Fusion Principles

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International School on Energy
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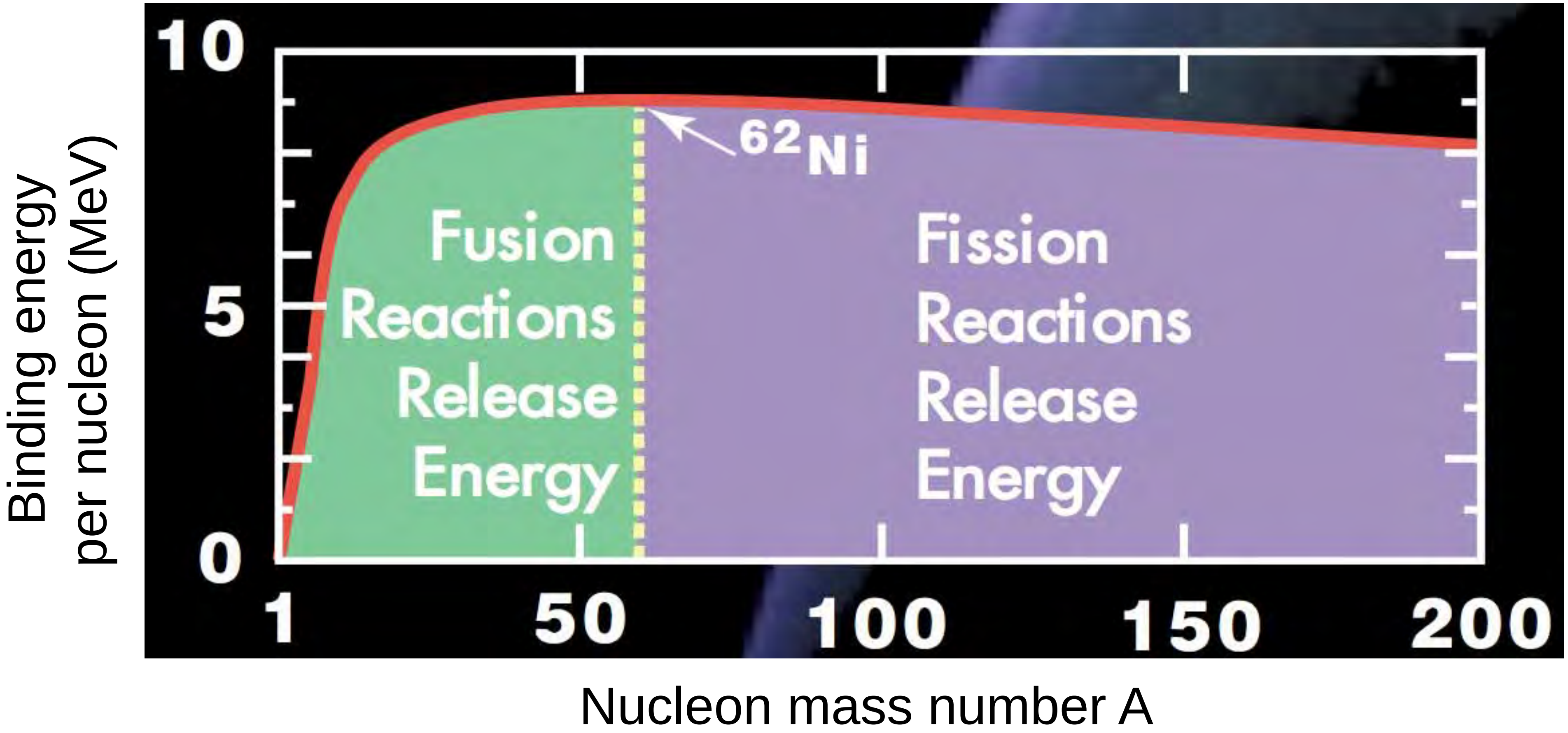
21 July 2014

Outline

- Fusion reactions
  - In the sun
  - On earth
- Two possible options to realize fusion on earth
  - Inertial Fusion
  - Magnetic Fusion
- Two possible options to realize magnetic fusion on earth
  - Using a plasma current : tokamak
  - Avoiding a plasma current : helical devices, stellarator
- Lawson Criterion

Energy gain in fusion reactions

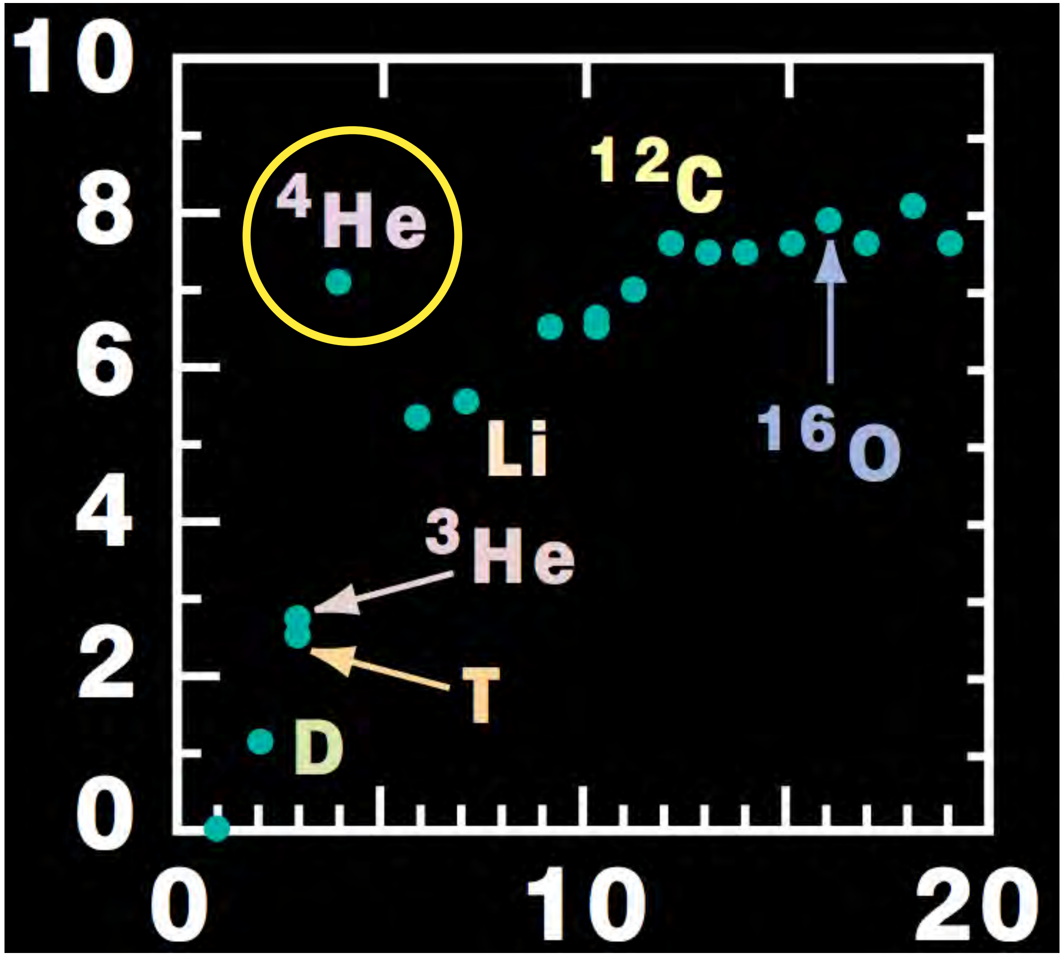
Results from the difference in binding energy between light nuclei and fusion products



Maximum at ~ ^{62}Ni : tremendous consequences for heavy stars

Energy gain in fusion reactions

^{4}He has a particularly large binding energy



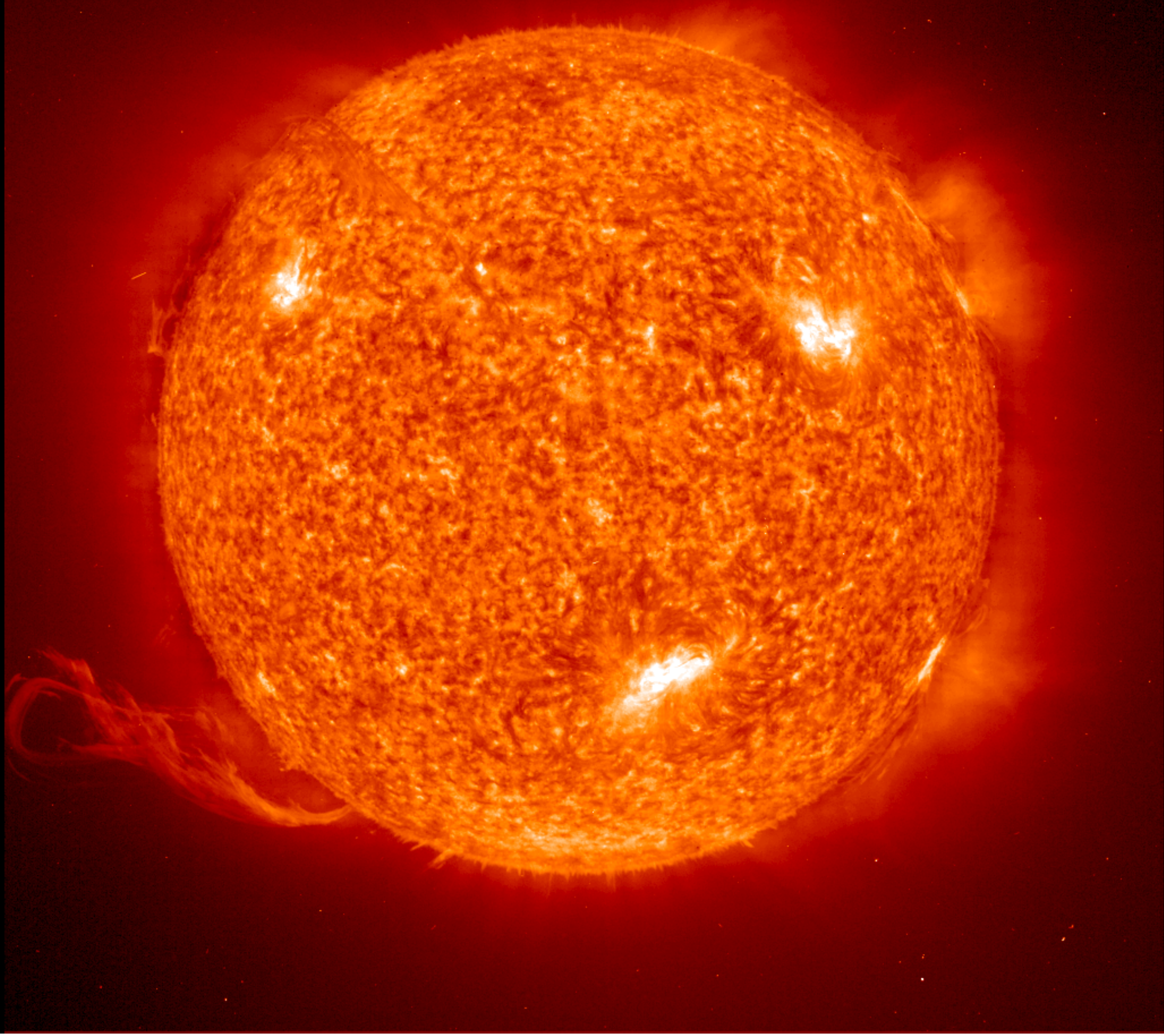
Binding energy per nucleon (MeV)

Nucleon mass number A

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

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

Fusion in the sun



Some facts about our sun

Temperature at edge

From Stefan-Boltzmann law and measured Luminosity L

$$L = 4\pi\sigma R^2_{sun} T^4_{edge} \rightarrow \mathbf{T_{edge} = 5780K}$$

(σ = Stefan-Boltzmann constant $=5.670\times10^{-8}$ J m^{-2} K^{-1} s^{-1})

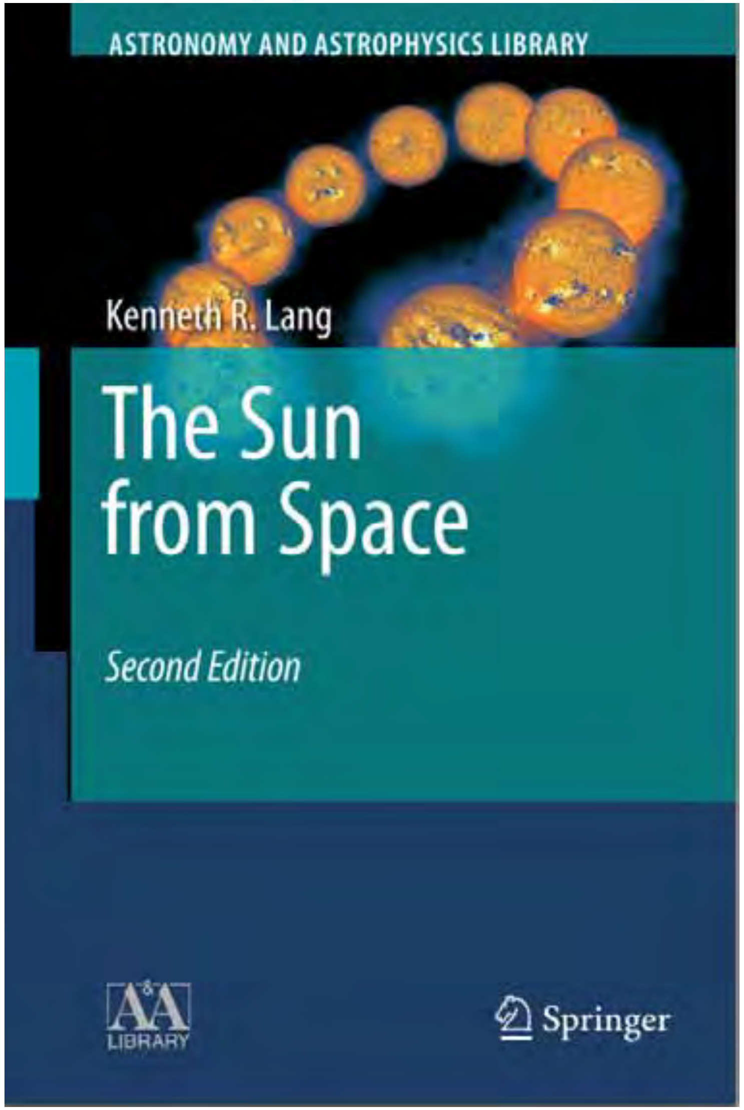
Temperature in centre:

Proton thermal energy in centre (= 3/2 kT) equal to potential energy from gravity per proton:

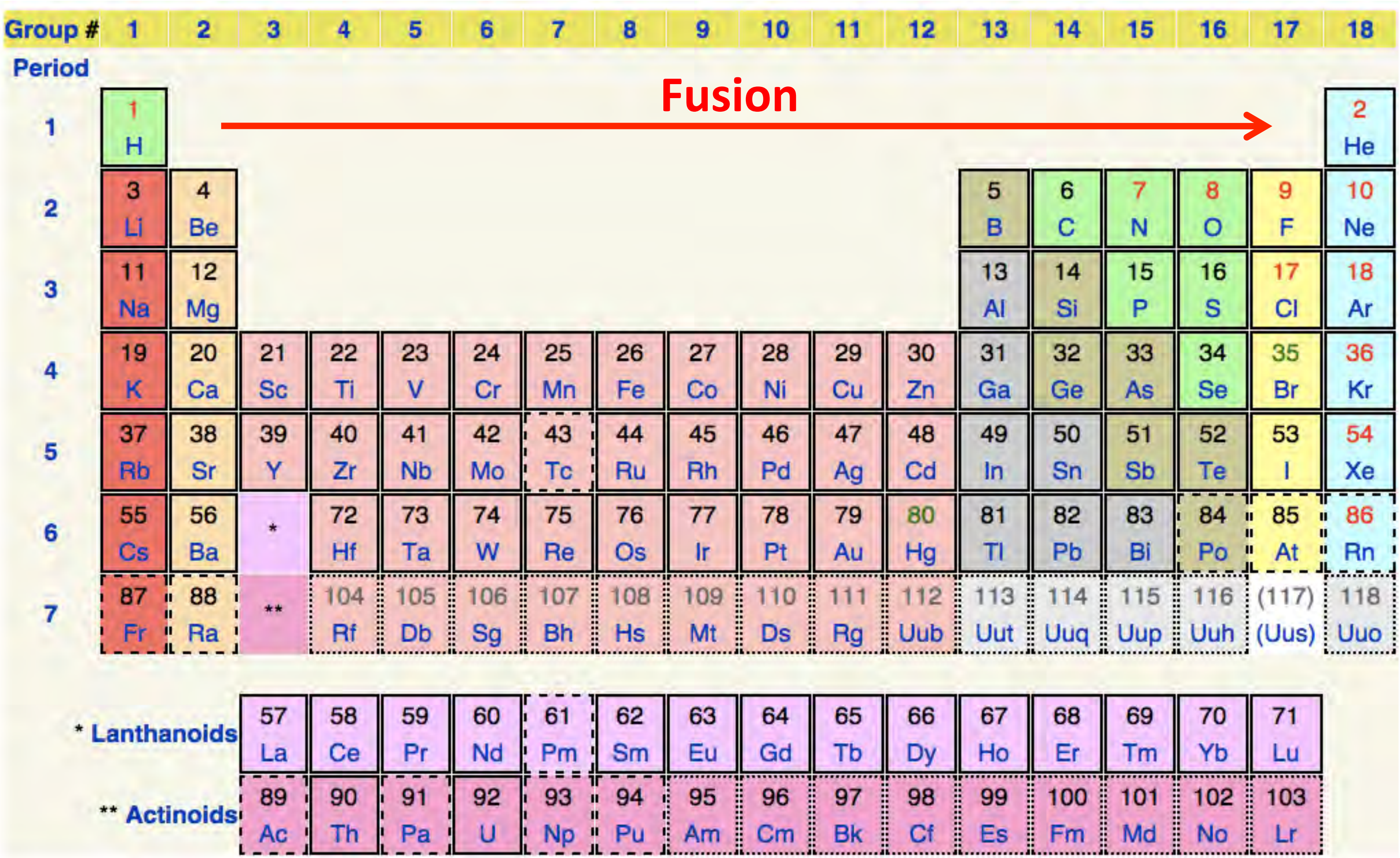
$$1.5k\,T_{centre} = Gm_p\,M_{sun}/R_{sun} \rightarrow \mathbf{T_{centre} = 15\,600\,000\ K}$$

(G=gravitational constant=6.6726 10^{-11} Nm^{2}kg^{-2}
k=Boltzmann's constant=1.38 10^{-23} J K^{-1}
m_p = mass of proton = 1.6726 × 10^{-27} kg.

