fusion has a large potential to contribute to our future energy mix
  - Low risk, no CO_2, no actinides, inexhaustible,...
  - But: difficult and will take time


Fusion: a necessary option for the future
More information:
http: / / www.iter.org