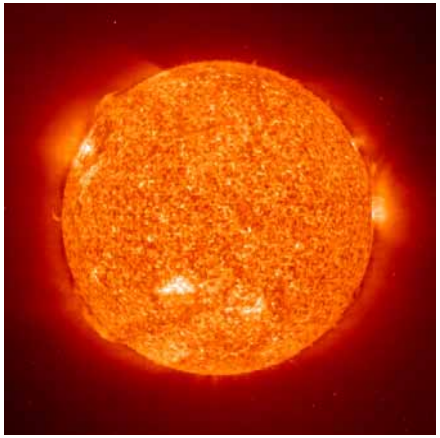
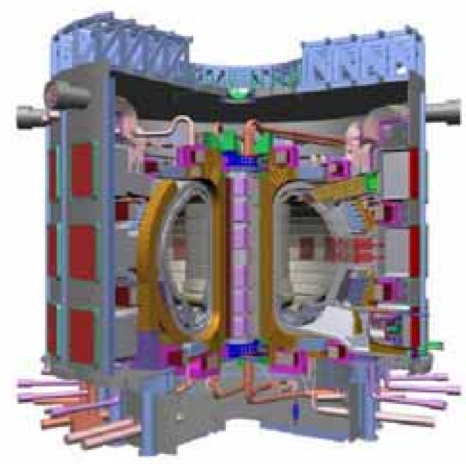


Controlled Fusion, from Basic Plasma Physics to Nuclear Engineering



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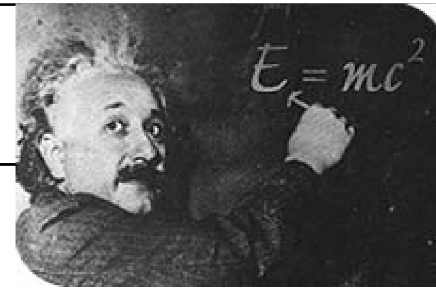
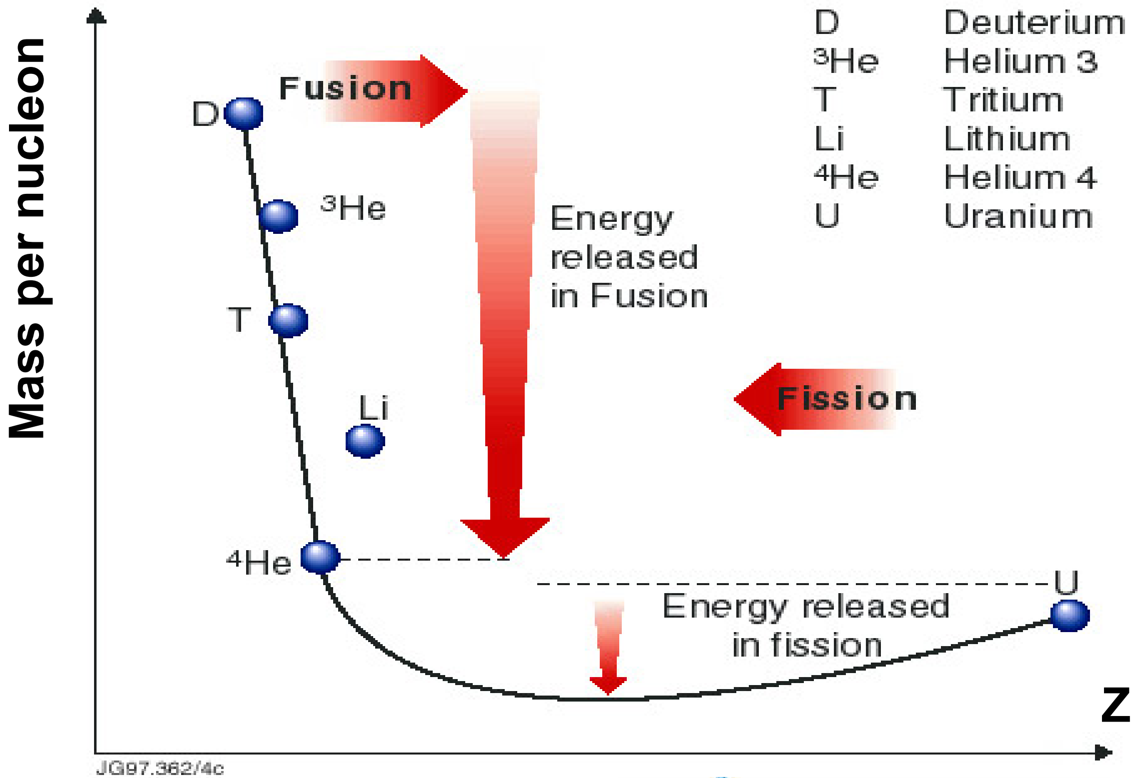
JET, United Kingdom

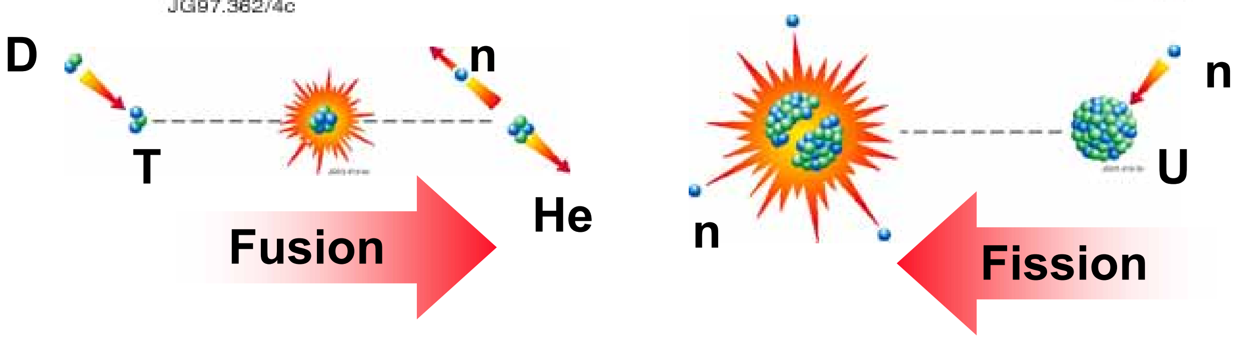
ICENES 2005, Brussels, August 22, 2005


• basic principles
• hurdles and achievements
• ITER
• nuclear aspects
• synergy of fission and fusion