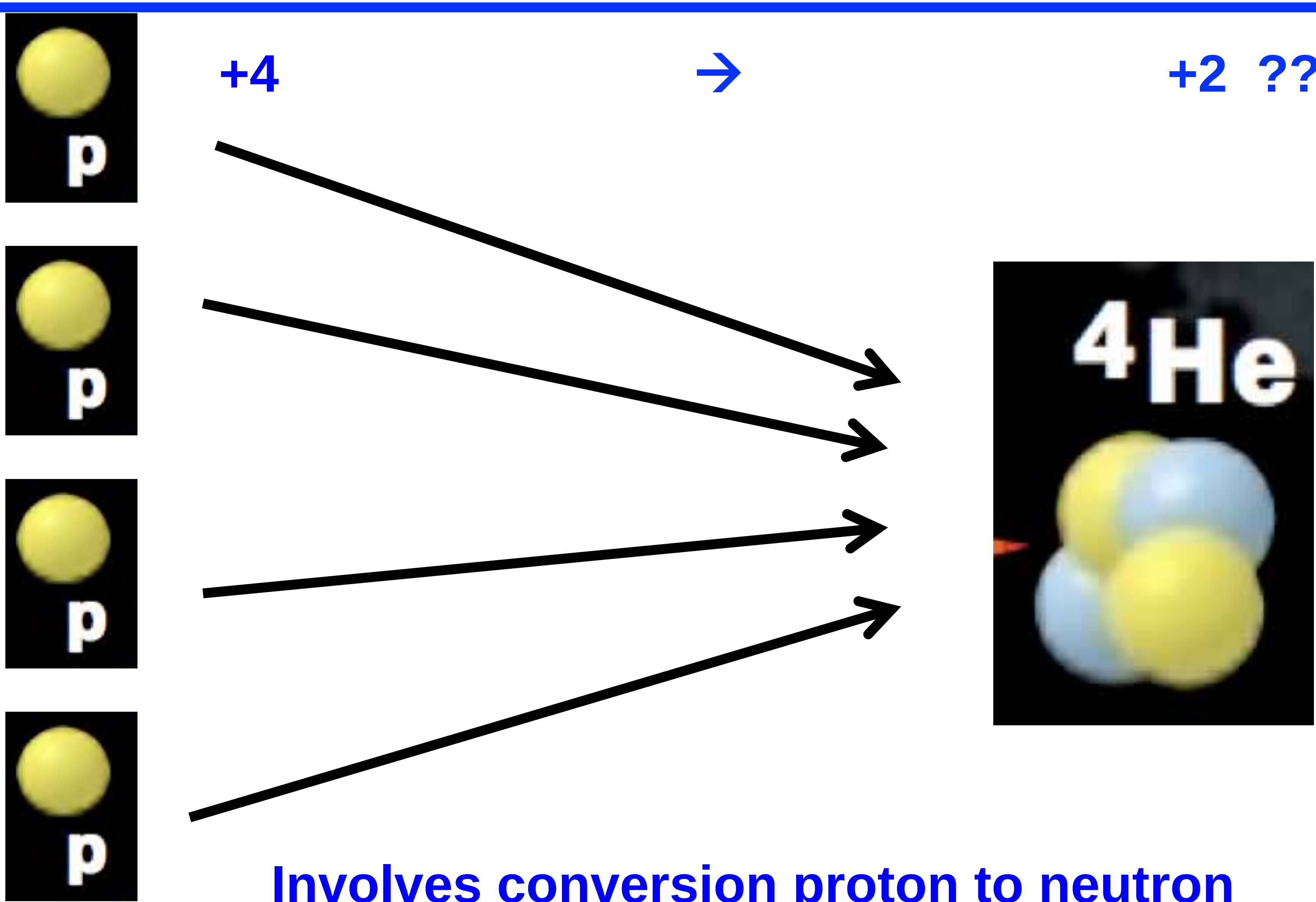
Interesting recent reference on our sun



Fusion from hydrogen to helium



Helium from protons only ?



Involves conversion proton to neutron

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

Sun : Every second : 4 million tonnes transformed → Energy

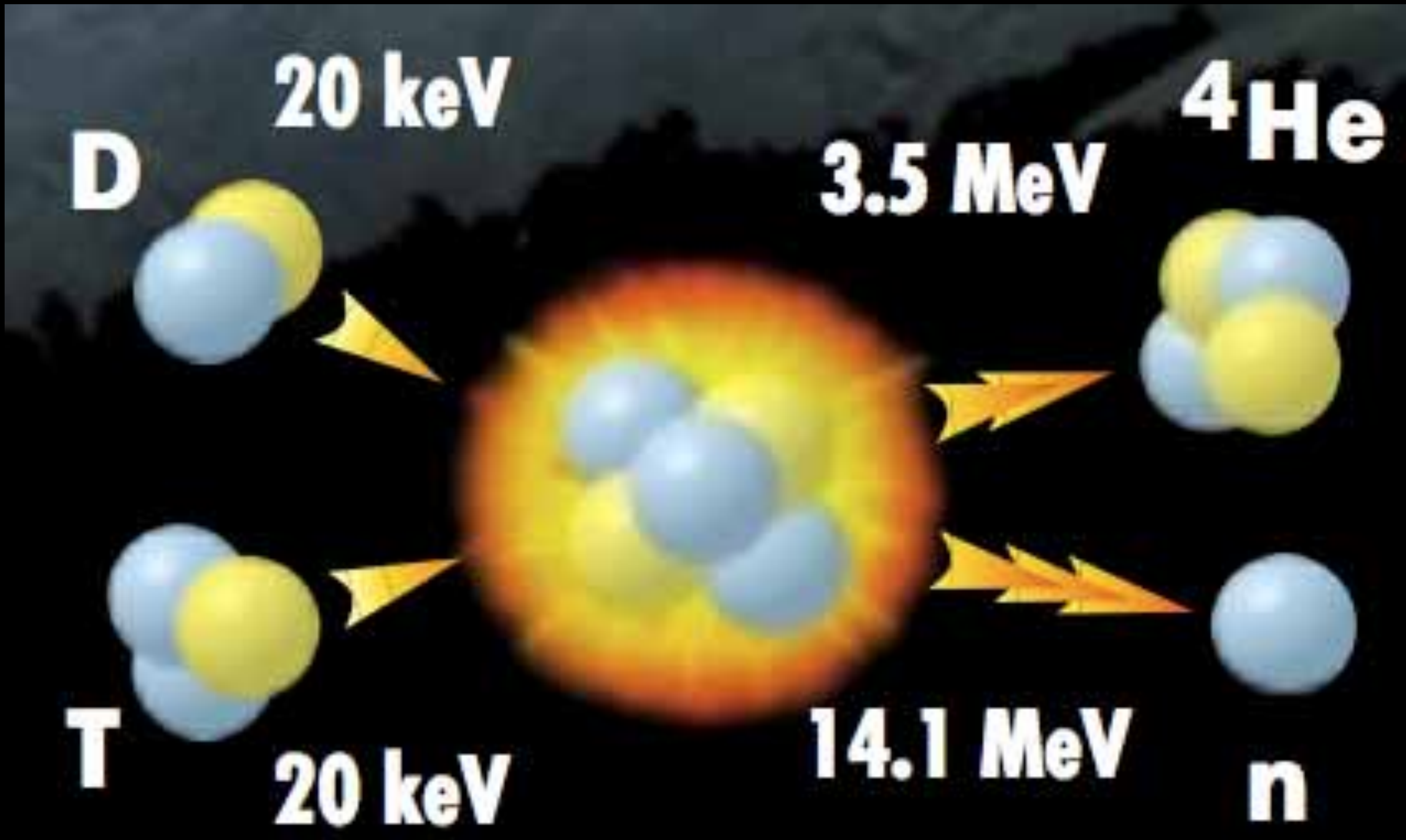
Fusion on earth

‘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

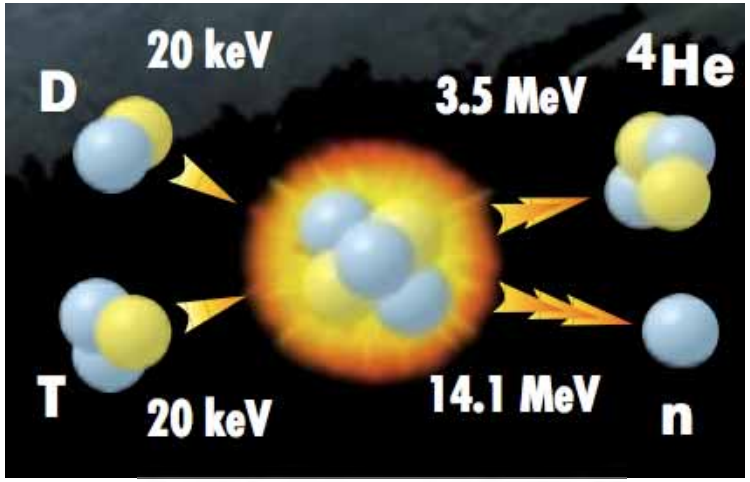
Extensive database on fusion reactions : http://pntpm3.ulb.ac.be/Nacre/barre_database.htm

The 'simplest' fusion reaction on earth

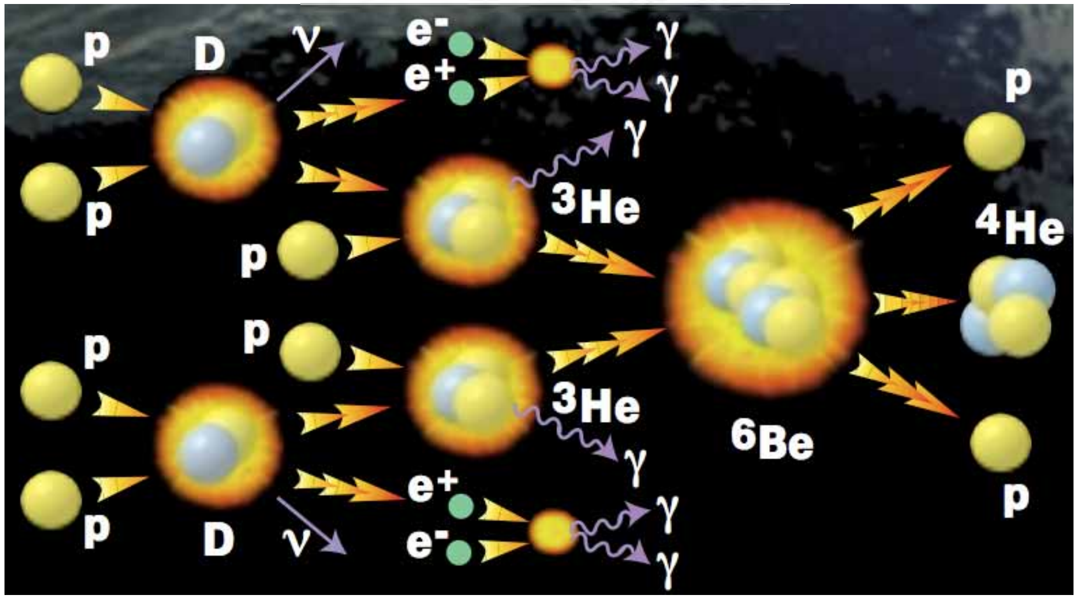


Comparison: fusion reaction on earth and in the sun

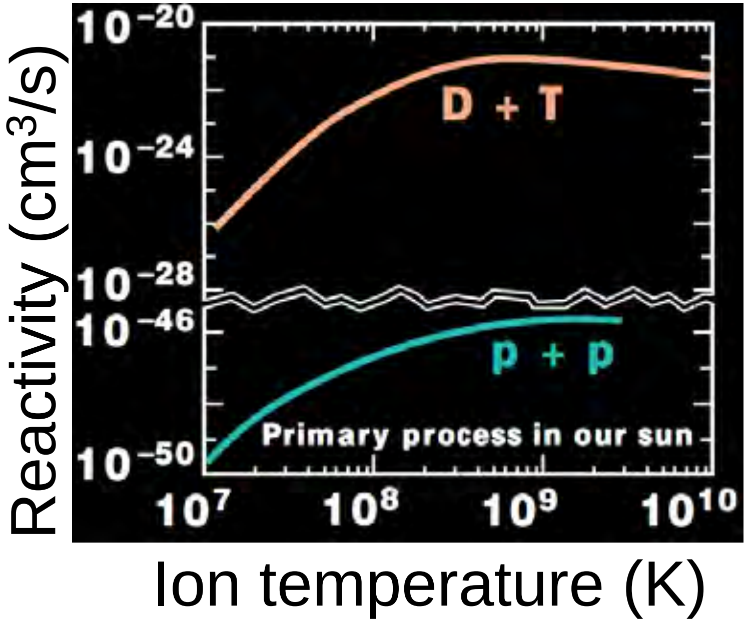
On earth (D-T)



In the sun (p-p)



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



Tritium Breeding inside the reactor

$$D + T \rightarrow {}^{4}He + n + \Delta E$$

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

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

$$D + Li \rightarrow {}^{4}He + 100 \times 10^{6}\ kWh/\ kg$$

Advantages of fusion

- Ash is ^{4}He
  - — 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
  - ⇒ 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

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

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

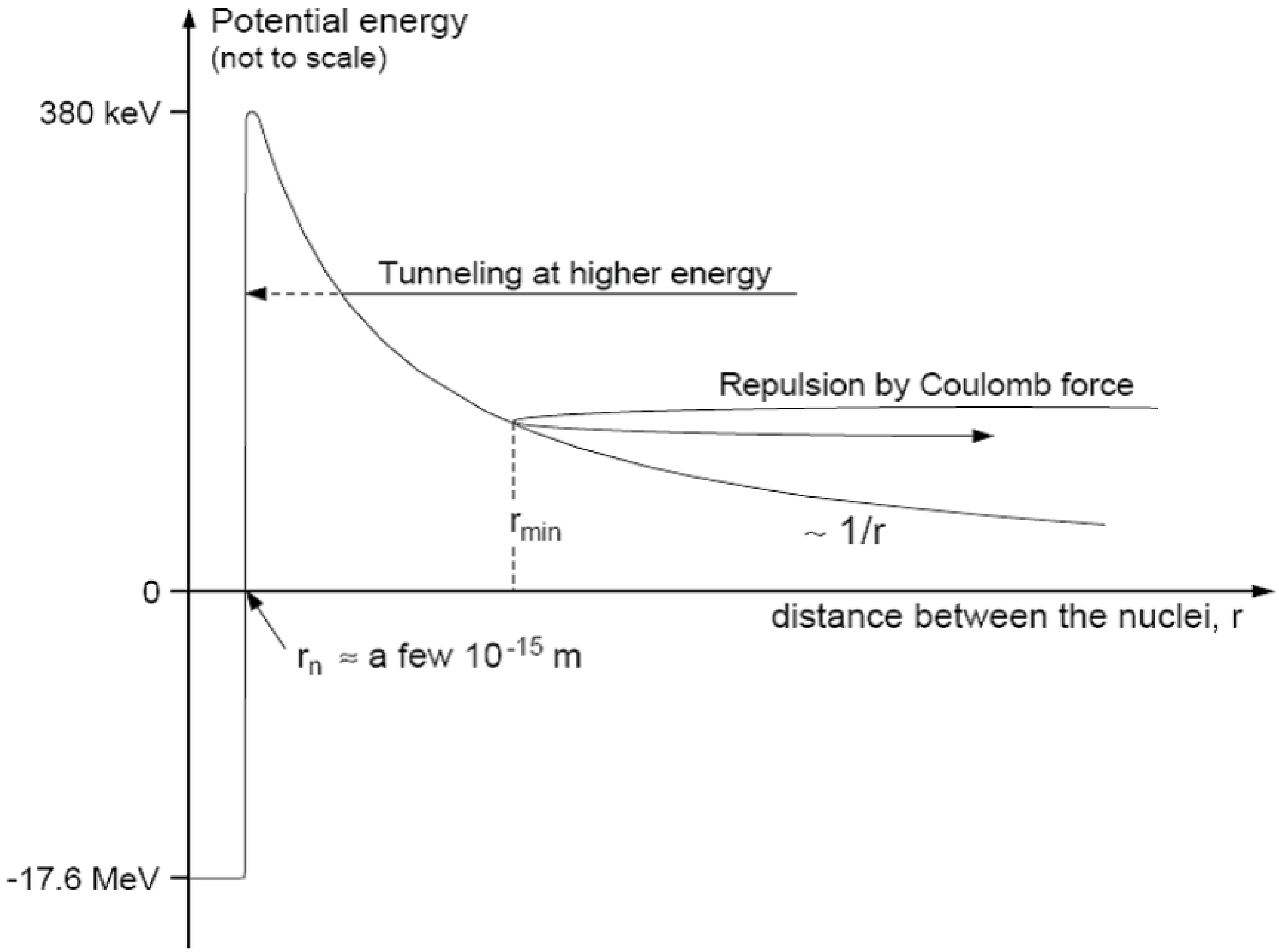
$$= 1.44 \frac{Z_x Z_y}{1.4(A_x^{1/3} + A_y^{1/3})} MeV$$