Fusion and fission work on the same principle







A number of reactions are possible

"easiest": "largest" cross section

at "lowest" temperature

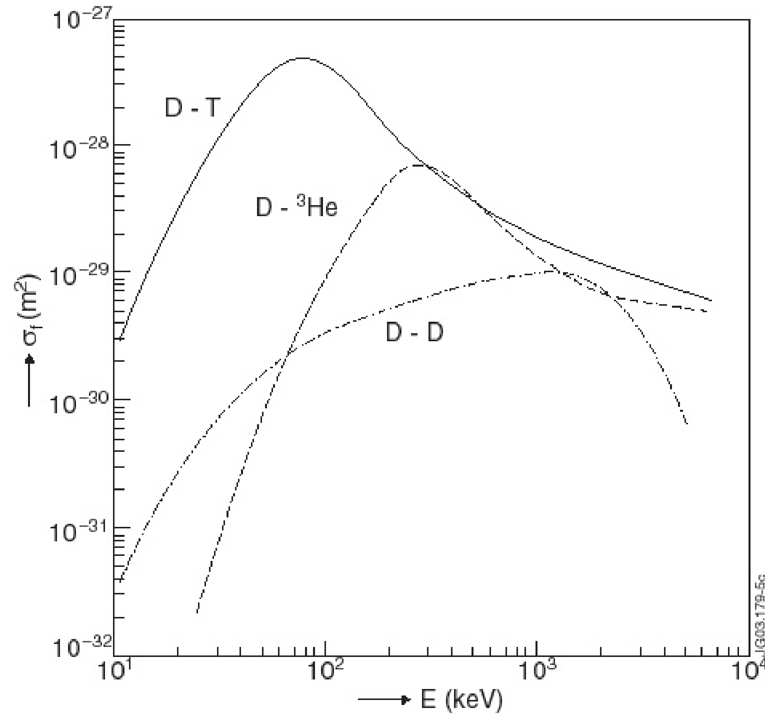
- D + T

- D + T → ^4He + n + ΔE

n + ^6Li → ^4He + T

n + ^7Li → ^4He + T + n

D + Li → ^4He + 4000 GW d/ Ton

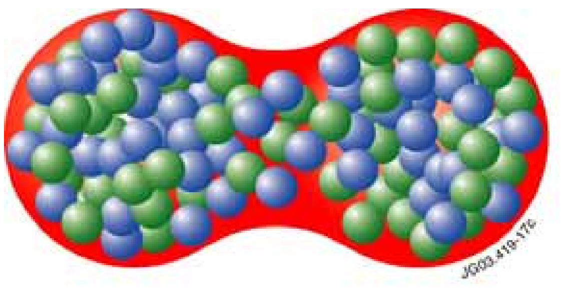


keV

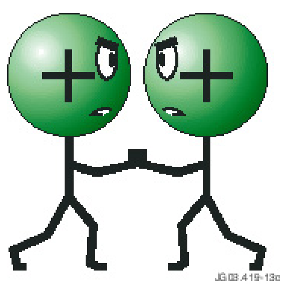
1 eV ≈ 10^4 K

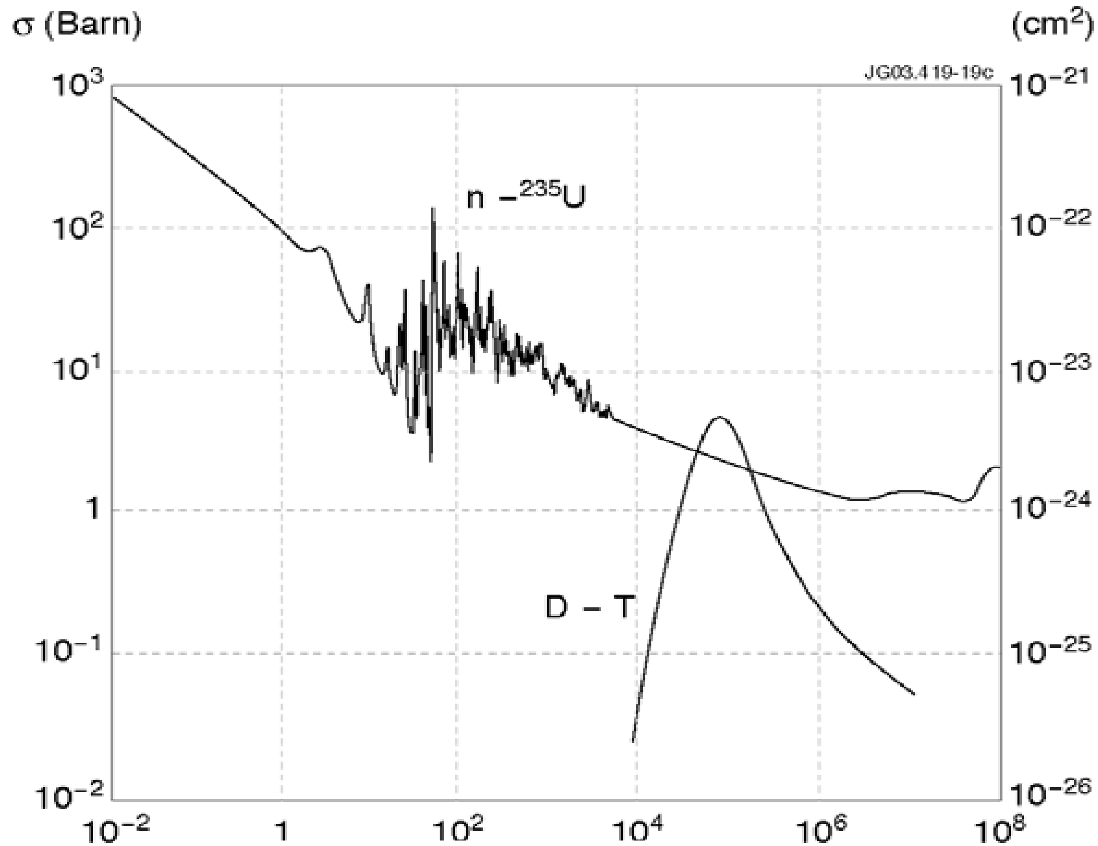
Conditions to achieve the reaction

Fission



Fusion



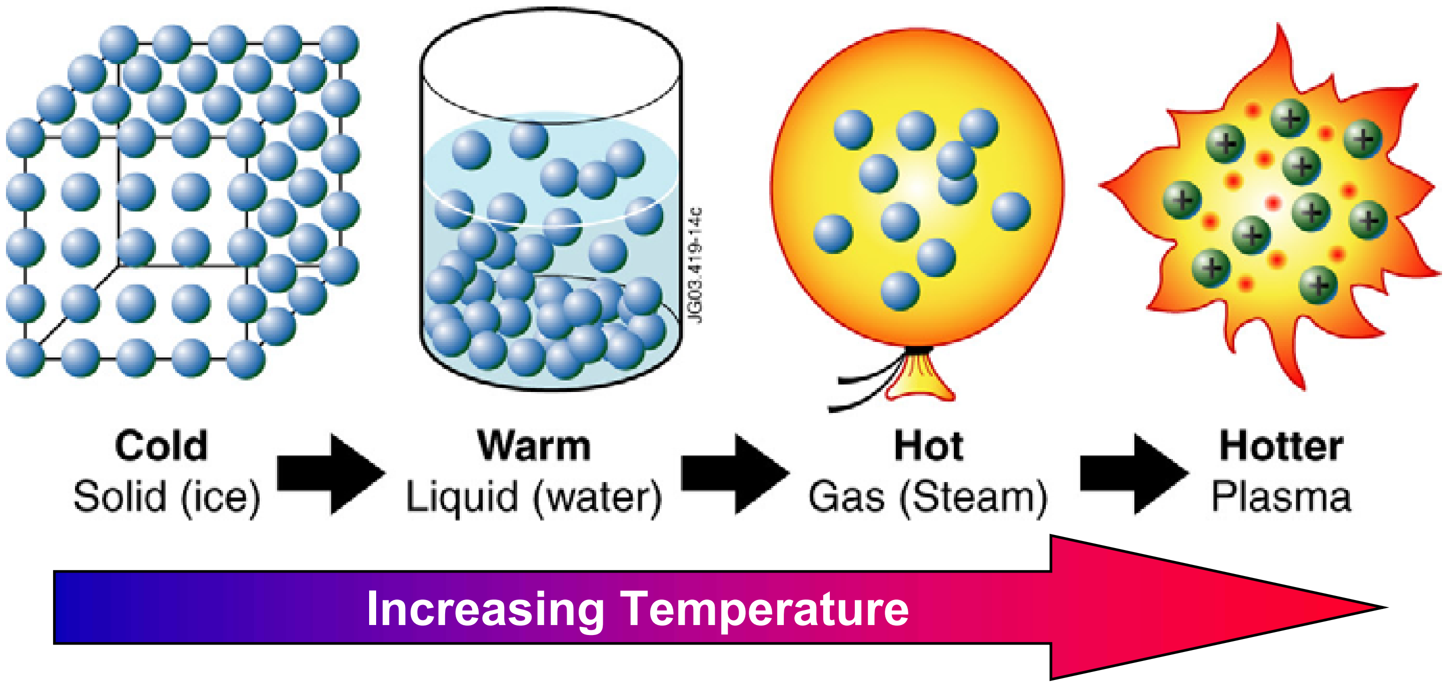


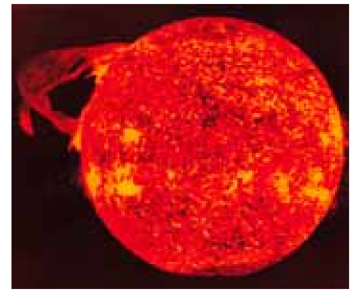
conditions to achieve fusion reaction:

sufficiently high energy → high enough temperature → plasma state

What is a plasma : fourth state of matter





A plasma is electrically conducting and very reactive

Conditions to sustain reaction

- fission: reaction propagated by neutrons → don't loose them

- fusion: for the reaction to propagate,
  conditions must be maintained

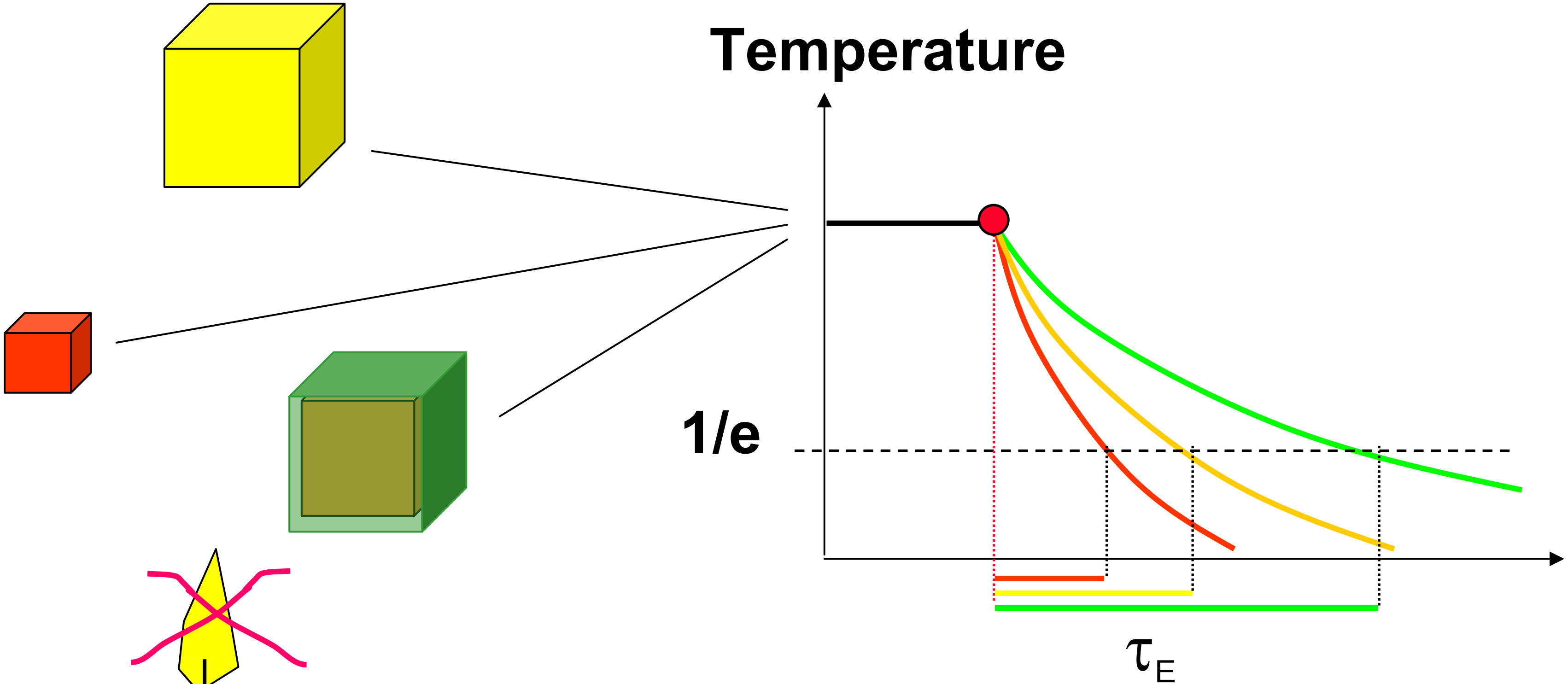
power must be large enough to compensate for the losses

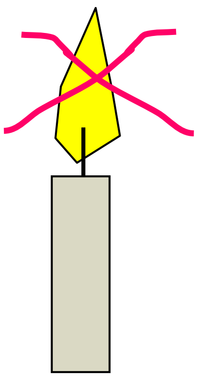
hot enough: T, temperature

dense enough: n, density

well enough insulated: τ_E, confinement time

What is the meaning of the confinement time τ_E?





τ_E is a measure of how fast the plasma looses its energy

The loss rate is smallest, τ_E largest
if the fusion plasma is big and well insulated

Lawson Criterium

power must be large enough to compensate for the losses

$n^2 \langle \sigma(T) v \rangle$ + external power

P_{fusion} — $P_{external}$

radiation losses $n^2 T^{1/2}$

convection and conduction $n T / \tau_E$

---

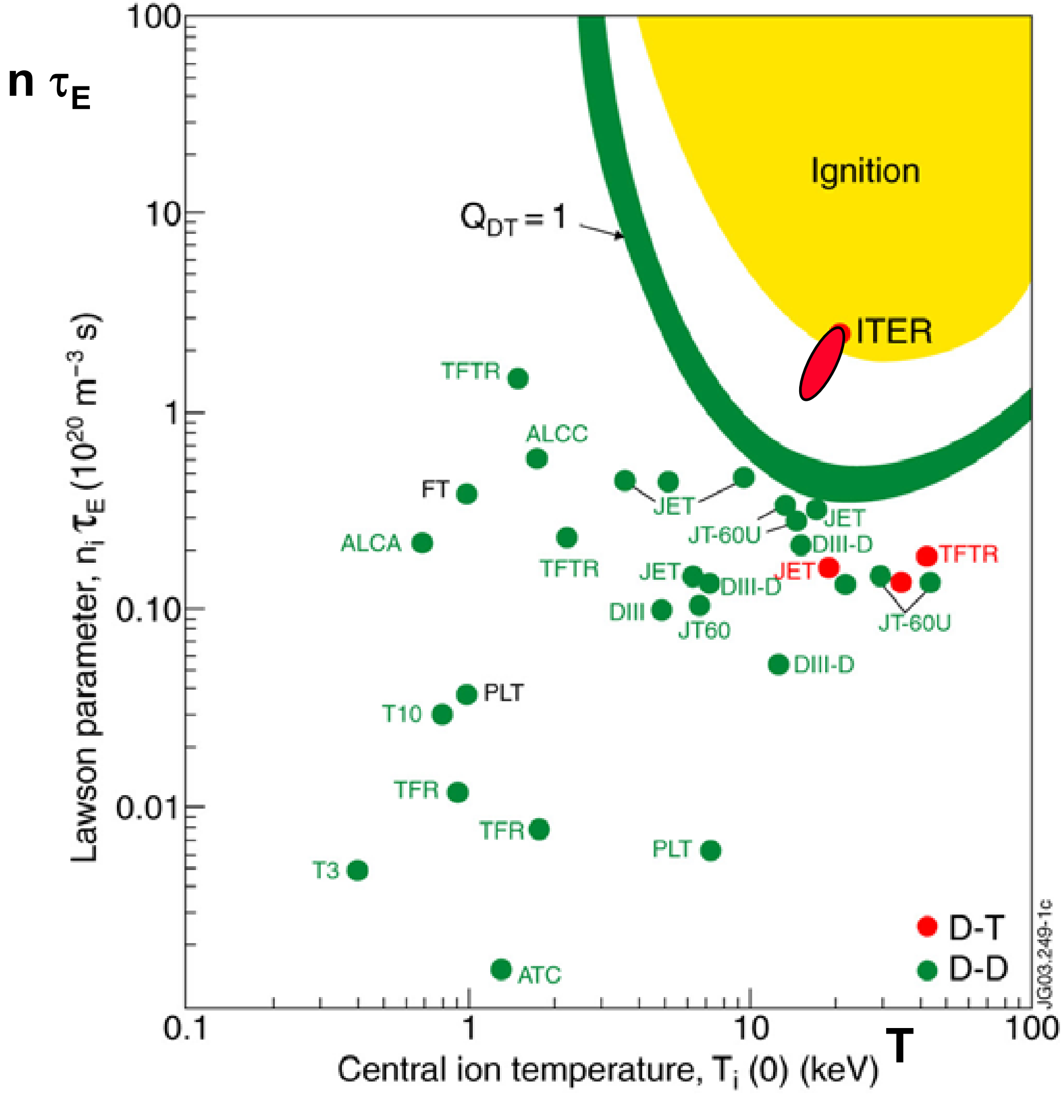
for $P_{external} = 0$ $\Rightarrow$ n (density) x τ_E (confinement time) > function of T (Temperature)

Lawson Criterium

for $P_{external} \neq 0$

$Q = P_{fusion} / P_{external}$ $\Rightarrow$ n x τ_E > function of T and Q

Lawson Criterium



$n \times \tau_E > f(T)$

$(P_{ext} = 0)$

$n \times \tau_E > f(T, Q = P_{fus}/P_{ext})$

$(P_{ext} \neq 0)$

$n \times \tau_E > f(T)$

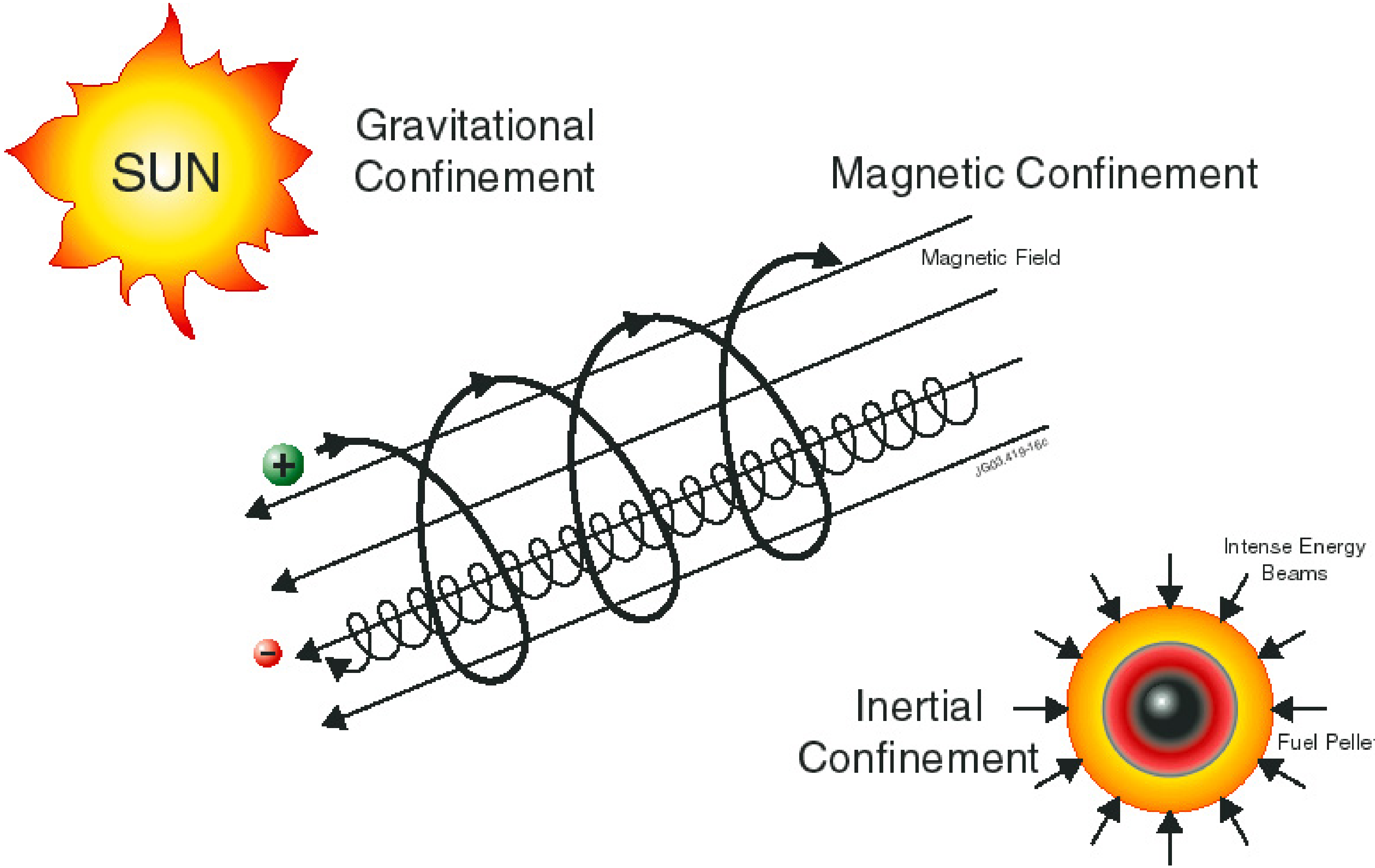
sometimes

also transformed into

(taking into account temperature dependence near minimum)

$n \times \tau_E \times T > 3\ 10^{21}$ (m^{-3} s keV)

How can a plasma be confined ?

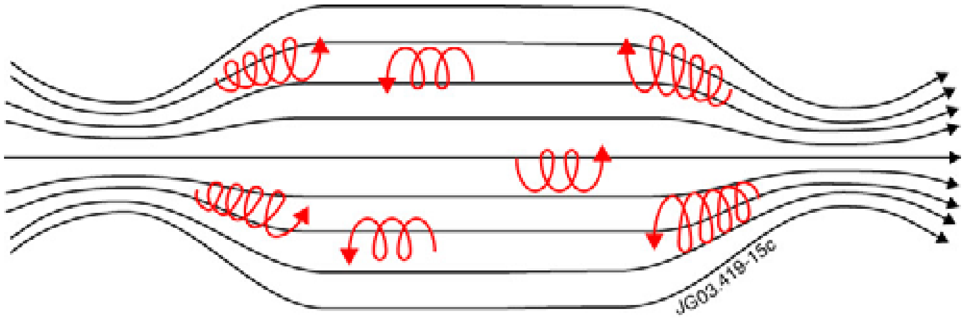


Magnetic confinement

Particles move freely along field lines:

how can we prevent losses in that direction ?

two solutions

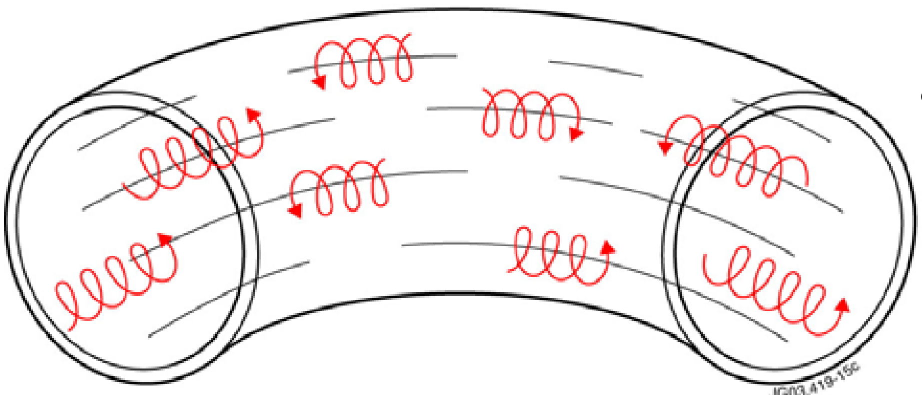


- **pinching the field lines at the end**

  ⇨ **reflection (“mirror”)**

  linear arrangement

  but still losses at the end



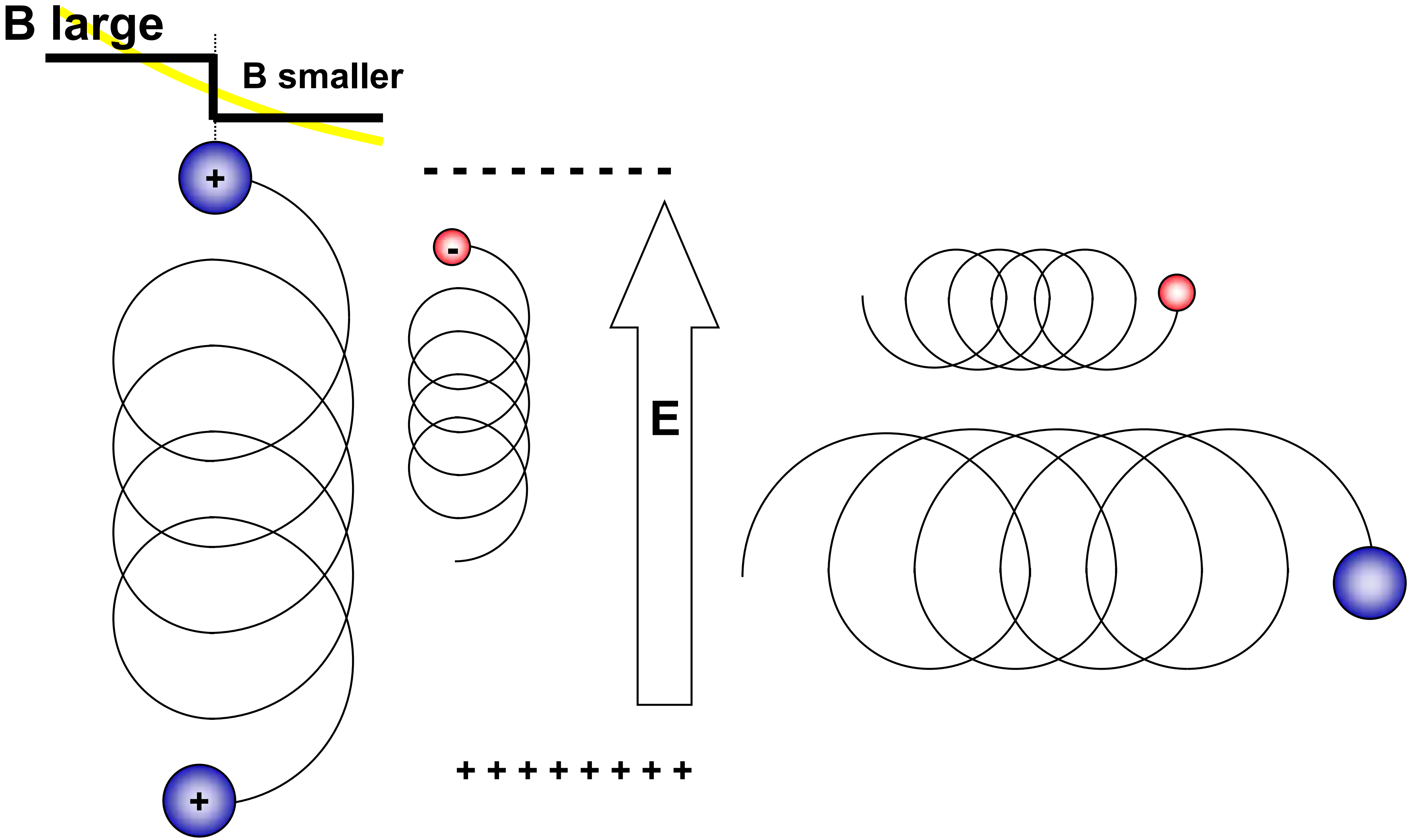
- **closing the field lines on themselves**