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

However the maximum fusion density
is reached at 10-15 keV or 110-160 10^6 K…

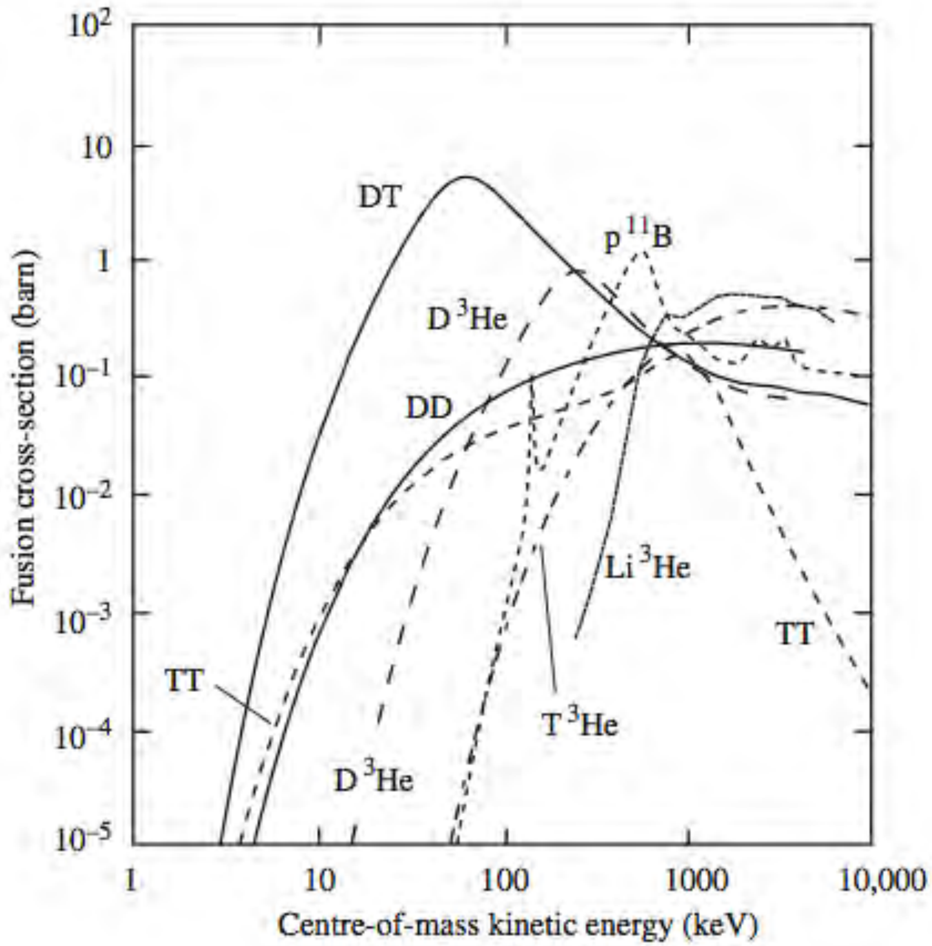
(Note : 1 eV ~ 11600 K, see appendix)

Most fusion reactions occur through tunneling

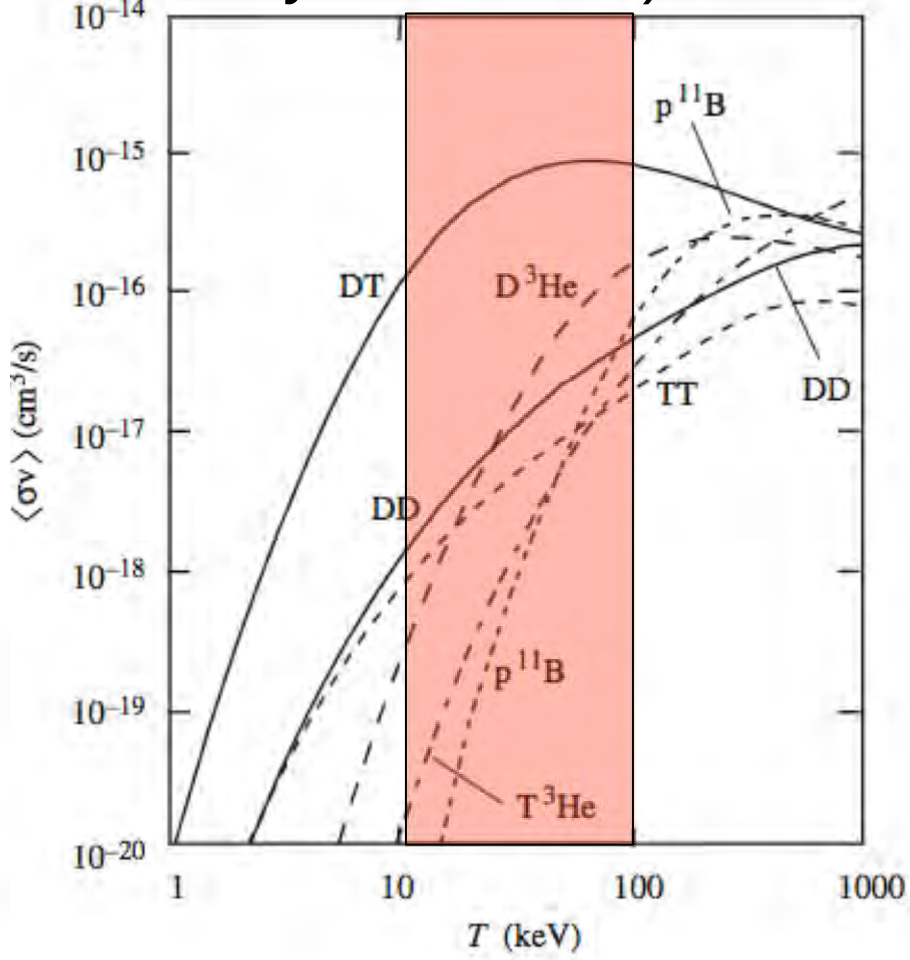


Fusion Cross-Sections and Reactivities

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



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



Fusion Power Density

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

Fusion power:

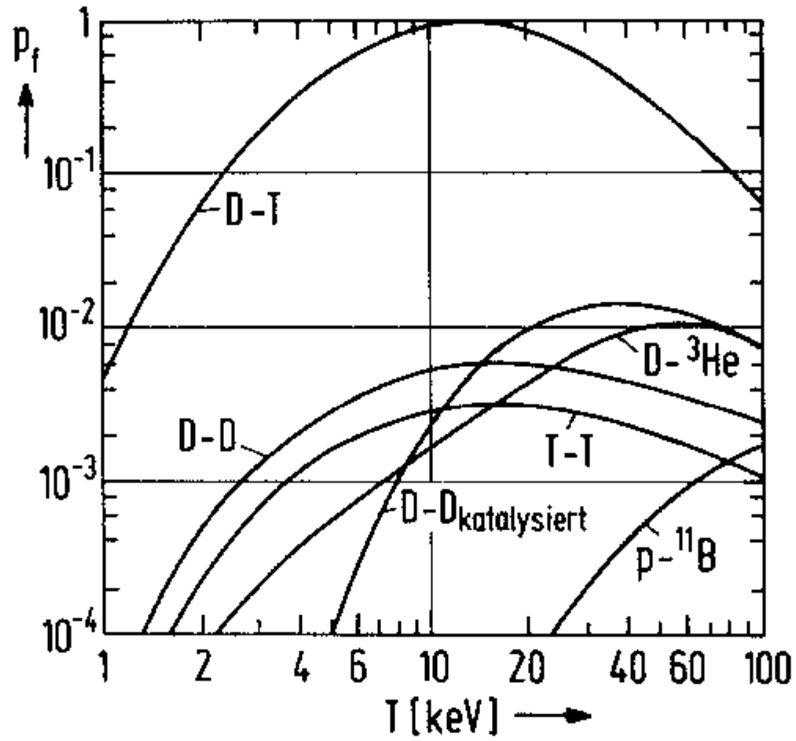
$P_{fusion} \sim n^2 <\sigma v> E_{fus}$

At fixed pressure

$p = cte = nkT$ -- > $n \propto 1/T$

Thus :

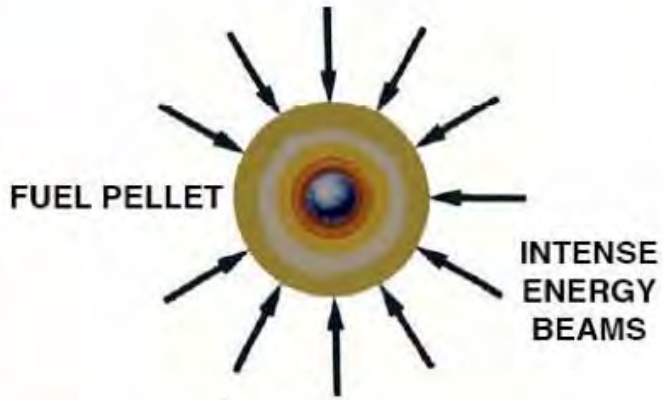
$P_{fusion} \sim <\sigma v> E_{fus} / T^2$



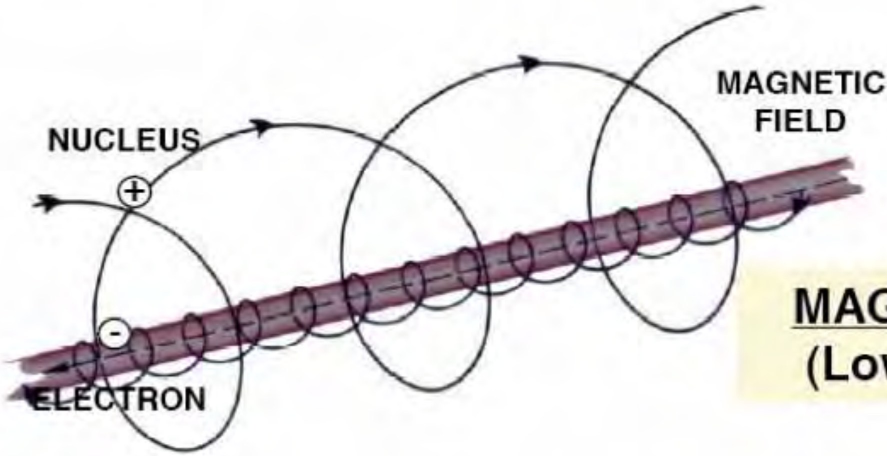
P_{fusion} normalized to max of D-T

How to confine matter at very high temperatures ?

GRAVITATIONAL CONFINEMENT
(High density for billions of years)



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



MAGNETIC CONFINEMENT
(Low density for seconds)

Brief history of fusion research

ITER construction start

2010

2005 – ITER location OK

2000

1997 – 16MW in JET

1990

1991 – JET first D-T exp worldwide

1980

1985 – Gorbachev, Reagan : ITER

1984 – JET, TFTR, JT60 operation start

1973 – Start of INTOR →later ITER

1972 – JET (EU), TFTR(USA), JT60 (Japan) proposed; reactor study

1970

1971 – First presentation of Inertial fusion systems (Frascati)

1971 – Tokamak fever; Conceptual design of reactor, Erice (Brunelli, Martellucci)

1968 – Novosibirsk IAEA Conference : Succes of tokamak

1960

1965 -- Failure of pinches: temperature not as high as expected (large thermal losses)

1961 -- 1st IAEA conference : first plasmas at 1-10 million degrees (ZETA, pinch)

1958 -- 2nd UN conference : stellarator, pinch, tokamak presented

1950

1956 -- Lawson criterion : performance of fusion systems

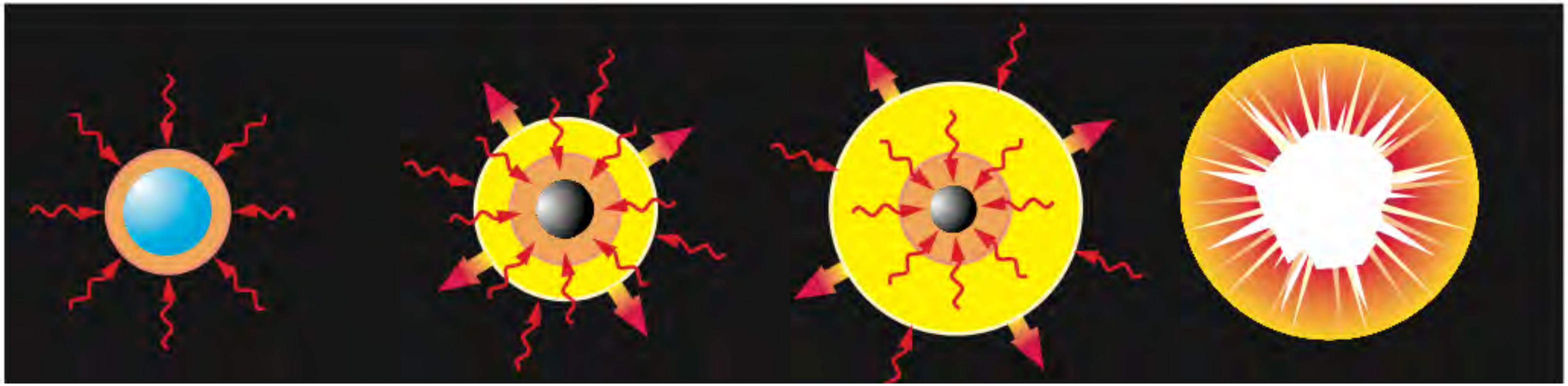
1955 -- 1st UN conference - Bhabha Statement : "in 20 years fusion; water as fuel"

1951 – Sakharov and Tamm (Kurchatov Institute, Moscow) : Propose Tokamak

Lots of 'unsurmountable' difficulties have been solved
But still a lot of challenges ahead

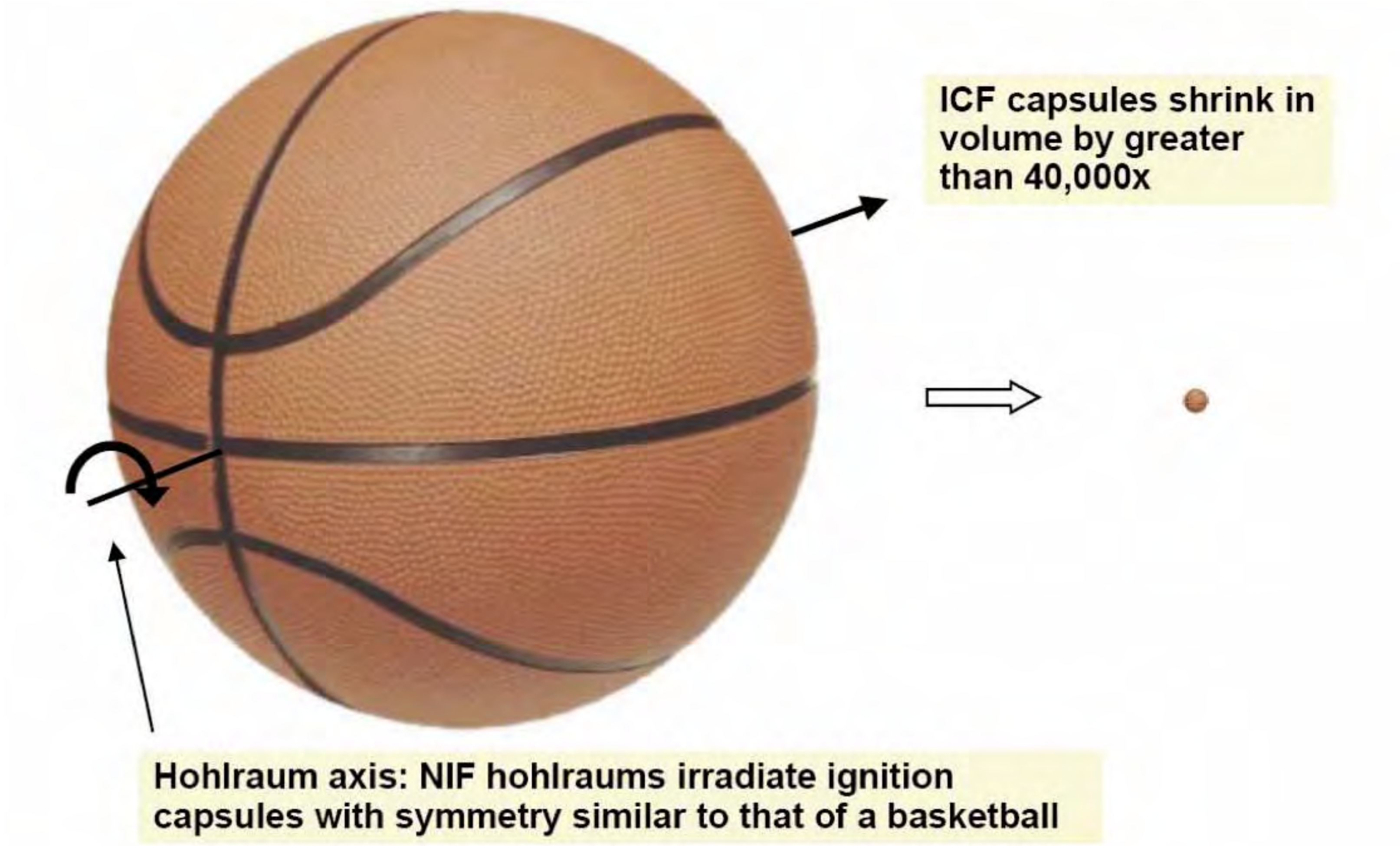
Realizing Fusion
A. Inertial Fusion

Using powerful laser or particle beams to compress a tiny pellet



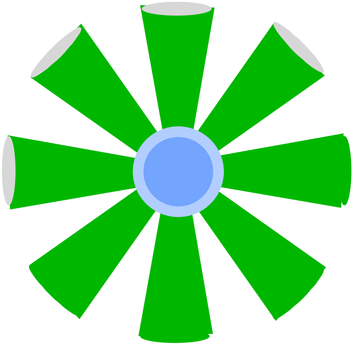
Surface Heating **Compression** **Ignition** **Fusion**