  ⇨ **no end losses**

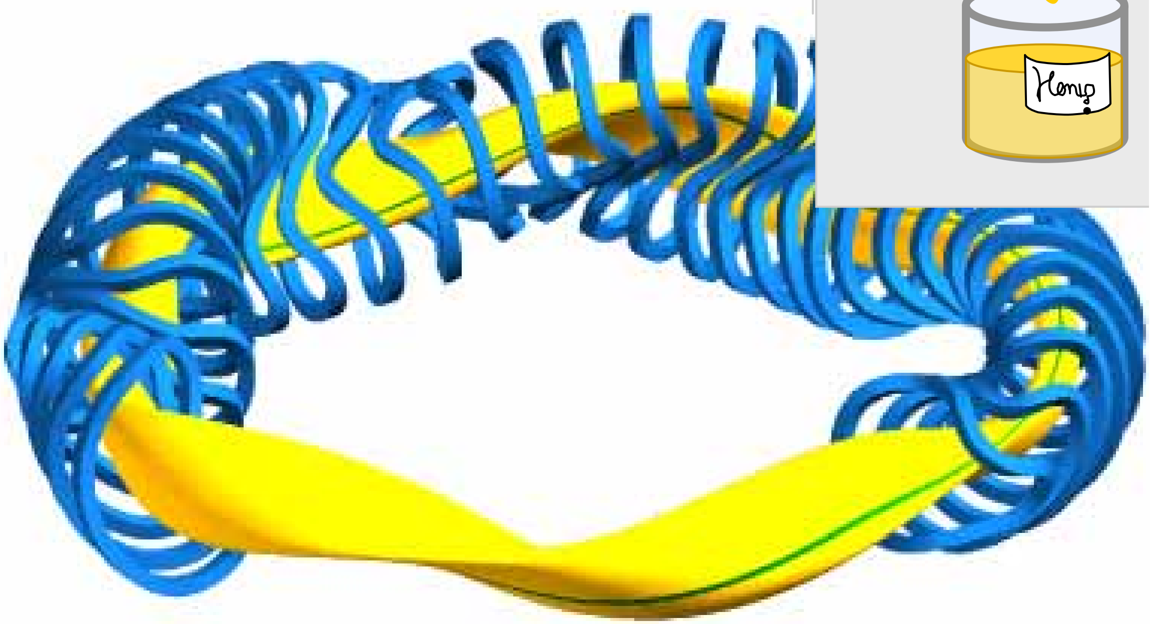
  toroidal confinement

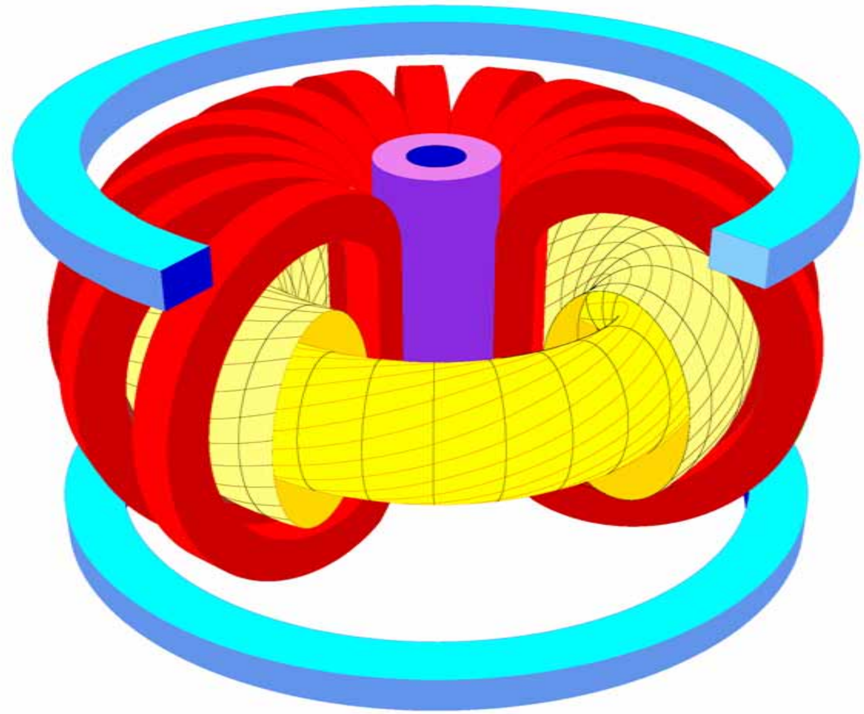
however: a pure toroidal field does not work