Realizing Fusion
A. Inertial Fusion

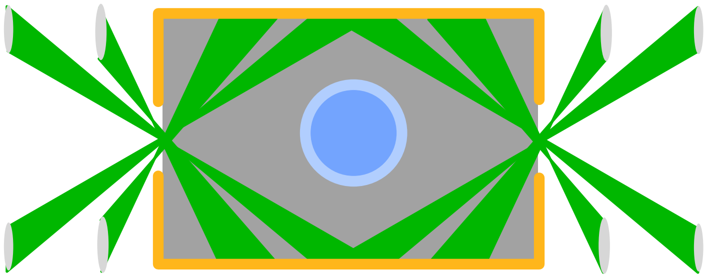


Very powerful laser systems needed
High requirements for isotropic illumination of target

Two options: direct and indirect drive



direct drive with lasers



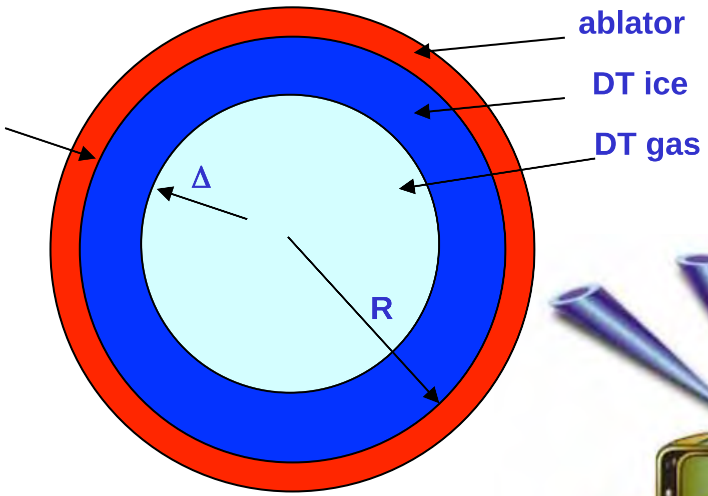
indirect drive by X-rays

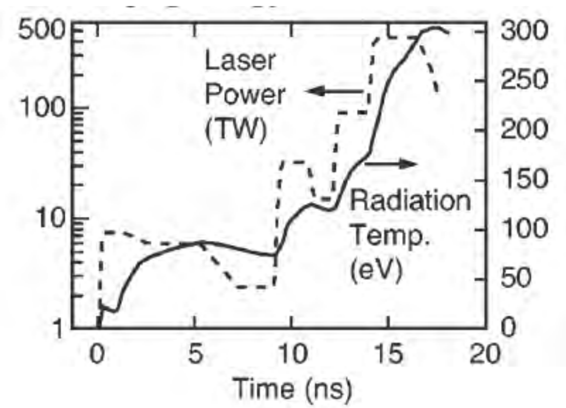
Better efficiency but:
- **less stable and**
- **less symmetric implosion**

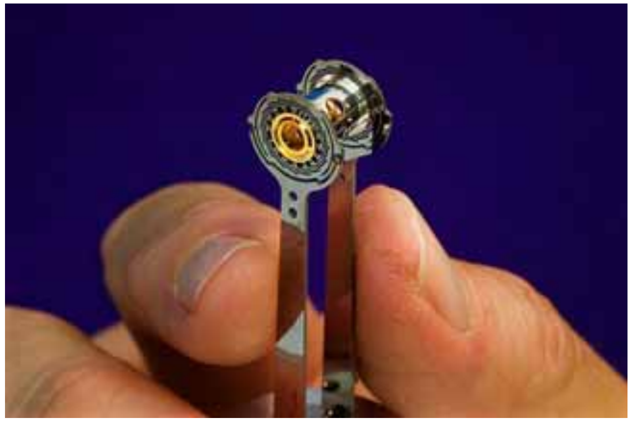
Less efficient but:
- **more stable and**
- **more symmetric implosion**

Inertial fusion facilities:
NIF (USA) and LMJ (France)
Planned (EU) : HiPER

Targets for Inertial Fusion







R ~ 1 mm
Δ ~ 0.2 mm

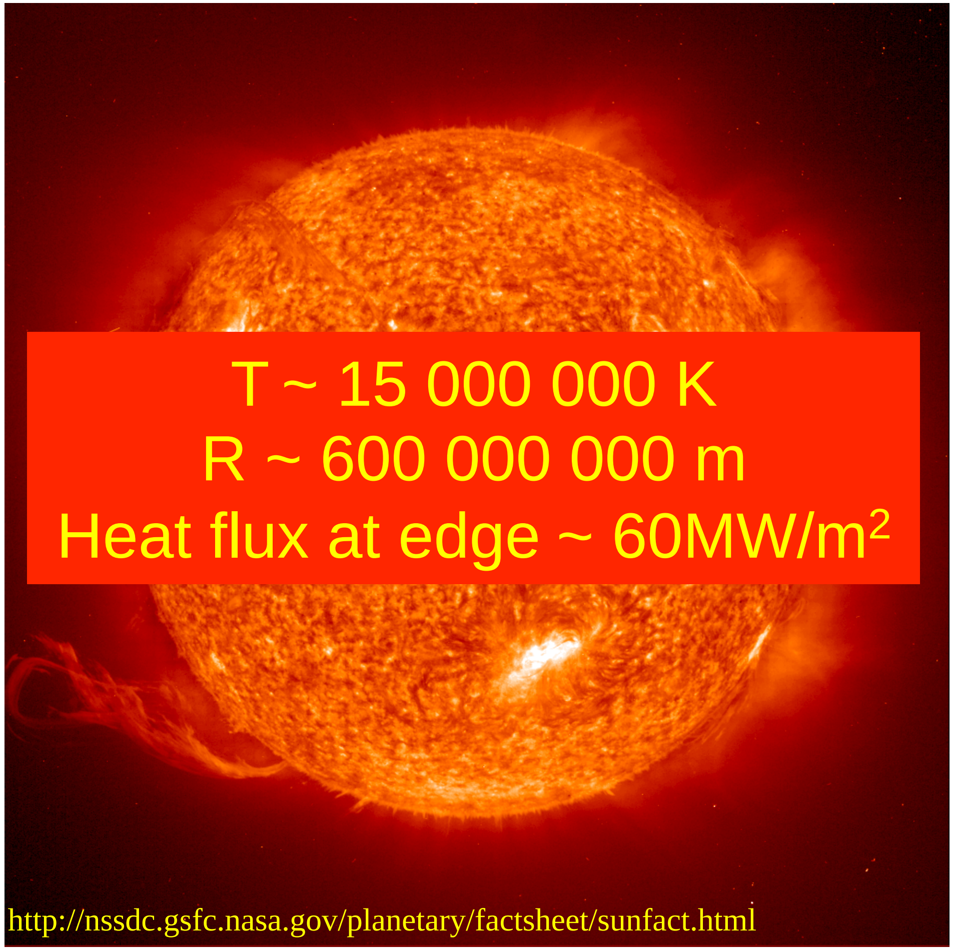
USA : National Ignition Facility (NIF)
Livermore, California
Experiments ongoing

in operation from March 2009

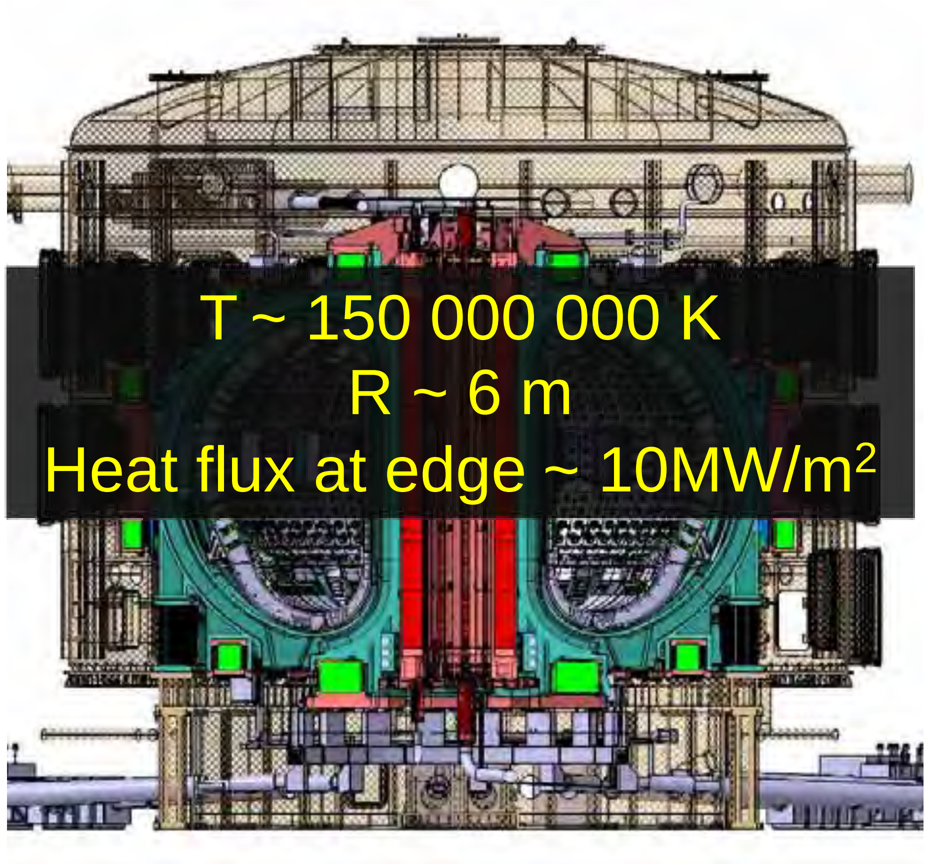
~ One experiment / week

Realizing Fusion:
B. Magnetic Fusion – a real challenge

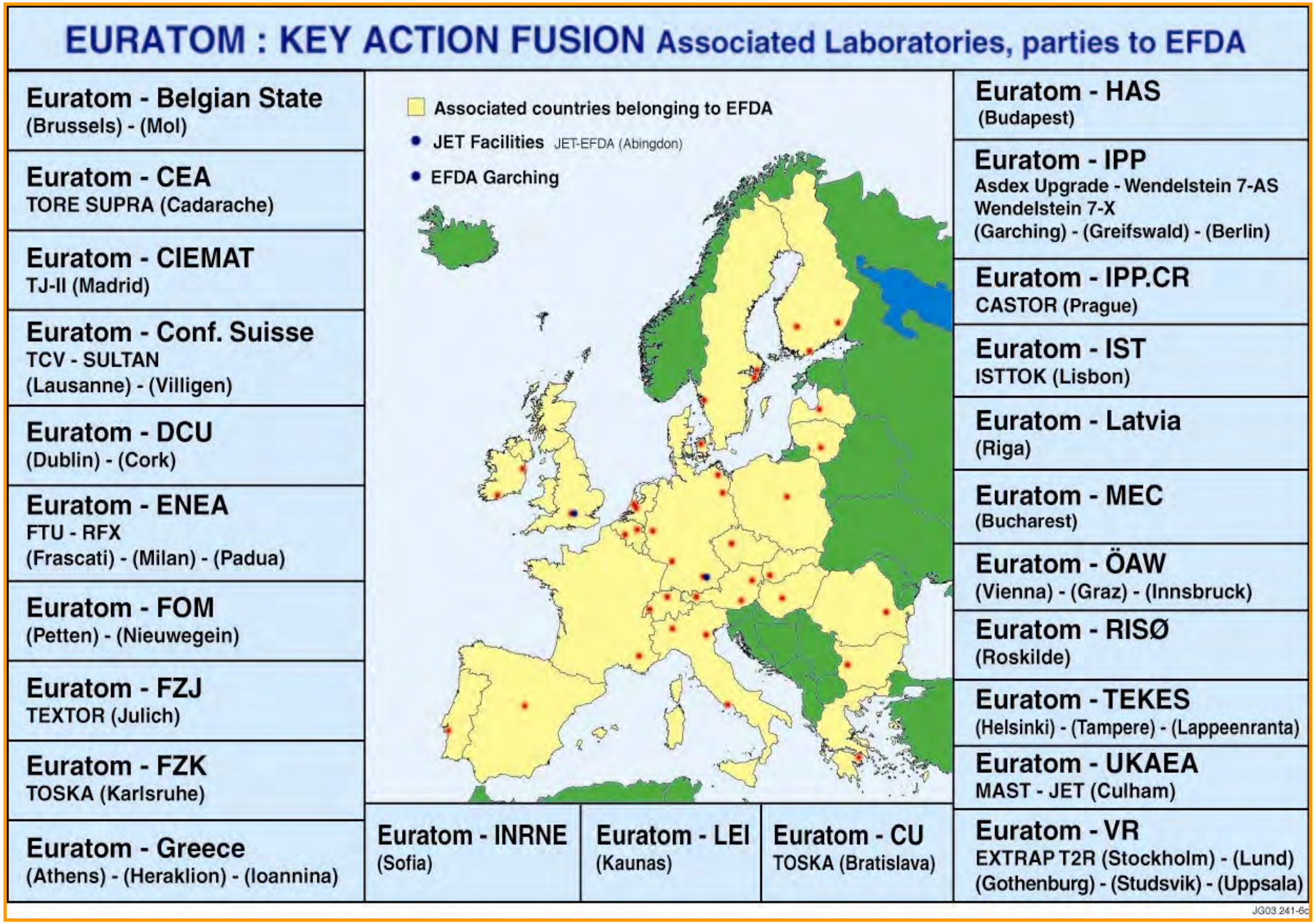
Sun



ITER (France, in construction)