Toroidal field alone is insufficient



Two major ways to avoid this charge separation

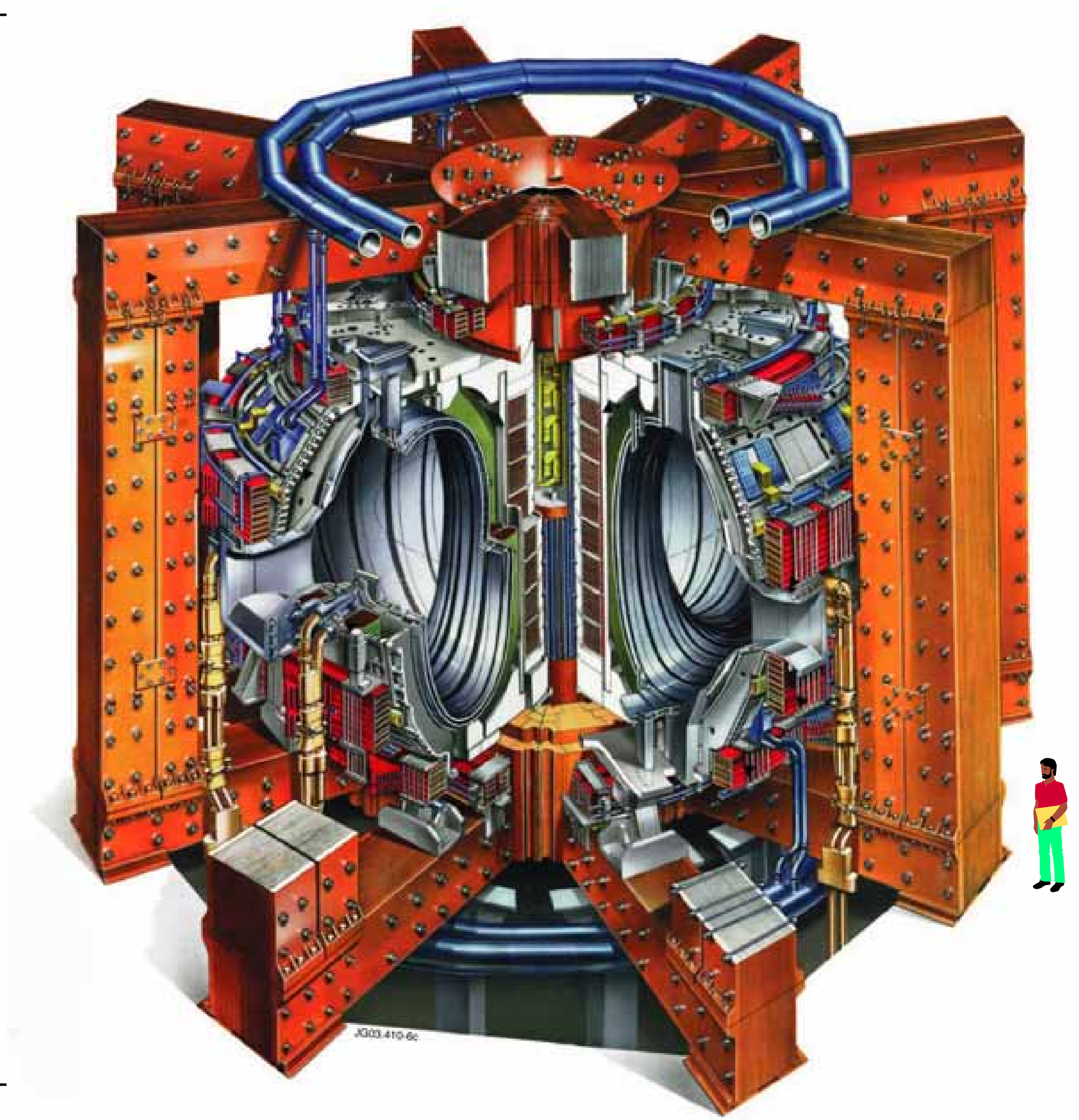




Stellarator **Tokamak**

JET: the European Tokamak

- plasma volume
- magn. field.
- plasma current



- 60 m^3
- up to 4 T
- up to 5 MA

- basic principles
- hurdles and achievements
- ITER
- nuclear aspects
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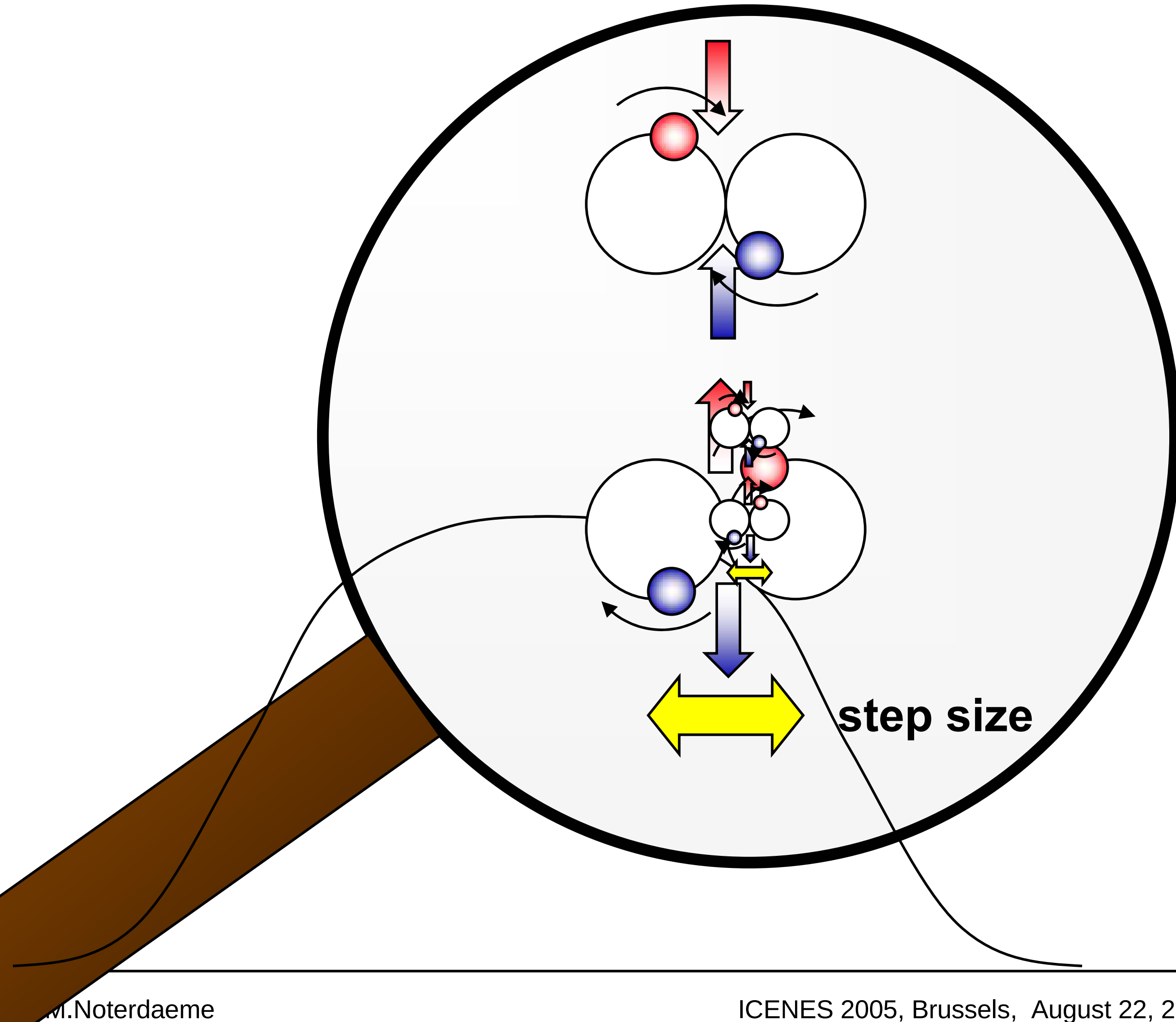
Heat and particle transport



" classical transport"

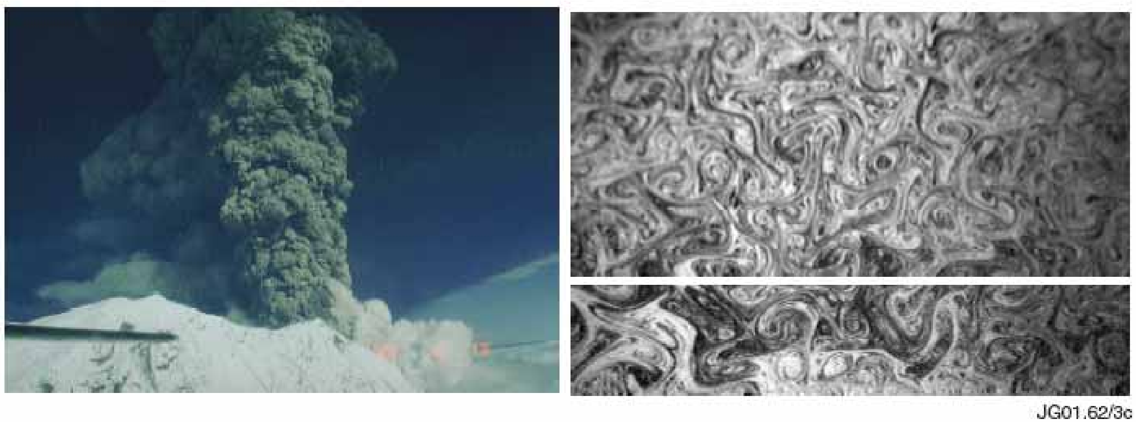
step size (5 T, 10 keV)

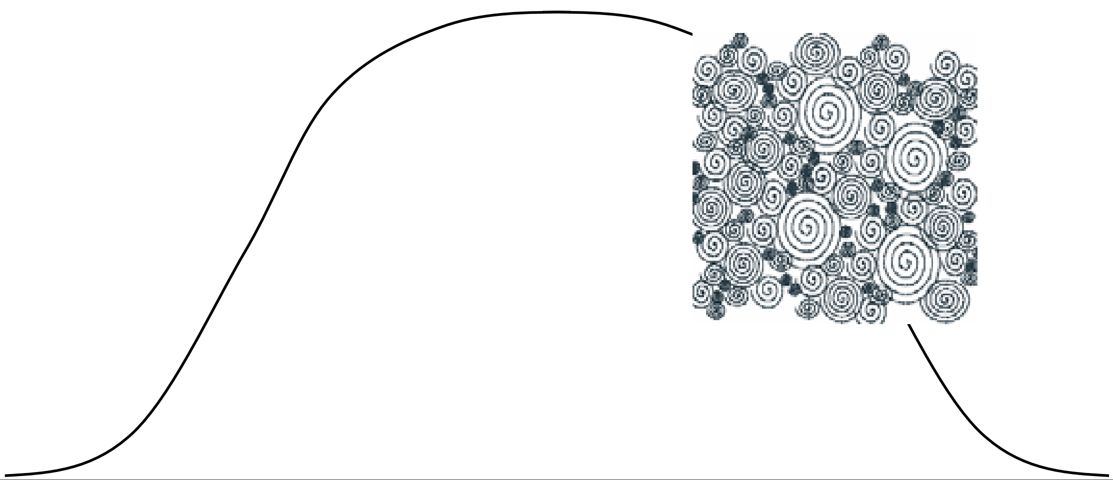
ion (H) = 2 mm

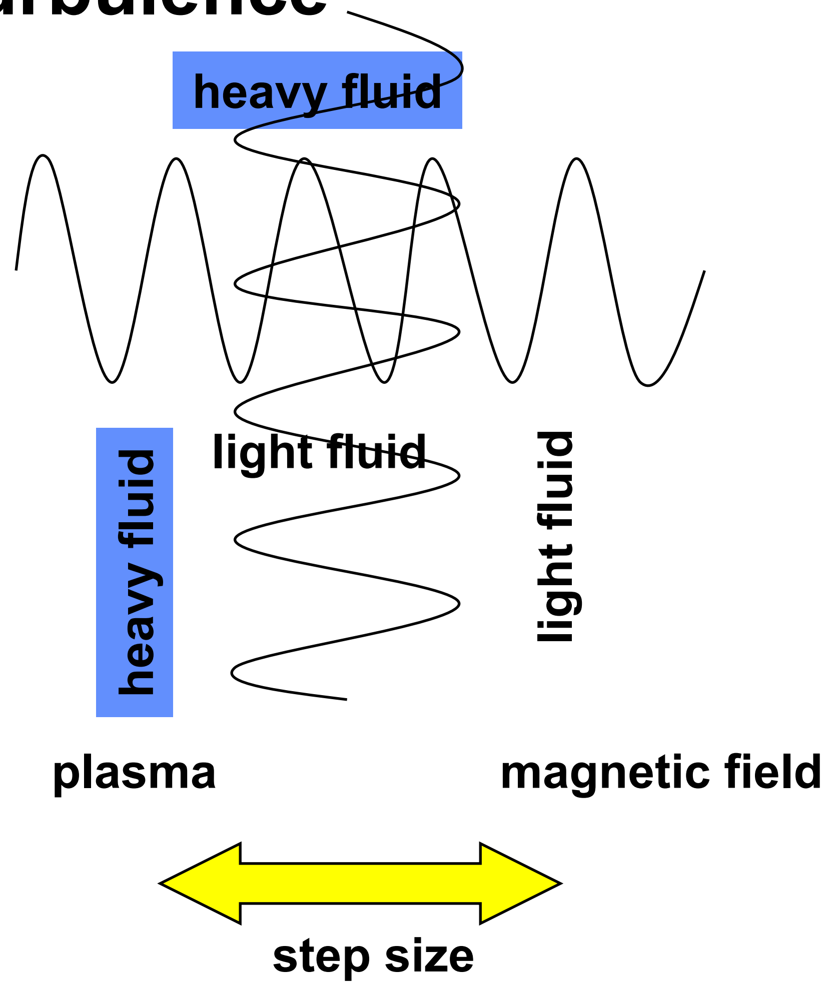
electron = 0.05 mm

Heat and particle transport

but, there are instabilities and turbulence







Transport dominated by turbulence

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

For diffusive processes:

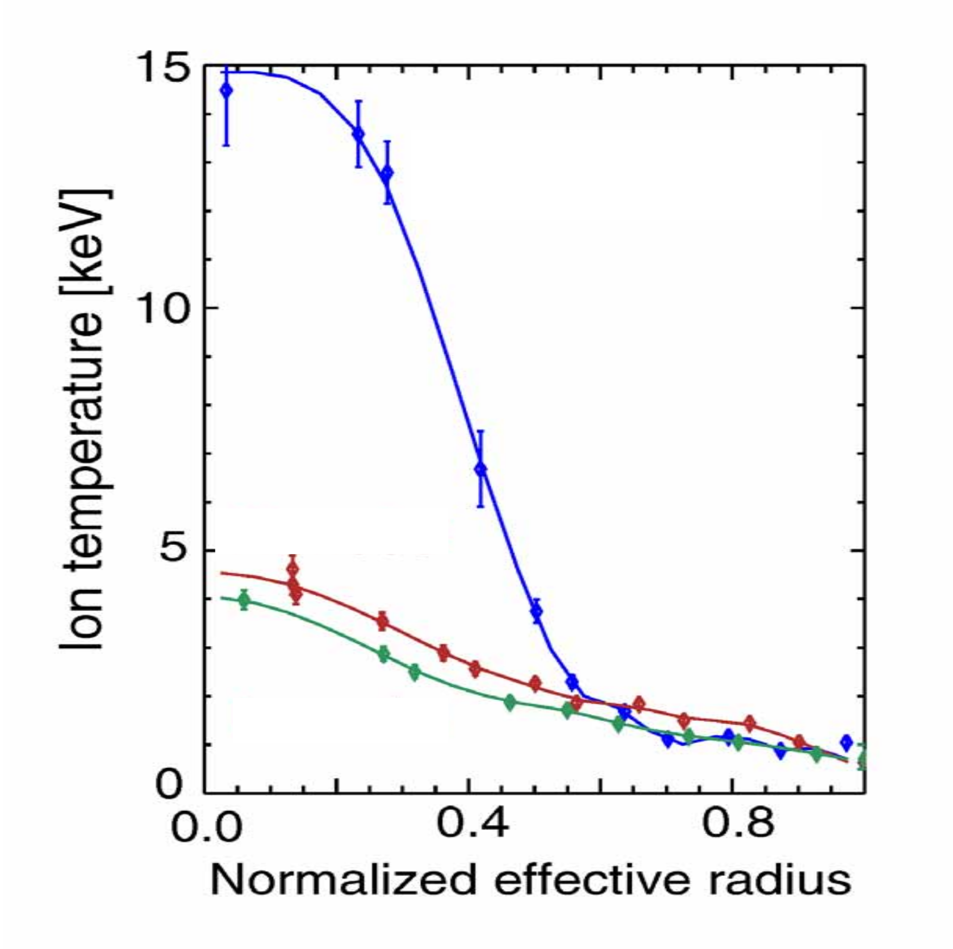
- **Confinement time $\tau_E \propto a^2/\kappa$**

  (a = small Plasmaradius,
  κ = heat conductivity)

smaller $\kappa \Rightarrow$ larger τ_E

Turbulence – one of the central theme of plasmaphysics

Improvement of the confinement



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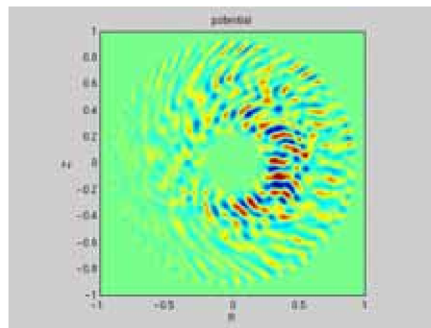
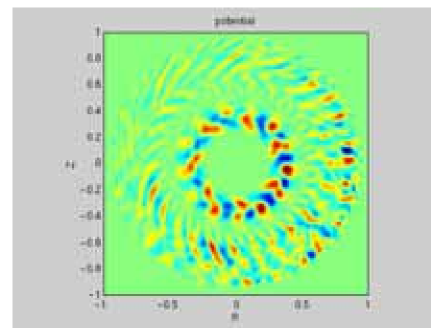
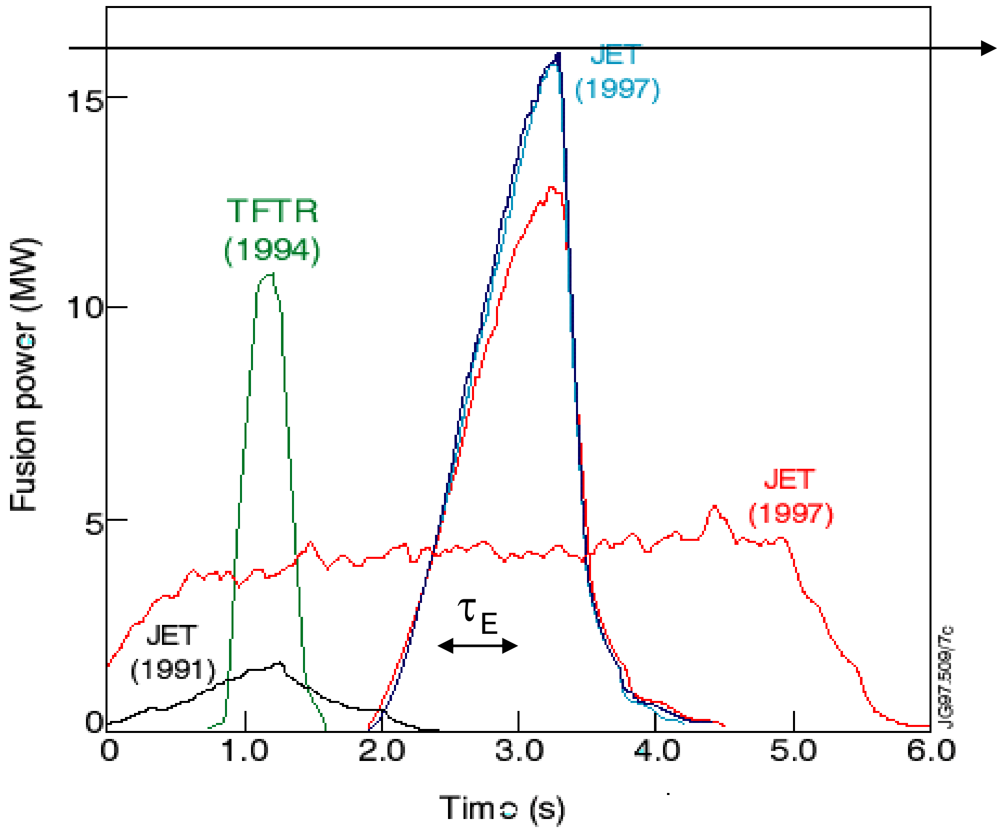




turbulence can be suppressed by a variation of rotation speed (shear in rotation) leading to an improvement of τ_E

What has been achieved ?