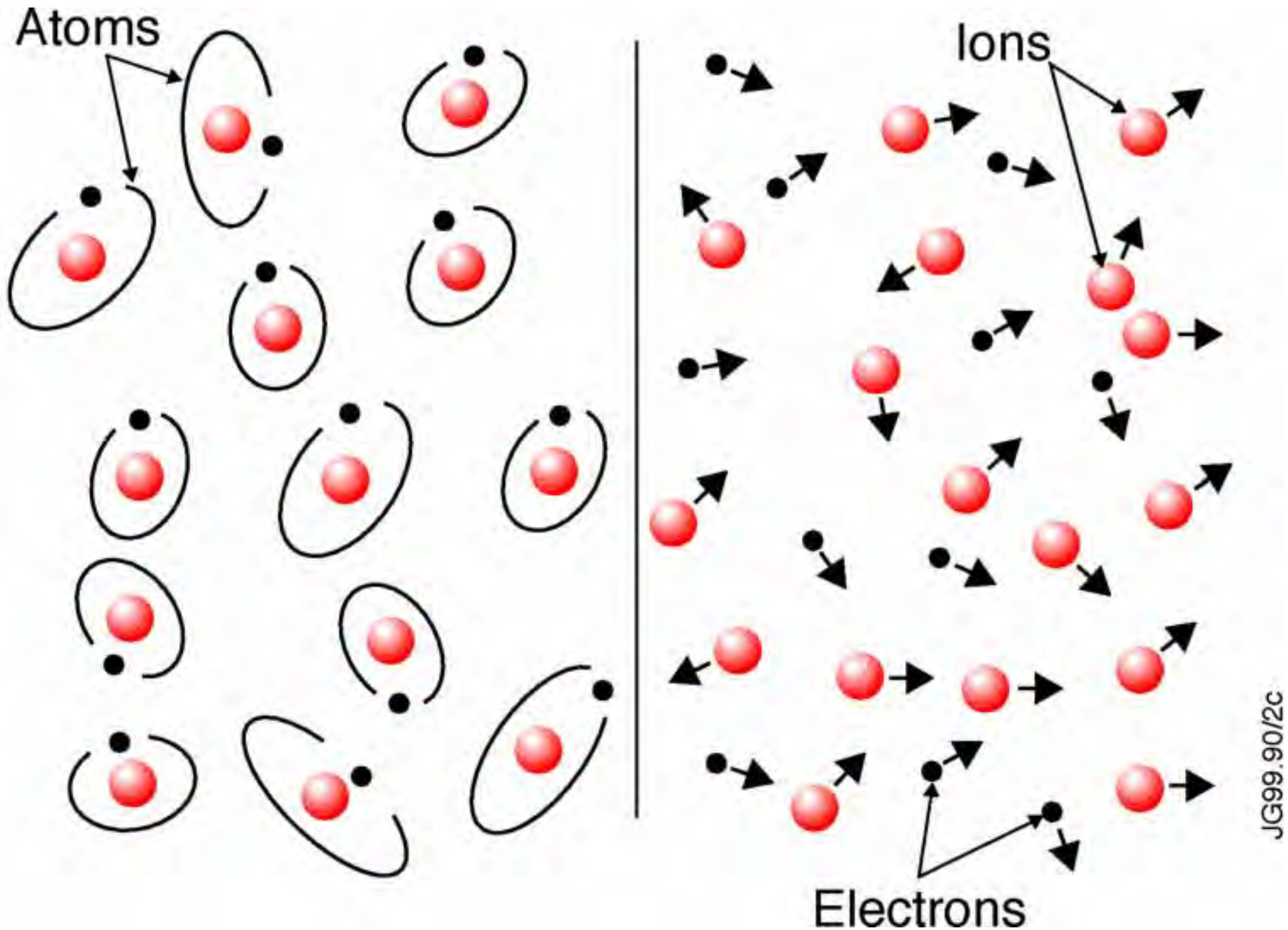


Fusion research in Europe



Principle of magnetic fusion

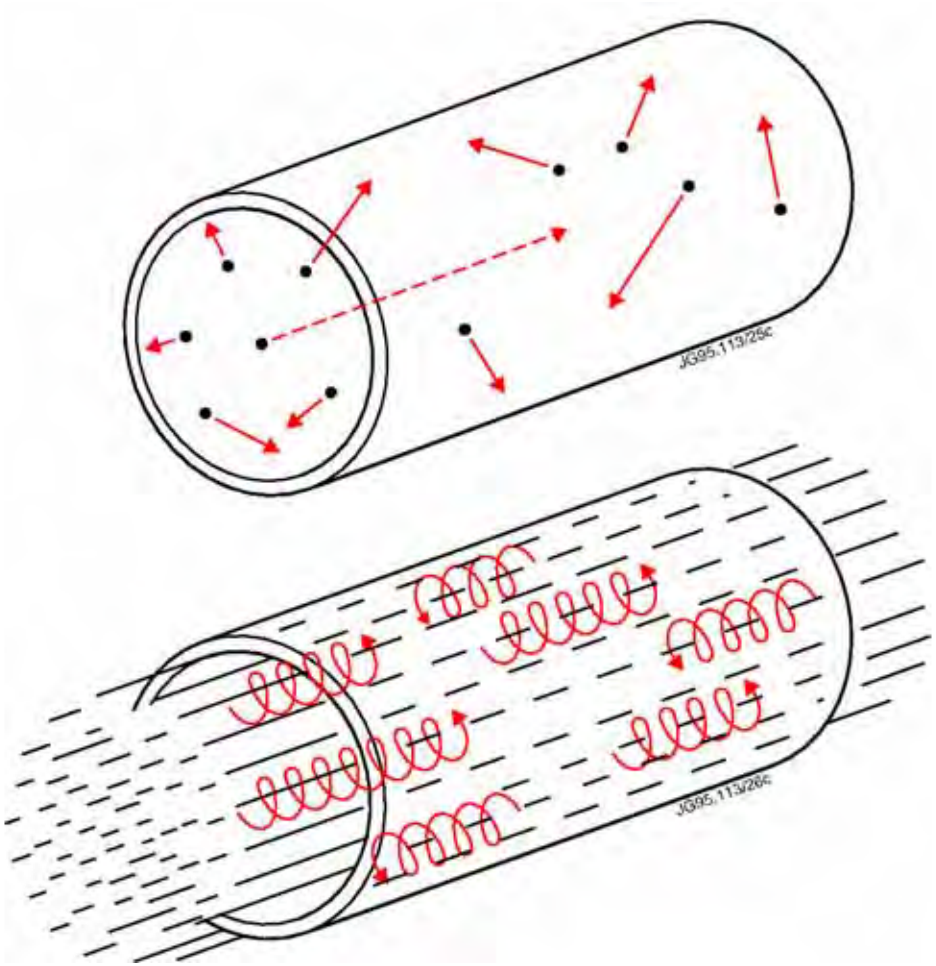
Neutral gas / Plasma



Low temperature / High temperature

Principle of magnetic fusion

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



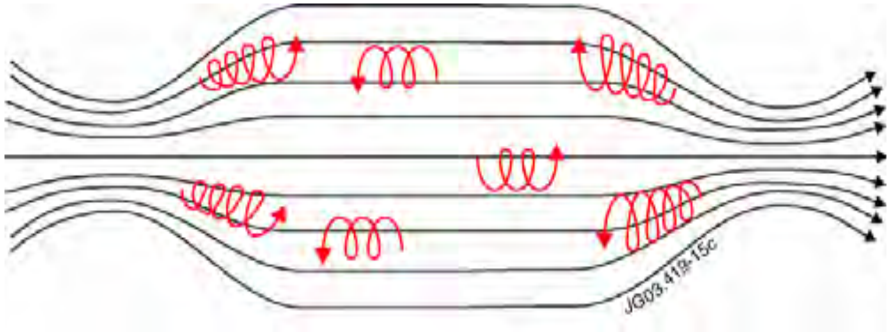
No magnetic field

With magnetic field

Principle of magnetic fusion

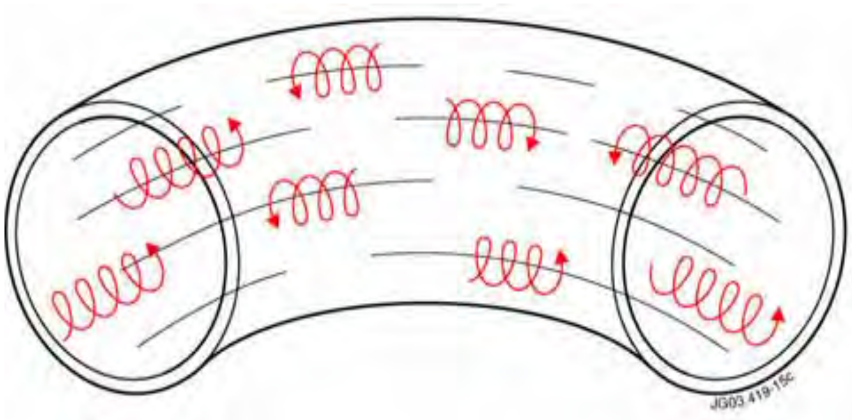
Particles follow magnetic fields
how to limit losses at the end of cylinder?

Two possible solutions



- ‘close' magnetic field at ends

  BUT : too high losses at ends



- 'close' magnetic fields on themselves

  ⇒ toroidal configuration, BUT…..

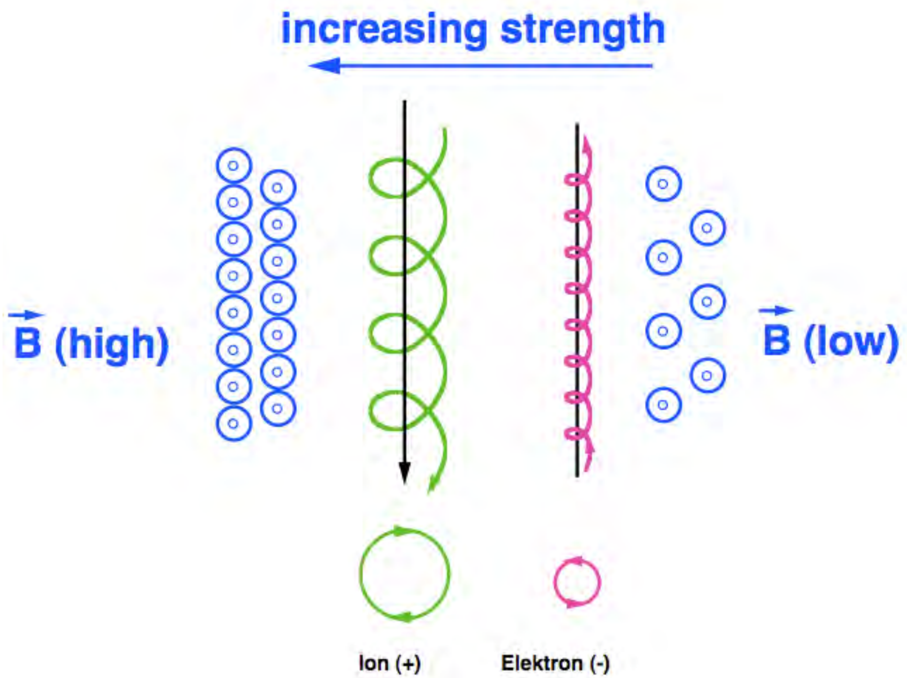
Pure Toroidal field does not work : Charge Separation !

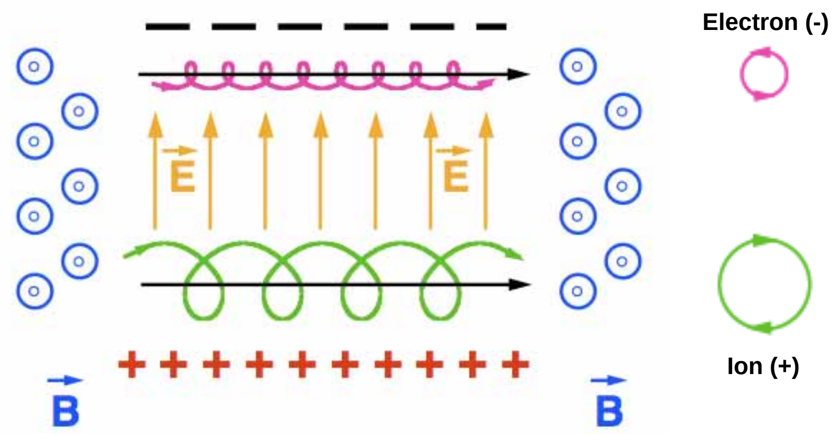
Fundamental Reason:
Gyroradius varies with magnetic field and particle speed

$$\rho_L = \frac{mv_\perp}{qB}$$

Pure toroidal magnetic field
Charges Separate → Electric Field

Magnetic field + Electric Field
ALL particles move outward !

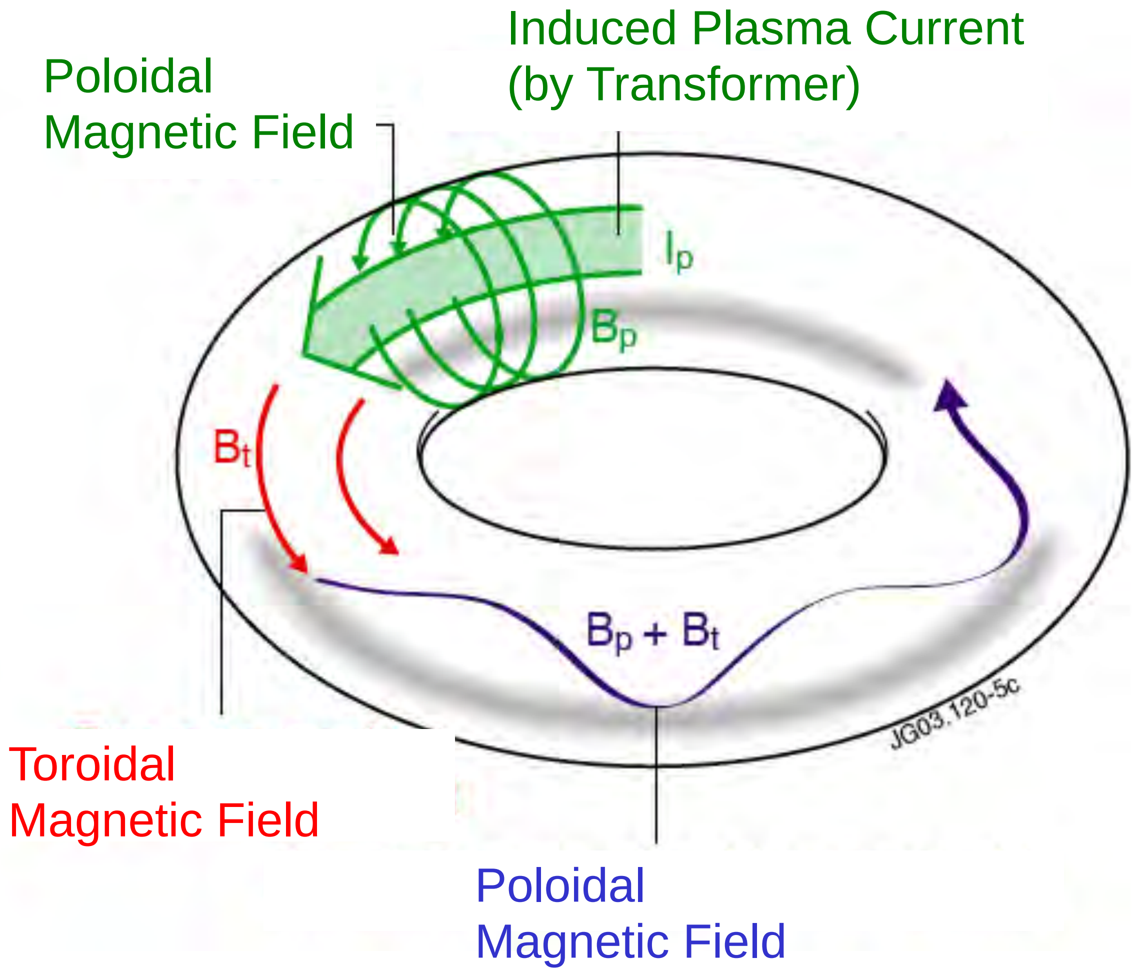




Realizing a helicoidal magnetic field : Option 1

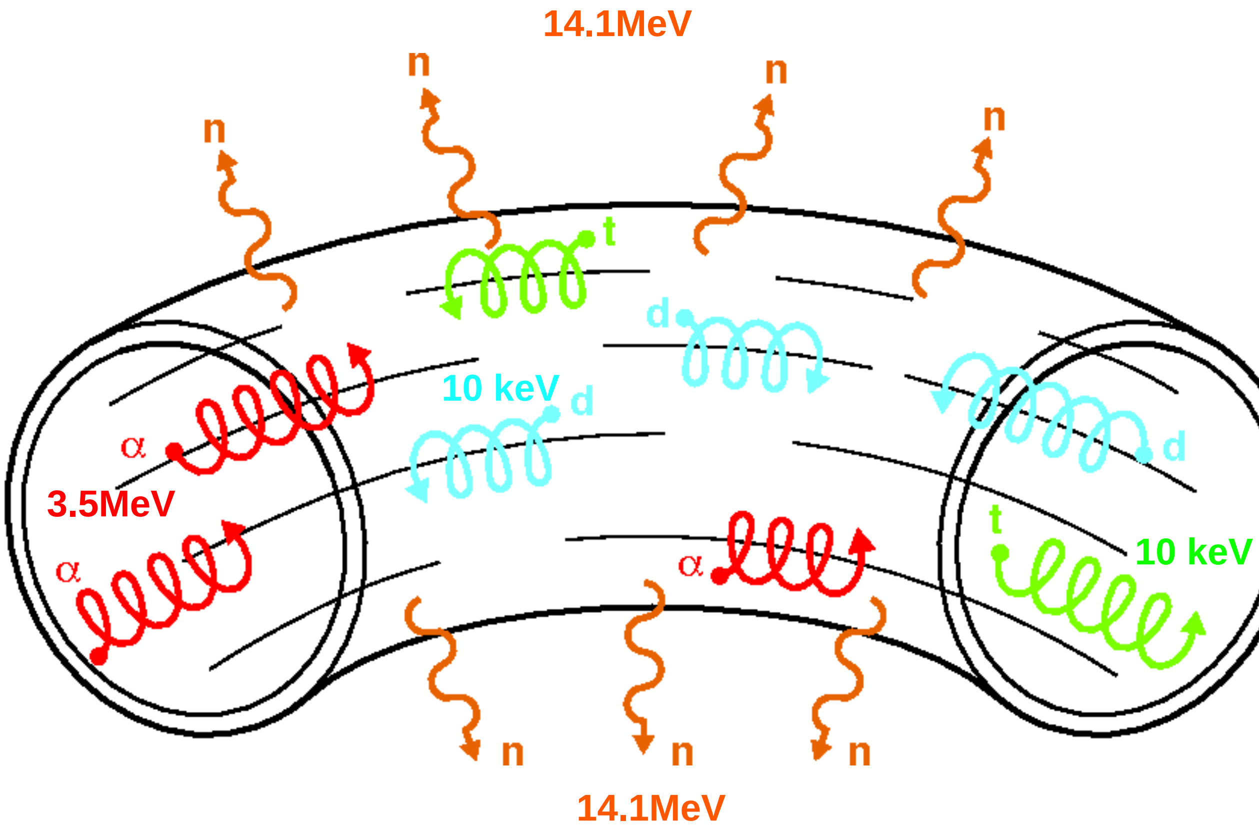
Tokamak

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

Tokamak – Summary

- **Tokamak**, from the Russian words:

  toroidalnaya **ka**mera, s **ma**gnitnami **k**atushkami

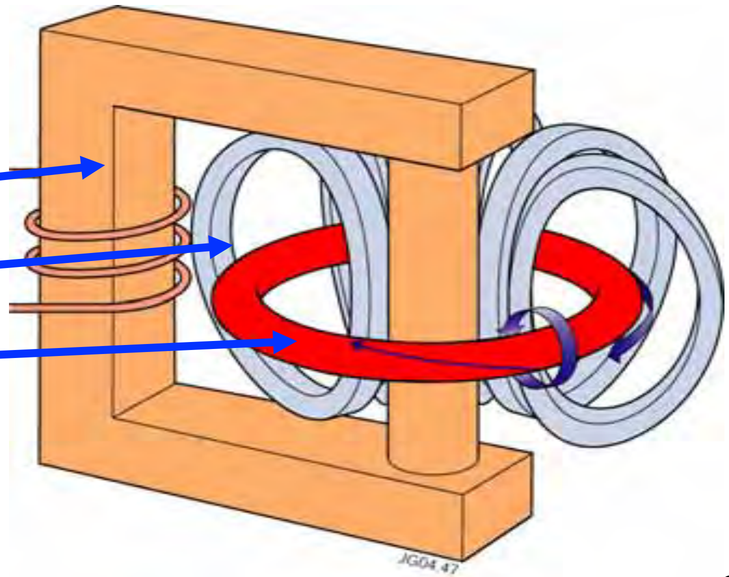
  meaning "**toroidal chamber**" with "**magnetic coils**"

- Invented by : Andrei Sacharov and Igor Tamm

  (both Noble Prize Winners)

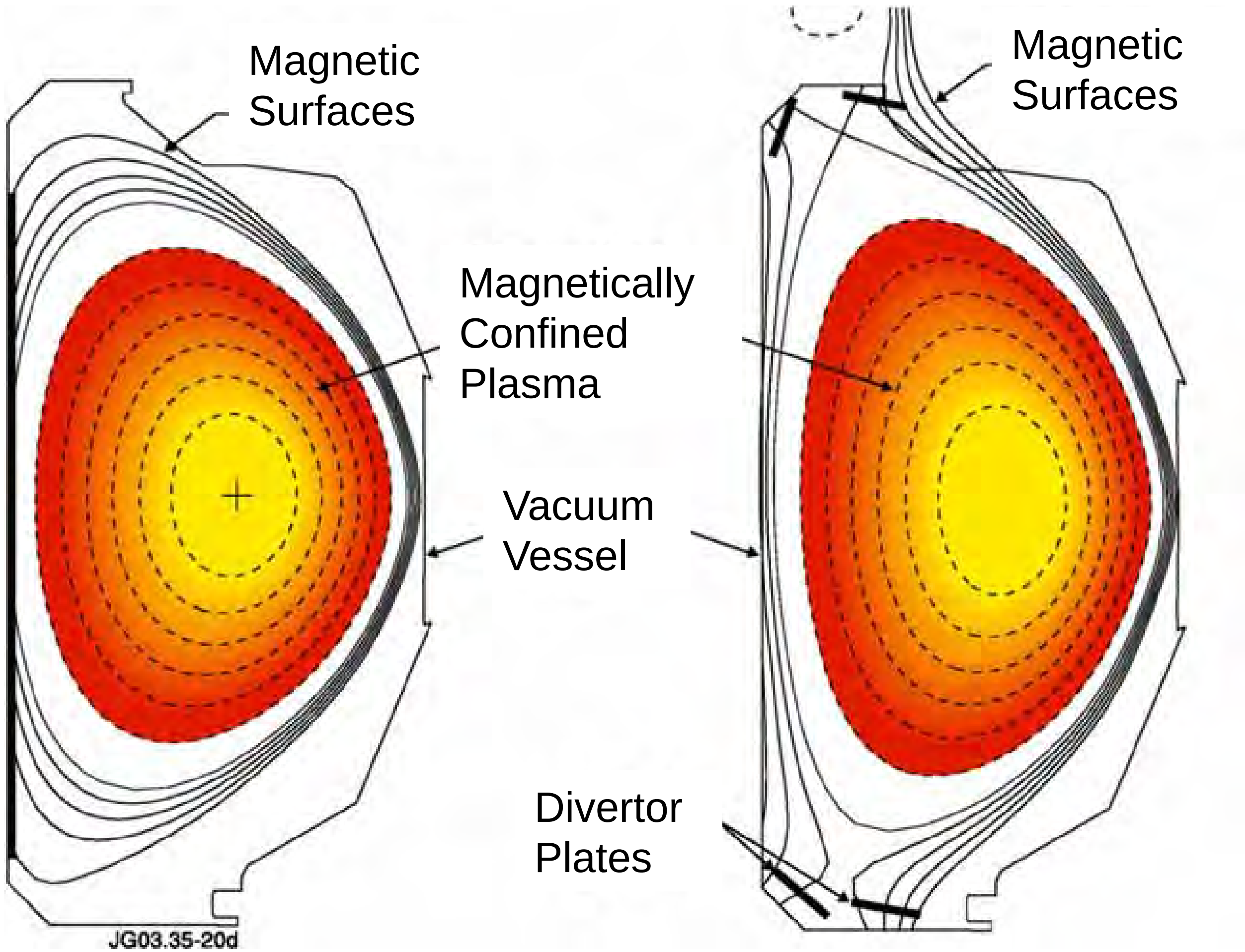
  at the Kurchatov Institute in Moscow in 1950

- Essentially a tokamak consists of :
  — large transformer
  — coils for magnetic fields
  — plasma ring with large plasma current



Two tokamak configurations in use

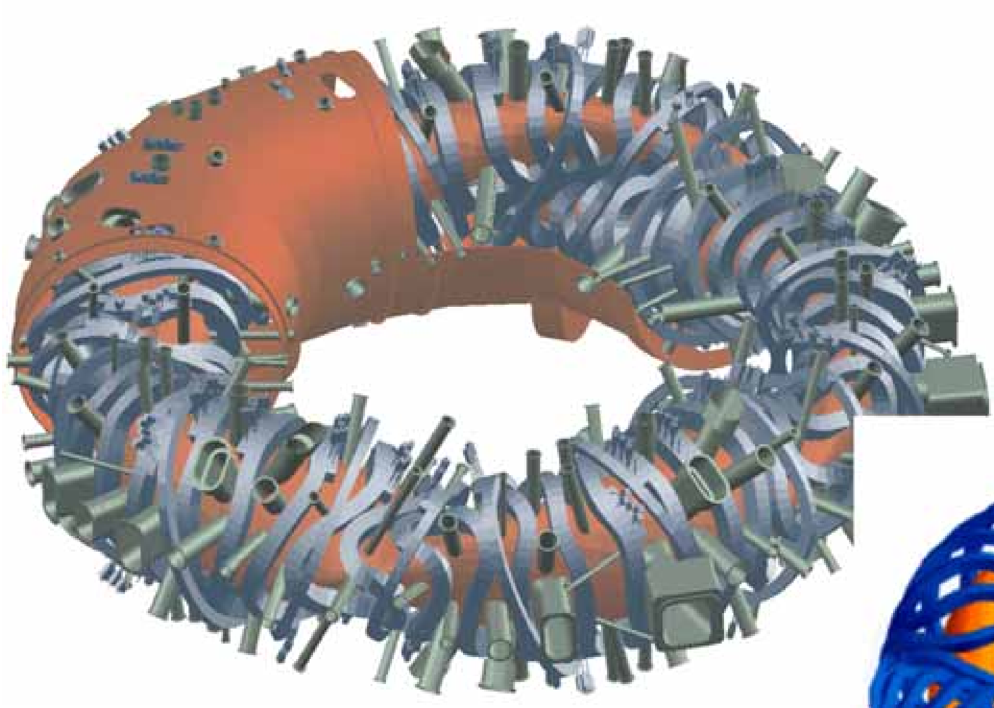
Limiter Configuration | Divertor Configuration

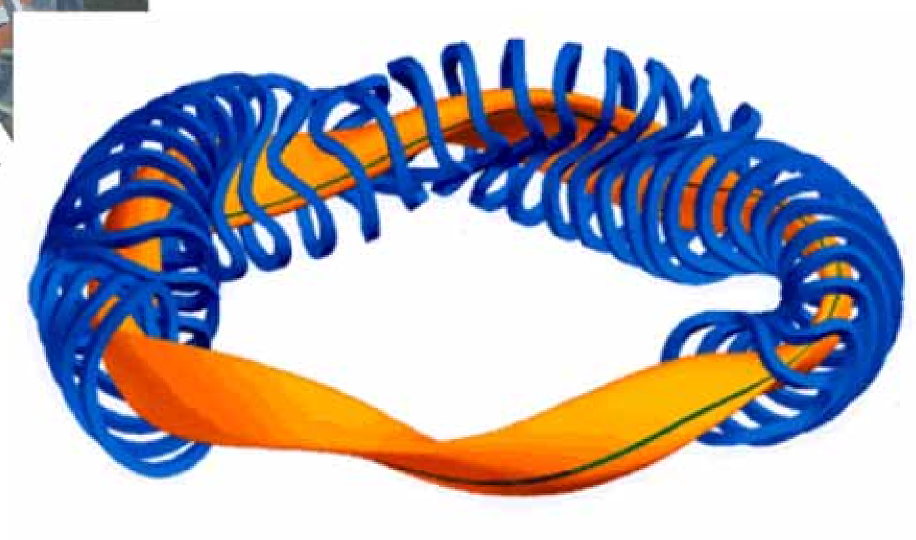


Realizing a helicoidal magnetic field : Option 2

Stellarator

Complex 3D coils create directly a helical field





No plasma current

$\Rightarrow$ no transformer

$\Rightarrow$ 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

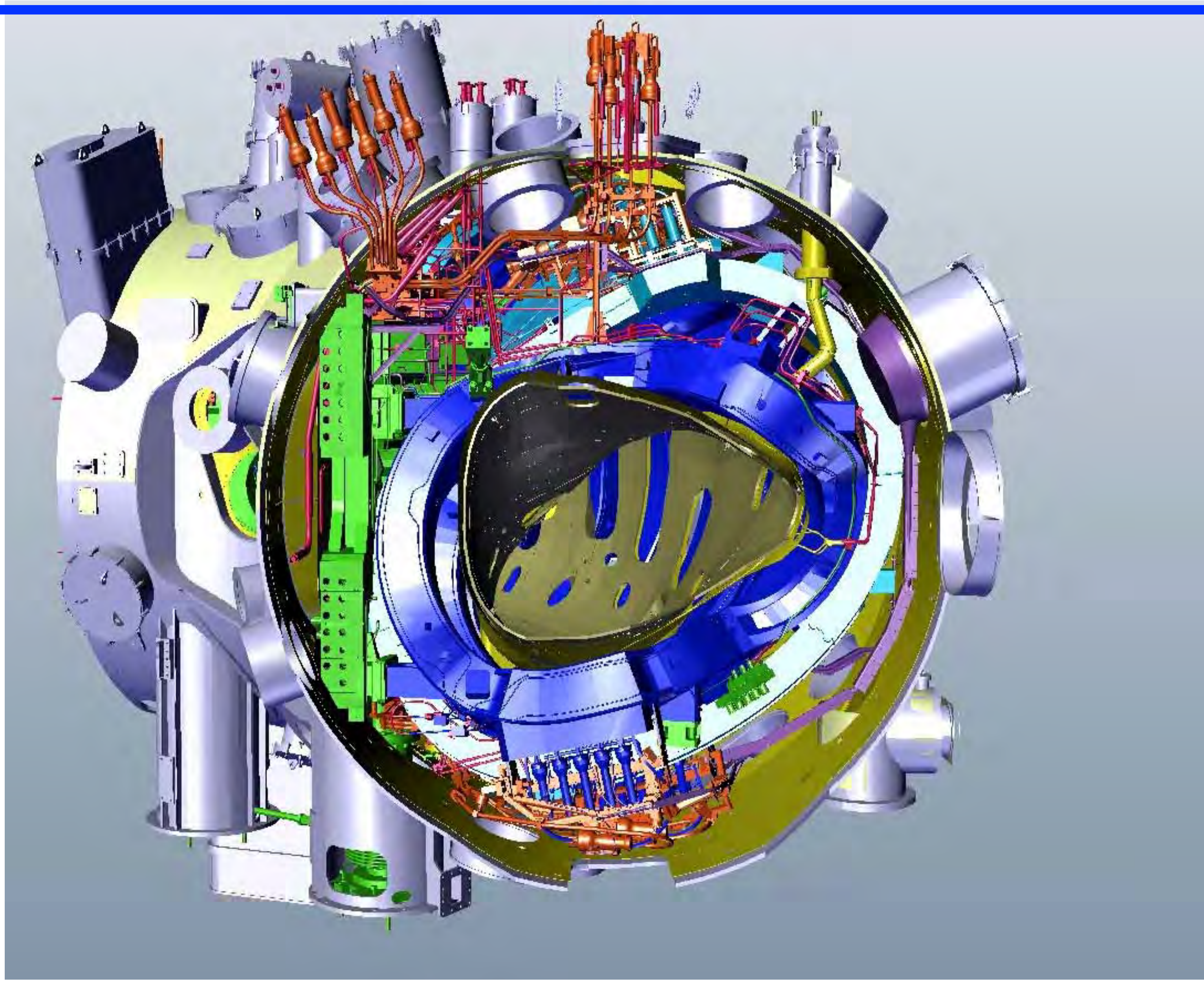
- physics experiment: *H, D plasmas only, additional planar coils*
- heating systems 10*MW ECRH, 20 MW NBI, ICRH*
- mimic α-particle heating: ICRH, *NBI*
- low impurity content, heat removal *divertor*

Technological goals

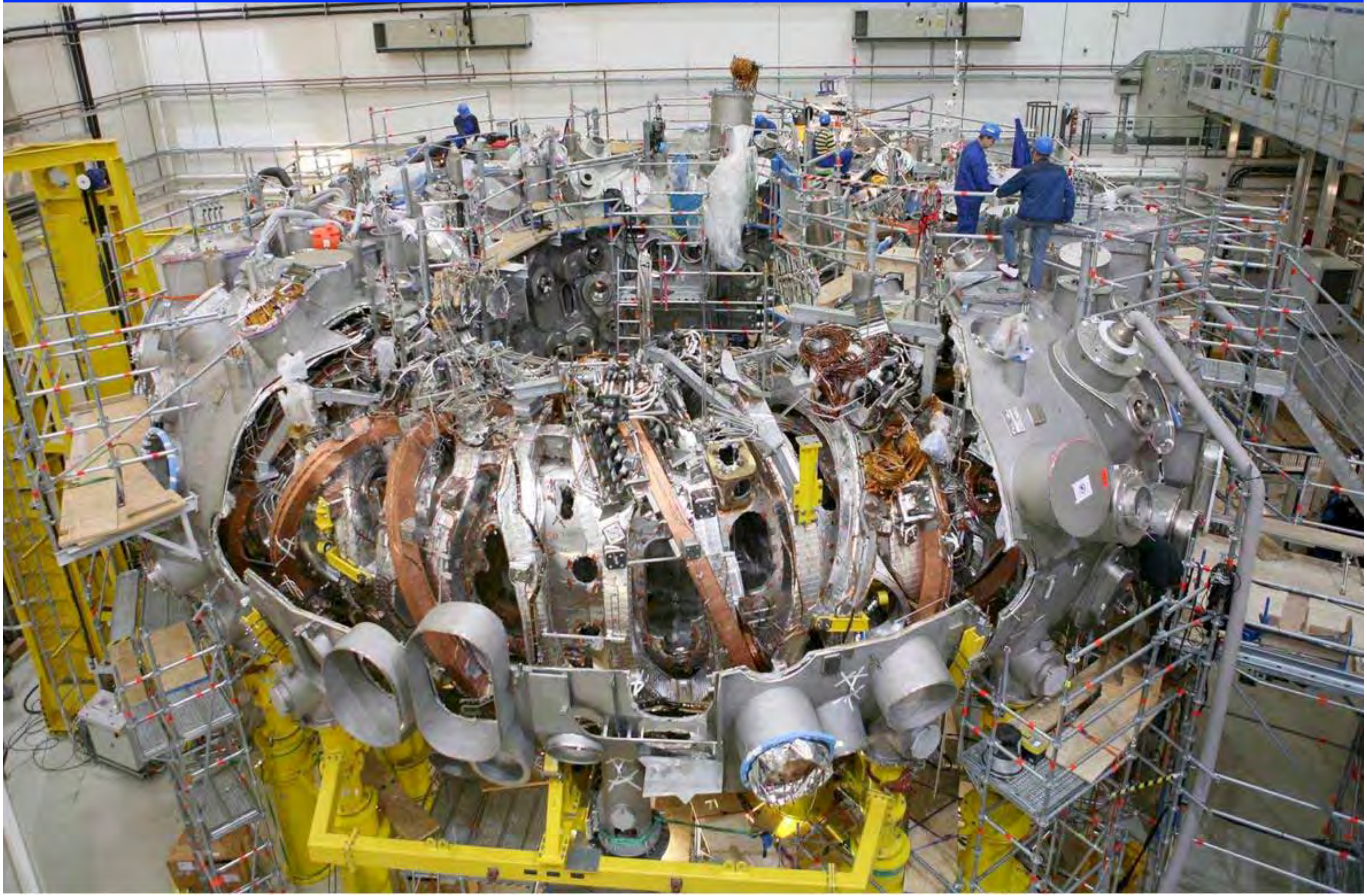
Reactor feasability of stellarators

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

Wendelstein 7-X : Largest Stellarator in the world



Wendelstein 7-X : November 2011



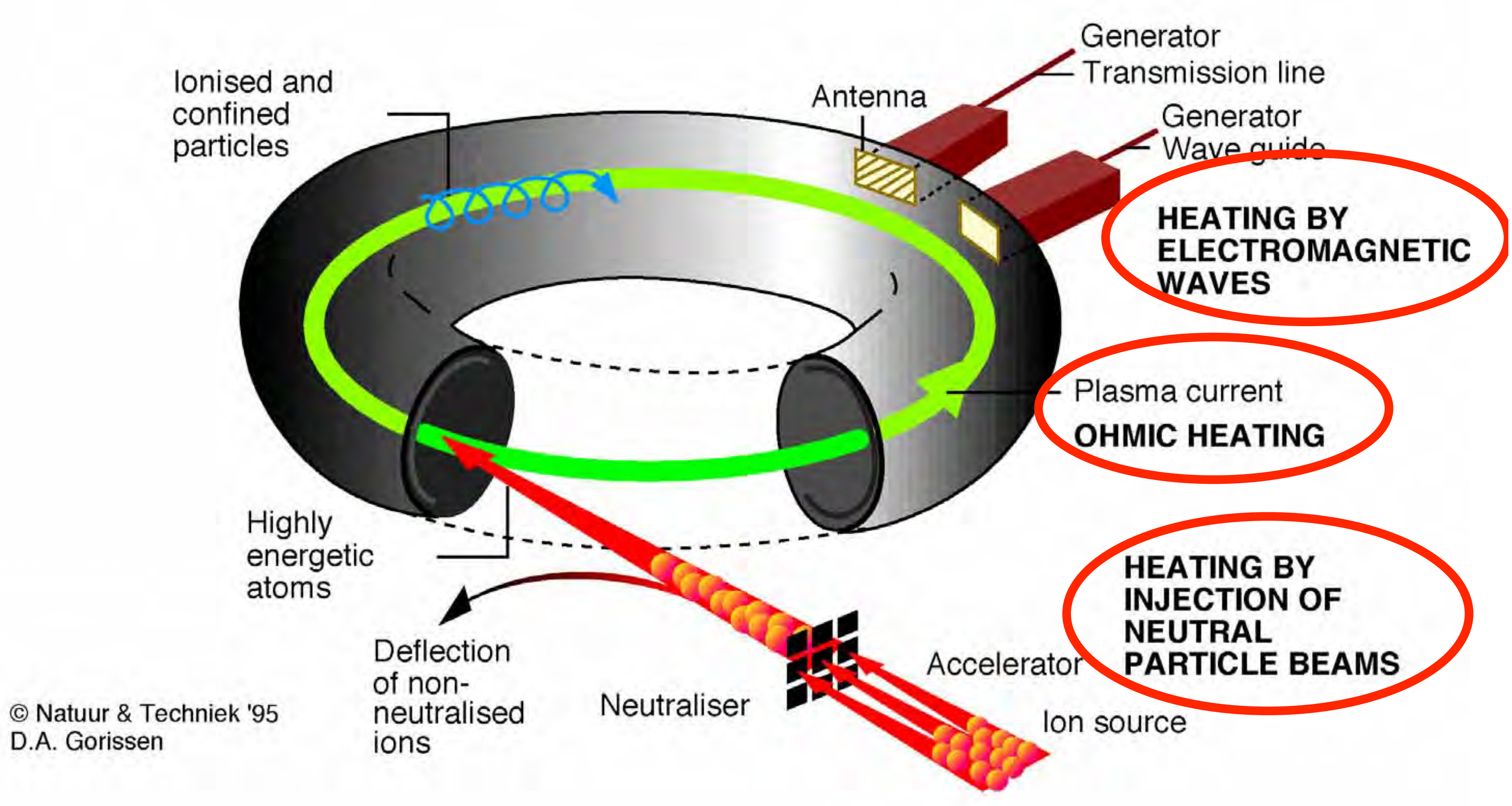
Wendelstein 7-X : January 2013

Stellarator W7-X: Completion of assembly 2014

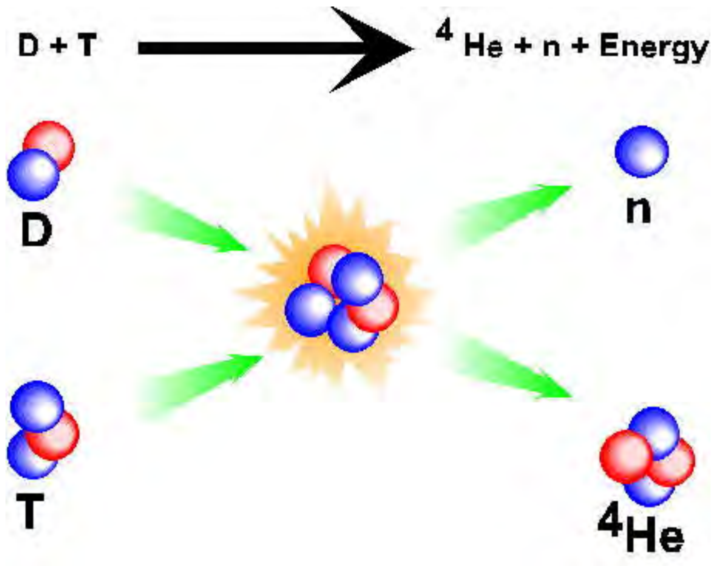
Start of Commissioning of W7-X: 20 May (~ 2 months ago)

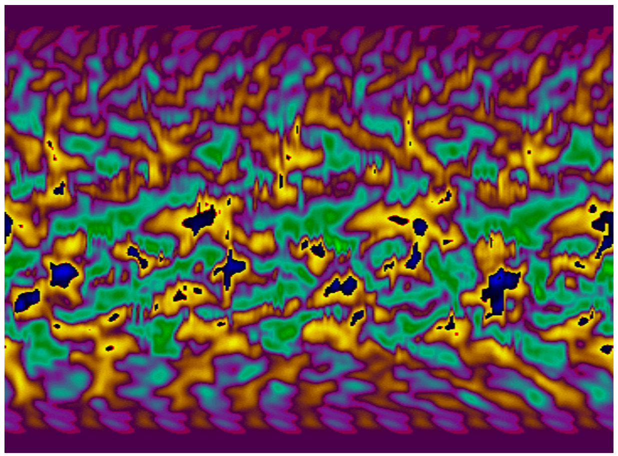
How to create the ultra high temperatures needed ?

In a future fusion reactor: α-particle heating



The main difficulty of magnetic fusion: keep a huge T gradient





• Two positive nuclei (D^+ and T^+) at short distance

— strong repulsion

EXTREMELY HIGH temperatures needed to bring the nuclei close enough together : ~200 000 000 K

• Special methods needed to heat and confine the fuel

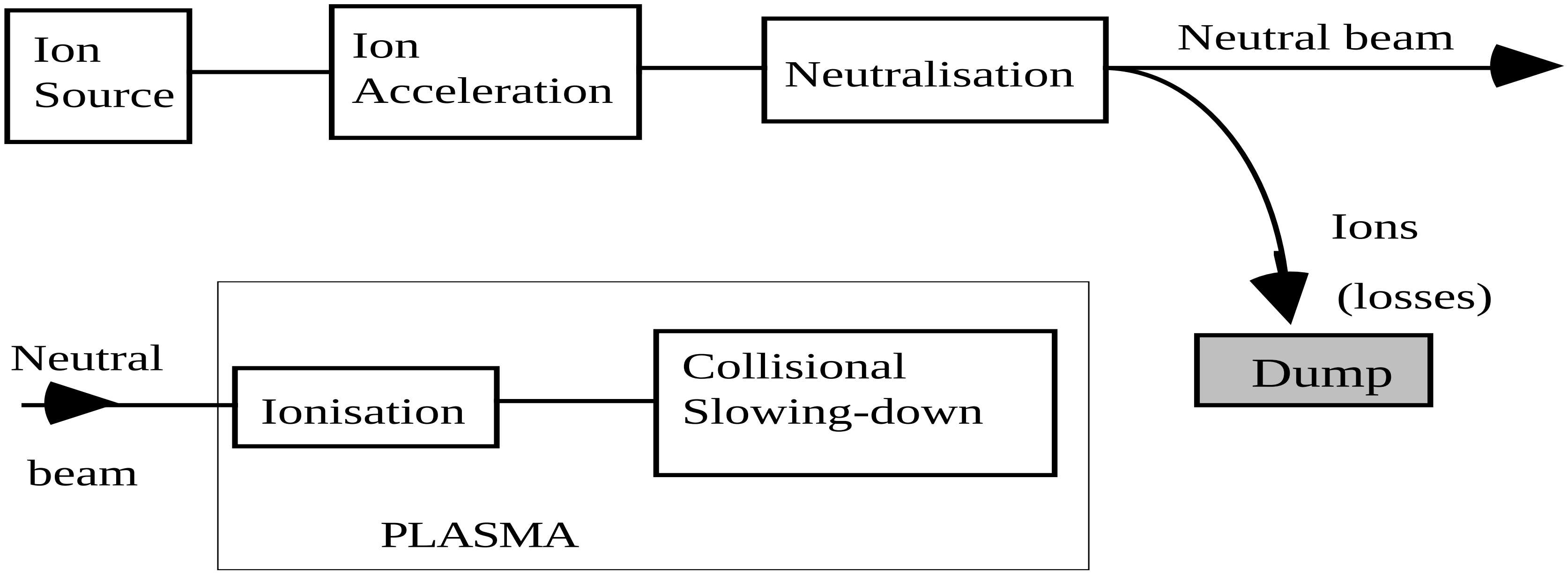
• Very large gradient in temperature (~ 200 000 000K/m)

— gradients limited by turbulence

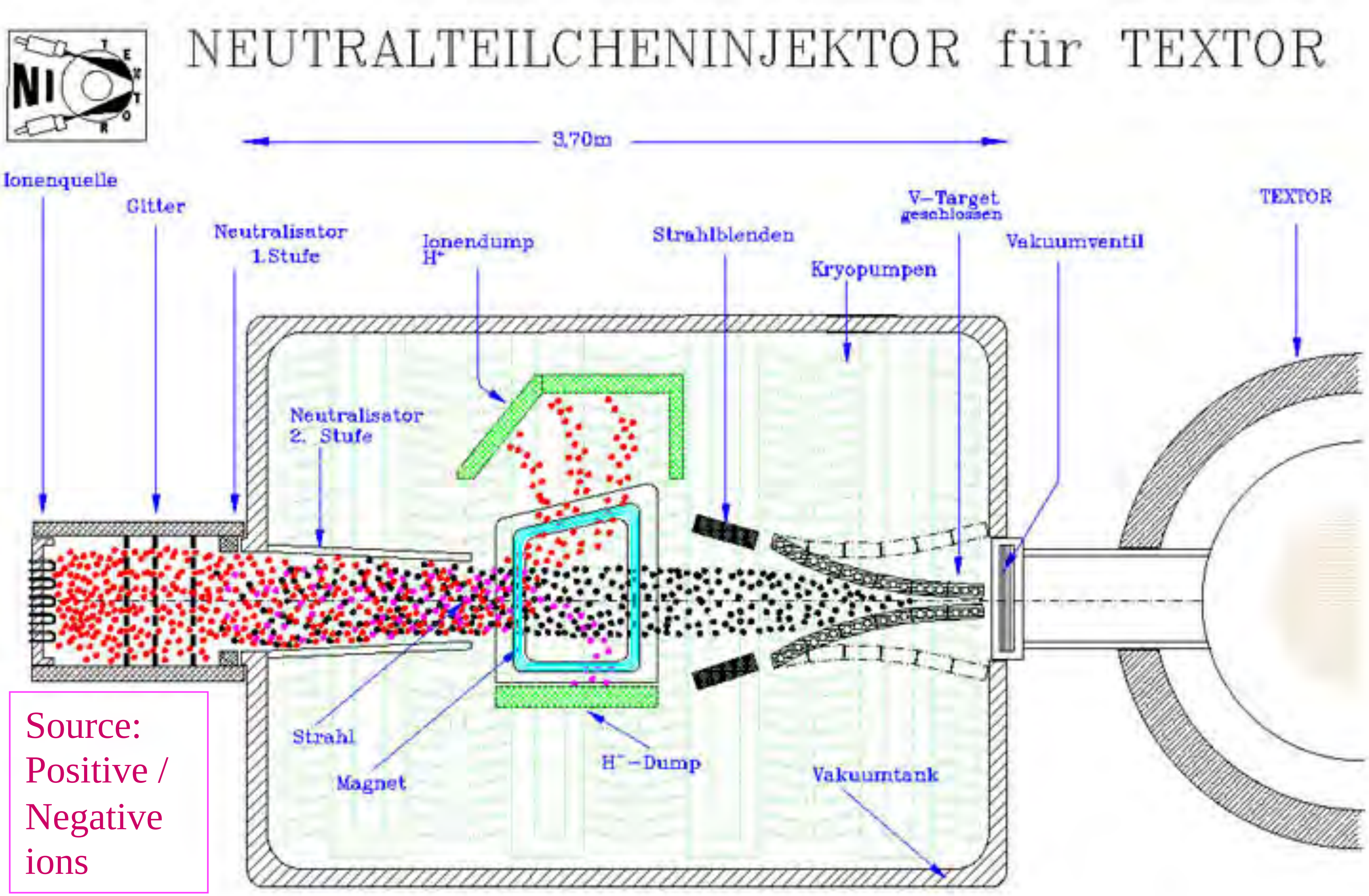
⇒ TURBULENT medium : very complex physics

Neutral beam injection

- Principle:

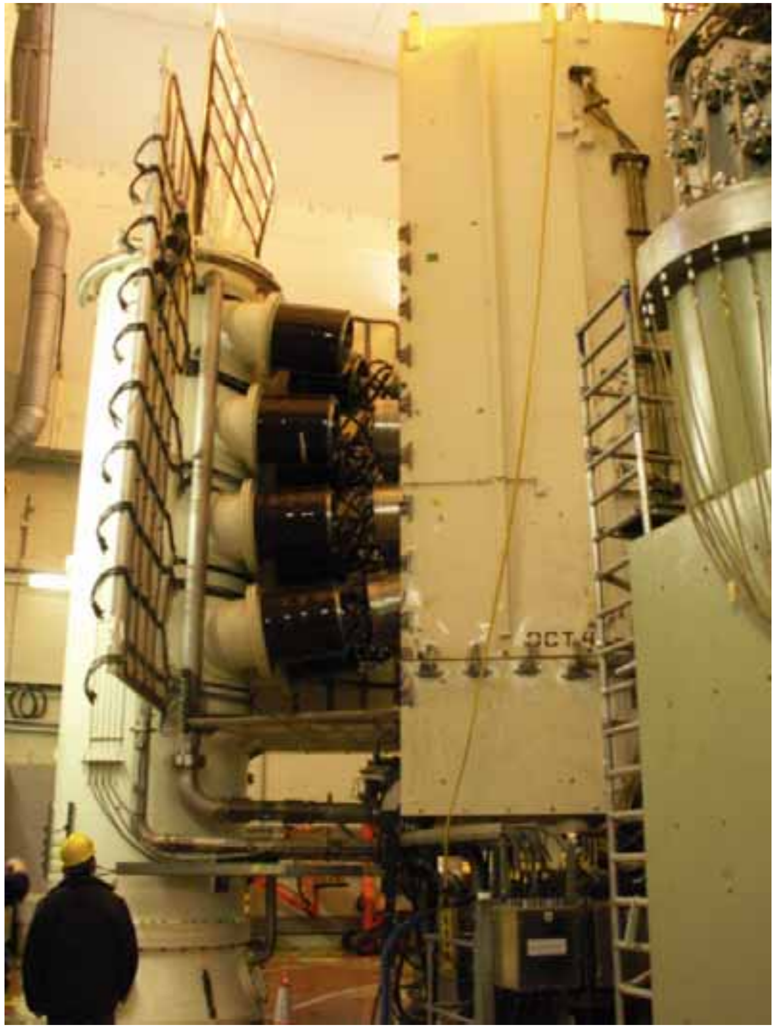


Neutral beam injection in practice



Source:
Positive /
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

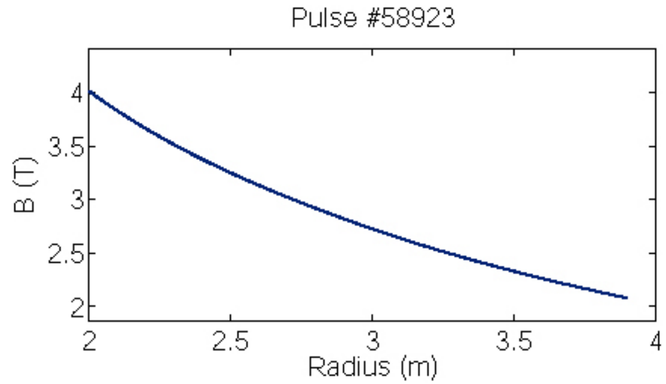
How do radiowaves heat plasmas ?

Particles turn around magnetic field line @ ion cyclotron frequency :

$$\omega_{ci} = 2\pi f_{ci} = \frac{q}{m} B \propto \frac{Z}{A} B$$

Z=ion charge, A=ion mass

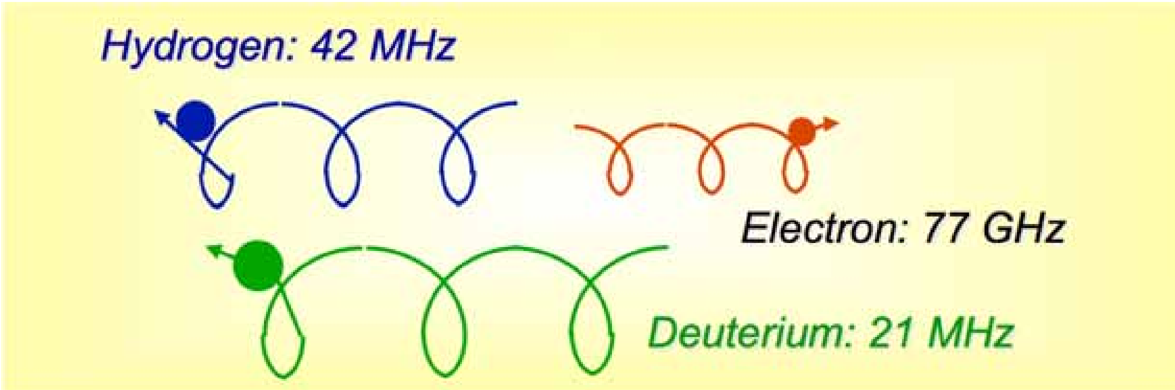
f_{ci} different for D ions, H ions, electrons



B magnetic field = function of radius

f_{ci} depends on the position in the plasma

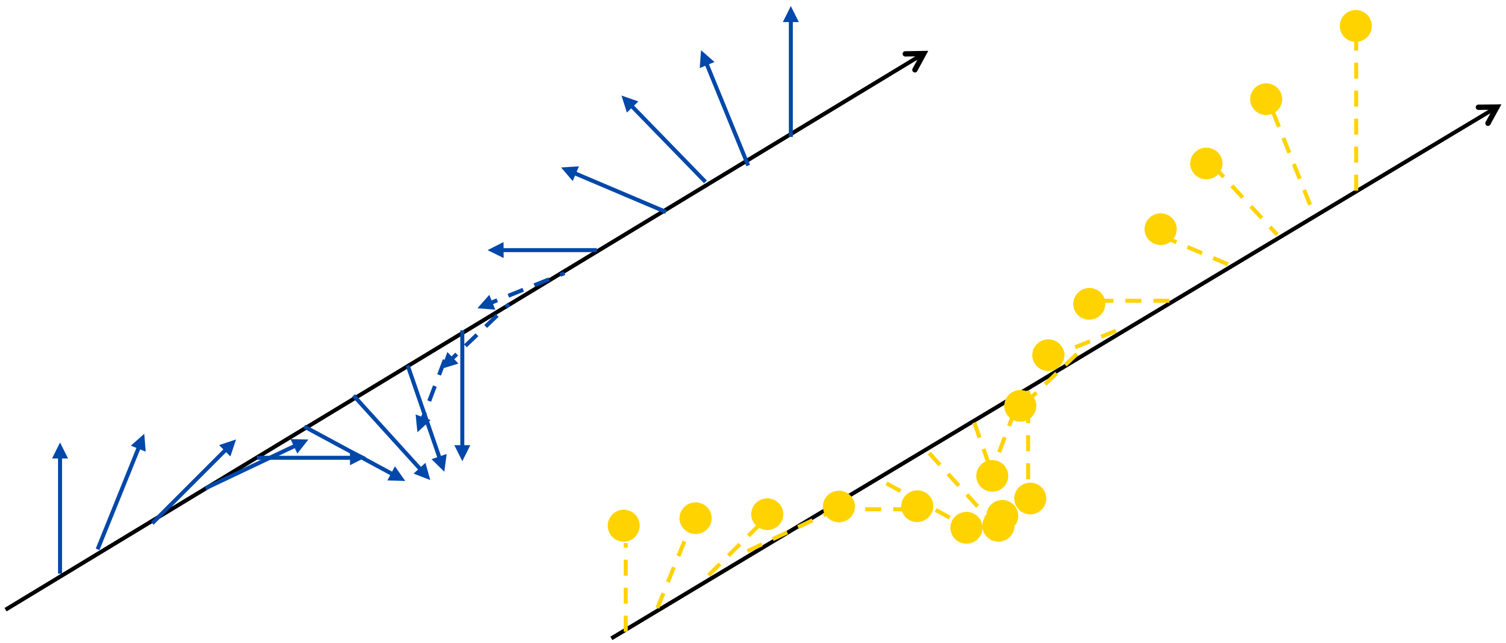
Example in plasma centre at R ~ 3m and for B ~ 2.7 Tesla in JET



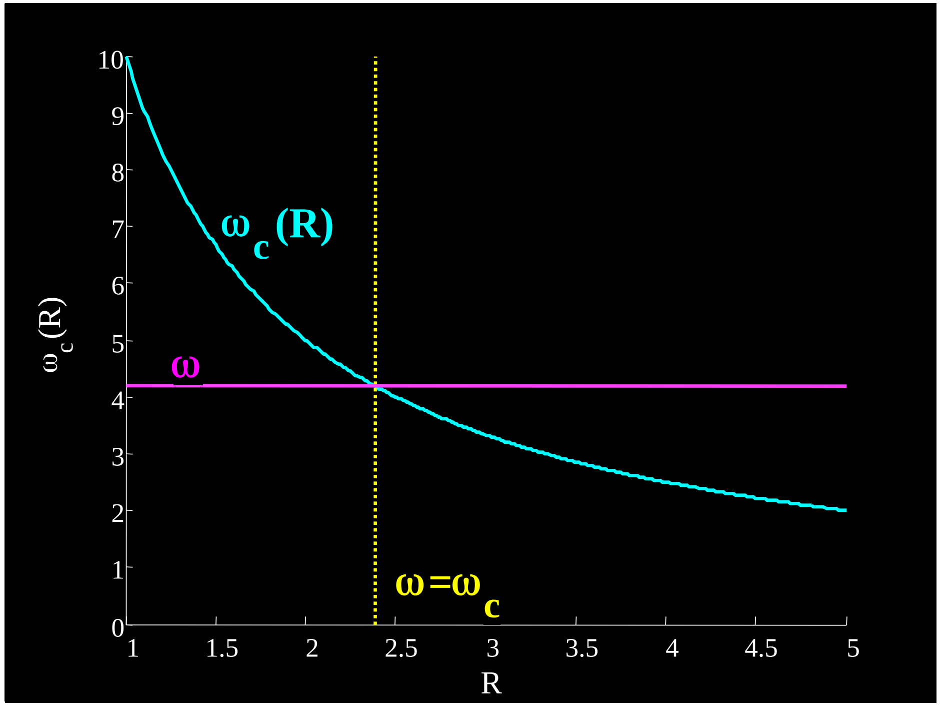
How do radiowaves heat plasmas ?

If RF Wave frequency f_{ICRF} = ion cyclotron frequency f_{IC}

- ✓ These ions see a constant electric field
- ✓ These ions absorb the energy RF wave ➔ they become very energetic
  - ➡ *Energy gained transferred by collisions to background electrons and ions ➔ general plasma heating*
- ✓ These ions are said to be "resonant" with the wave

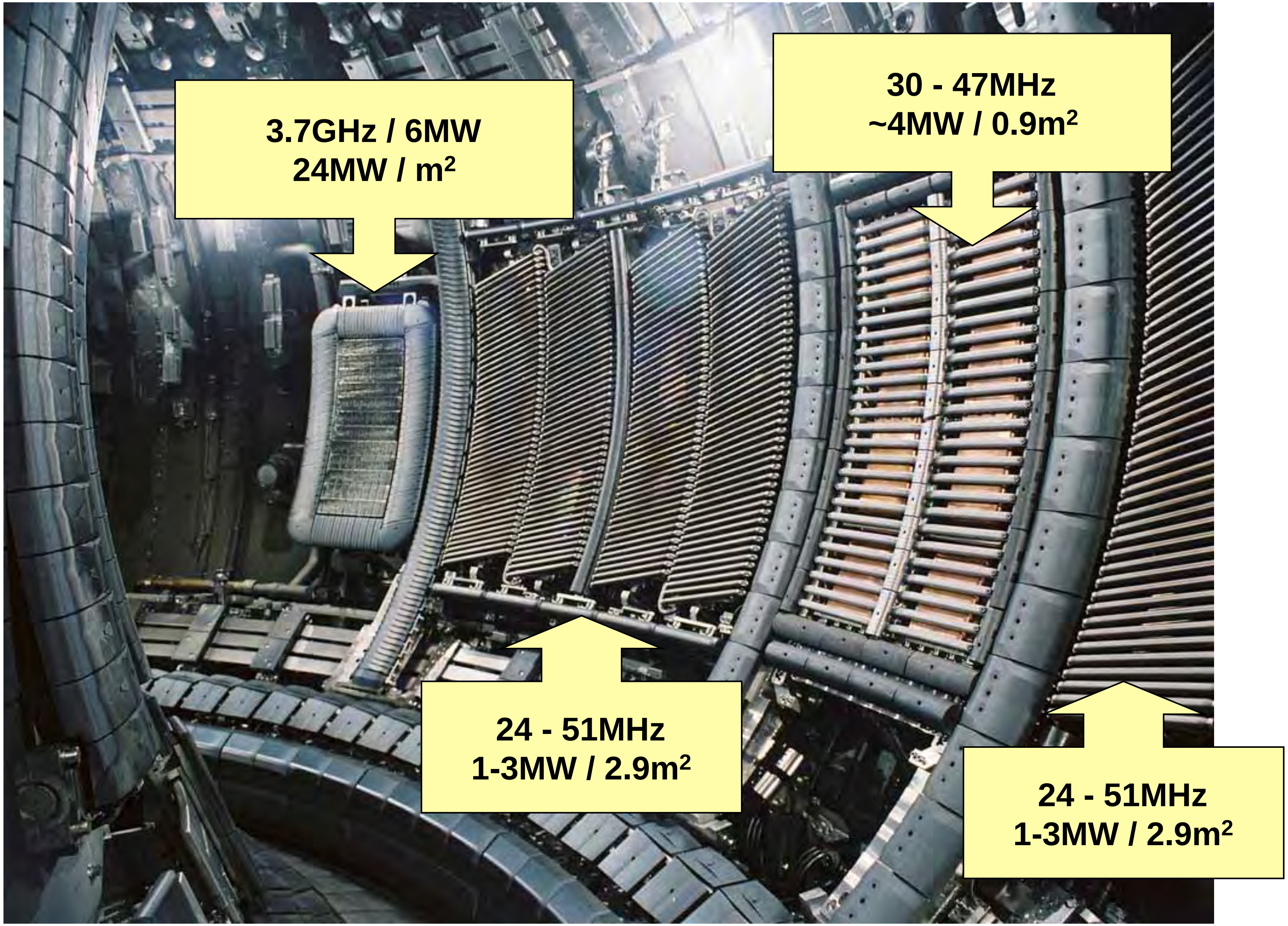


How do radiowaves heat plasmas ?



$$\omega_c=(q/m)B$$

Example of RF heating systems (in JET)



Power Amplification Factor Q, Break-even, Ignition

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

Breakeven Q=1

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

Ignition Q = ∞

when $P_{external\ heating} = 0$: no external heating needed
Selfsustained fusion reaction

Note:

Q relates to 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

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

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

P_{heat} Q = P_{fusion} = 5 P_{α}

$$P_{\alpha}\left(\frac{Q+5}{Q}\right) \geq \frac{W_p}{\tau_E} + C_B T_e^{1/2} n_e^2$$

Plasma neutrality : $n_i = n_e$ ➔ $W_p = 3\ n_e k T_e$

50%-50% D-T reaction : $n_T = n_D = ½\ n_e$

$$\frac{1}{4} n_e^2 E_a < \sigma v > \left(\frac{Q+5}{Q}\right) \geq \frac{3 n_e k T_e}{\tau_E} + C_B T_e^{1/2} n_e^2$$

Lawson Criterium for Breakeven (Q=1)

$$n_e \tau_E = \frac{3kT_e}{\frac{<\sigma v> E_\alpha (Q+5)}{4Q} - C_B T_e^{1/2}}$$

Condition for Breakeven (Q=1) at 15 keV in D-T

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

Lawson Criterium for Ignition (Q=∞)

$$n_e \tau_E \geq \frac{3kT_e}{\frac{<\sigma v> E_\alpha}{4} - C_B T_e^{1/2}}$$

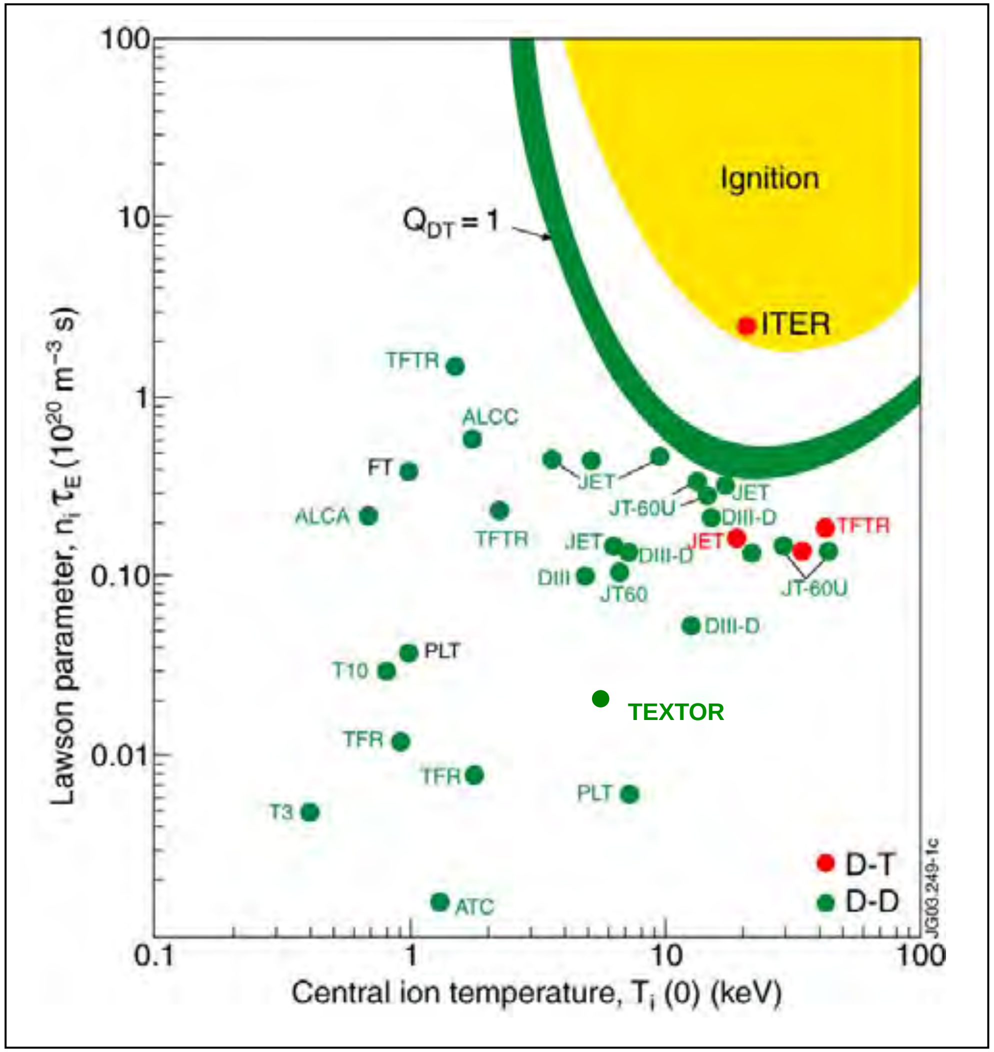
Condition for Ignition (Q=∞) at 15 keV in D-T

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

Present tokamak devices close to Break-Even

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 **(close to Ignition Q=∞)**



APPENDIX

Some parameters of our sun (for ref.)

Table 3.1 Physical parameters of the Sun[a]

Mass	1.989×10^{30} kg (332,946 Earth masses)
Radius	6.955×10^{8} m (109 Earth radii)
Volume	$1.412 \times 10^{27}\ m^3$ (1.3 million Earths)
Density (center)	$151,300\ kg\ m^{-3}$
Density (mean)	$1,409\ kg\ m^{-3}$
Pressure (center)	2.334×10^{11} bars
Pressure (photosphere)	0.0001 bar
Temperature (center)	15.6×10^{6} K
Temperature (photosphere)	5,780 K
Temperature (corona)	$2–3 \times 10^{6}$ K
Luminosity	$3.854 \times 10^{26}\ J\ s^{-1}$
Solar constant	$1,361\ J\ s^{-1}\ m^{-2} = 1,361\ W\ m^{-2}$
Mean distance	$1.4959787 \times 10^{11}\ m = 1.0$ AU
Age	4.55 billion years
Principal chemical constituents (by number of atoms)	
Hydrogen	92.1%
Helium	7.8%
All others	0.1%

[a]Mass density is given in kilograms per cubic meter, or $kg\ m^{-3}$; the density of water is $1,000\ kg\ m^{-3}$. The unit of pressure is bars, where 1.013 bars is the pressure of the Earth's atmosphere at sea level. The unit of luminosity is $J\ s^{-1}$, power is often expressed in watts, where $1.0\ W = 1.0\ J\ s^{-1}$

Ref. Kenneth R.Lang, "The sun from space" Springer Editions, ISBN 978-3-540-76952-1

Particles in a gas at temperature T

Velocity described by a Maxwell Boltzmann distribution

$$p(v) \propto v^2 \exp(-\frac{mv^2}{kT})$$

p(v) is the probability that the velocity is located in the interval [v, v+dv]

The kinetic energy E of a particle with the most probable speed is kT (k is the Boltzmann constant : 1.38 10^{-23} J/K

Conversion factor between eV and T

E = 1eV = 1.602 10^{-19} J

→ T = 1.602 10^{-19} / 1.38 10^{-23} ~ 11600 K

Fusion reactions and energy release

	Energy released (MeV)
Main controlled fusion fuels	
$D + T \rightarrow \alpha + n$	17.59
$D + D \rightarrow T + p$	4.04
$D + D \rightarrow {}^3He + n$	3.27
$D + D \rightarrow \alpha + \gamma$	23.85
$T + T \rightarrow \alpha + 2n$	11.33
Advanced fusion fuels	
$D + {}^3He \rightarrow \alpha + p$	18.35
$p + {}^6Li \rightarrow \alpha + {}^3He$	4.02
$p + {}^7Li \rightarrow 2\alpha$	17.35
$p + {}^{11}B \rightarrow 3\alpha$	8.68
The p–p cycle	
$p + p \rightarrow D + e^+ + \nu$	1.44
$D + p \rightarrow {}^3He + \gamma$	5.49
${}^3He + {}^3He \rightarrow \alpha + 2p$	12.86
CNO cycle	
$p + {}^{12}C \rightarrow {}^{13}N + \gamma$	1.94
$[{}^{13}N \rightarrow {}^{13}C + e^+ + \nu + \gamma]$	2.22
$p + {}^{13}C \rightarrow {}^{14}N + \gamma$	7.55
$p + {}^{14}N \rightarrow {}^{15}O + \gamma$	7.29
$[{}^{15}O \rightarrow {}^{15}N + e^+ + \nu + \gamma]$	2.76
$p + {}^{15}N \rightarrow {}^{12}C + \alpha$	4.97
Carbon burn	
${}^{12}C + {}^{12}C \rightarrow {}^{23}Na + p$	2.24
${}^{12}C + {}^{12}C \rightarrow {}^{20}Na + \alpha$	4.62
${}^{12}C + {}^{12}C \rightarrow {}^{24}Mg + \gamma$	13.93

Reactions involving H or isotopes

'Aneutronic' fusion reactions

Reactions in the stars:
p-p, CNO, Carbon burn,…

Reference:
S. Atzeni, J. Meyer-ter-Vehn (2004). "Nuclear fusion reactions". The Physics of Inertial Fusion. University of Oxford Press. ISBN 978-0-19-856264-1

Fusion Cross-Sections and Reactivities

Reaction	σ (10 keV) (barn)	σ (100 keV) (barn)	σ_{max} (barn)	ϵ_{max} (keV)
$D + T \rightarrow \alpha + n$	2.72×10^{-2}	3.43	5.0	64
$D + D \rightarrow T + p$	2.81×10^{-4}	3.3×10^{-2}	0.096	1250
$D + D \rightarrow {}^3He + n$	2.78×10^{-4}	3.7×10^{-2}	0.11	1750
$T + T \rightarrow \alpha + 2n$	7.90×10^{-4}	3.4×10^{-2}	0.16	1000
$D + {}^3He \rightarrow \alpha + p$	2.2×10^{-7}	0.1	0.9	250
$p + {}^6Li \rightarrow \alpha + {}^3He$	6×10^{-10}	7×10^{-3}	0.22	1500
$p + {}^{11}B \rightarrow 3\alpha$	(4.6×10^{-17})	3×10^{-4}	1.2	550
$p + p \rightarrow D + e^+ + \nu$	(3.6×10^{-26})	(4.4×10^{-25})		
$p + {}^{12}C \rightarrow {}^{13}N + \gamma$	(1.9×10^{-26})	2.0×10^{-10}	1.0×10^{-4}	400
${}^{12}C + {}^{12}C$ (all branches)		(5.0×10^{-103})		

Energy of fusion reaction products

A + B → C + D

Momentum Conservation : $m_A\vec{v}_A + m_B\vec{v}_B = m_C\vec{v}_C + m_D\vec{v}_D$

Energy ~ keV <<< Energy ~ MeV

To a very good approximation: $m_C\vec{v}_C + m_D\vec{v}_D = 0$ or $m_C\vec{v}_C = - m_D\vec{v}_D$

Thus also : $|m_C\vec{v}_C| = |m_D\vec{v}_D|$ and therefore $m^2_C v^2_C = m^2_D v^2_D$

Ratio of energies of products C and D: $$\frac{E_C}{E_D} = \frac{\frac{1}{2} m_C v_C^2}{\frac{1}{2} m_D v_D^2} = \frac{m_D}{m_C}$$

Conclusion : Lightest particle get largest share in energy

Examples :

D+T → ^4He + n: neutron gets 80% of the energy

D+D → t + p or ^3He + n: proton or neutron gets 75% of the energy