16 MW

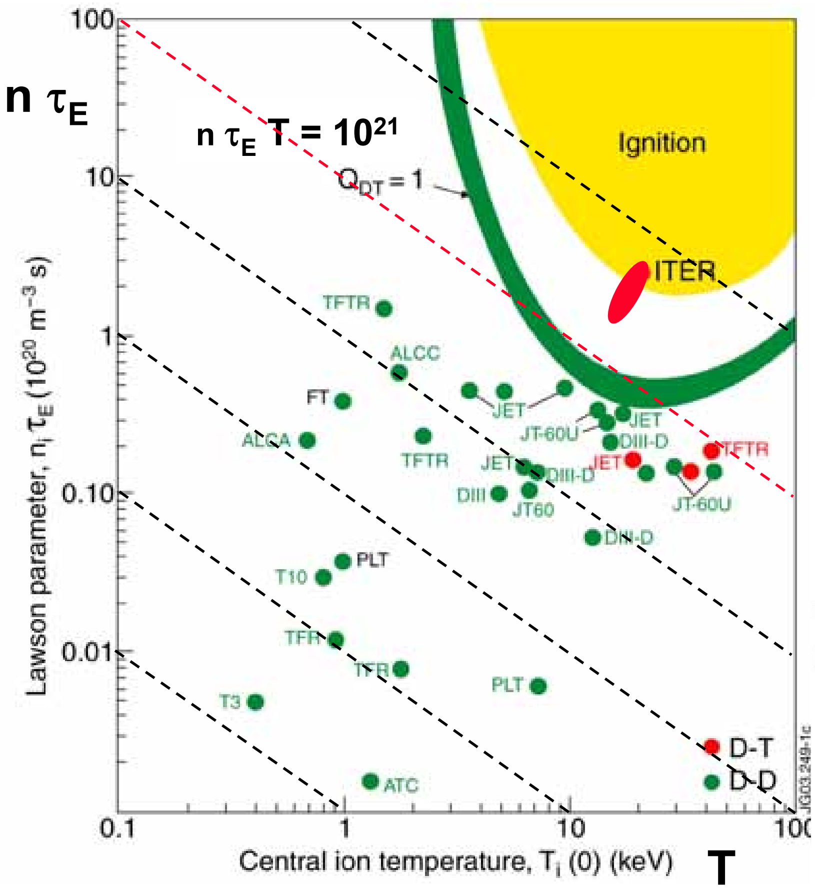
in a D-T plasma,

with 20 MW input
into the plasma

total output : max 16 MW

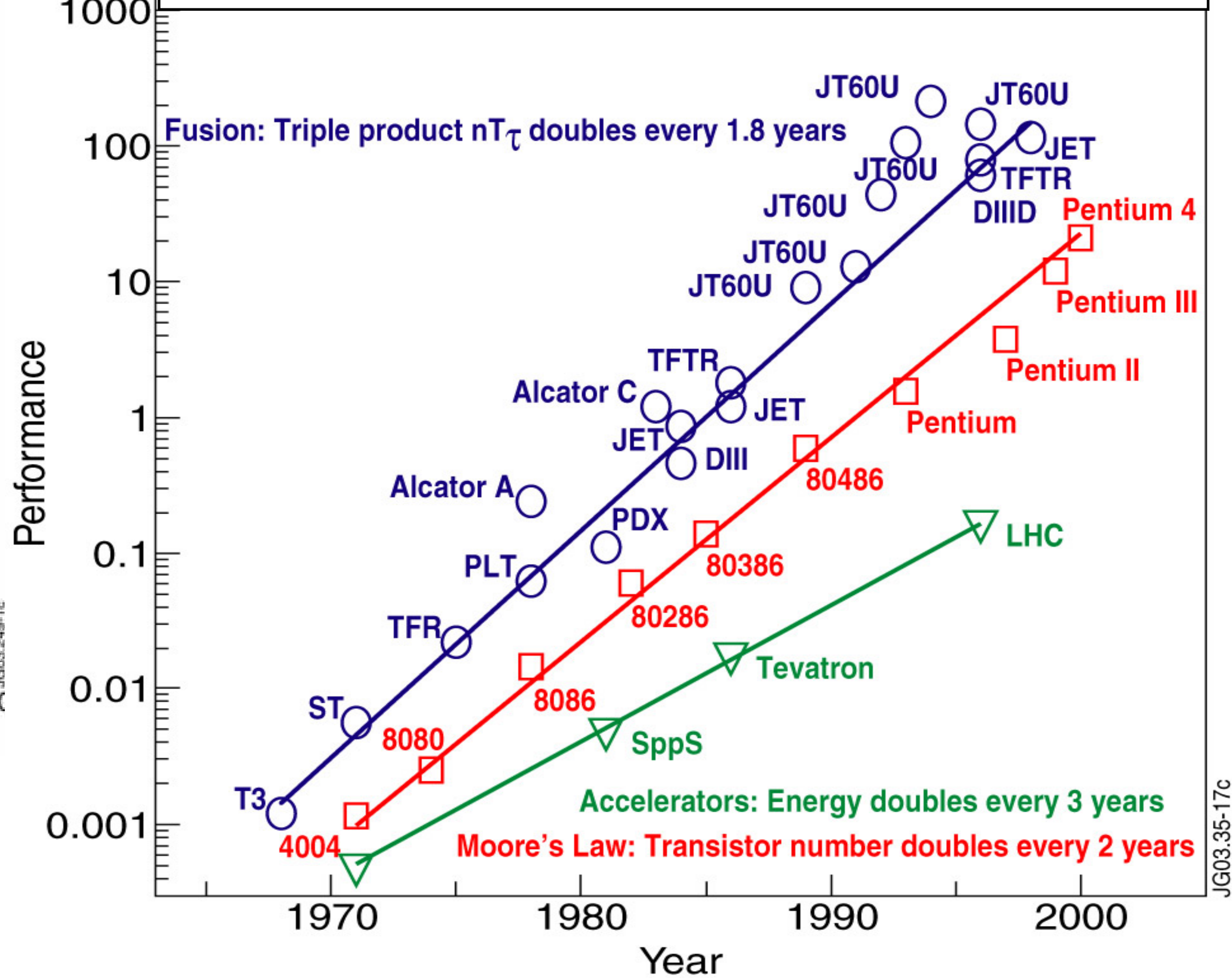
record (Q = 0.8) but
not yet self sustaining !

How far are we on the road to the sustained fusion conditions



single parameter: $n\ \tau_E\ T$

Evolution of the performance over the years matches that of computers "Moore's law"



- basic principles
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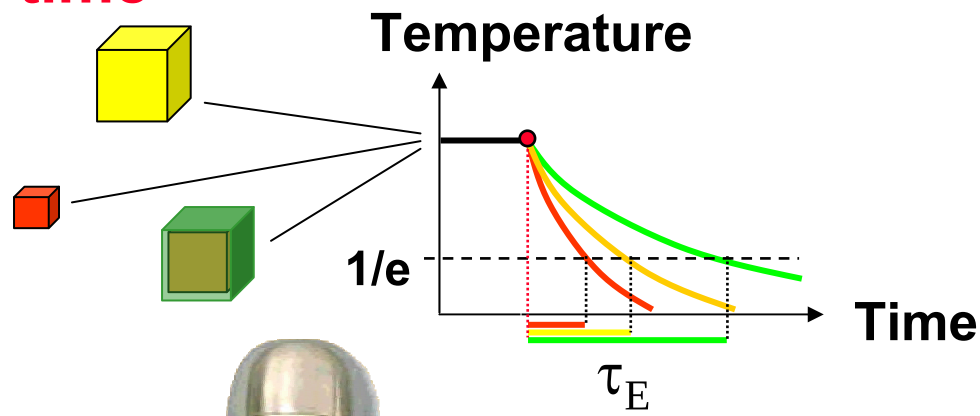
We need a larger machine

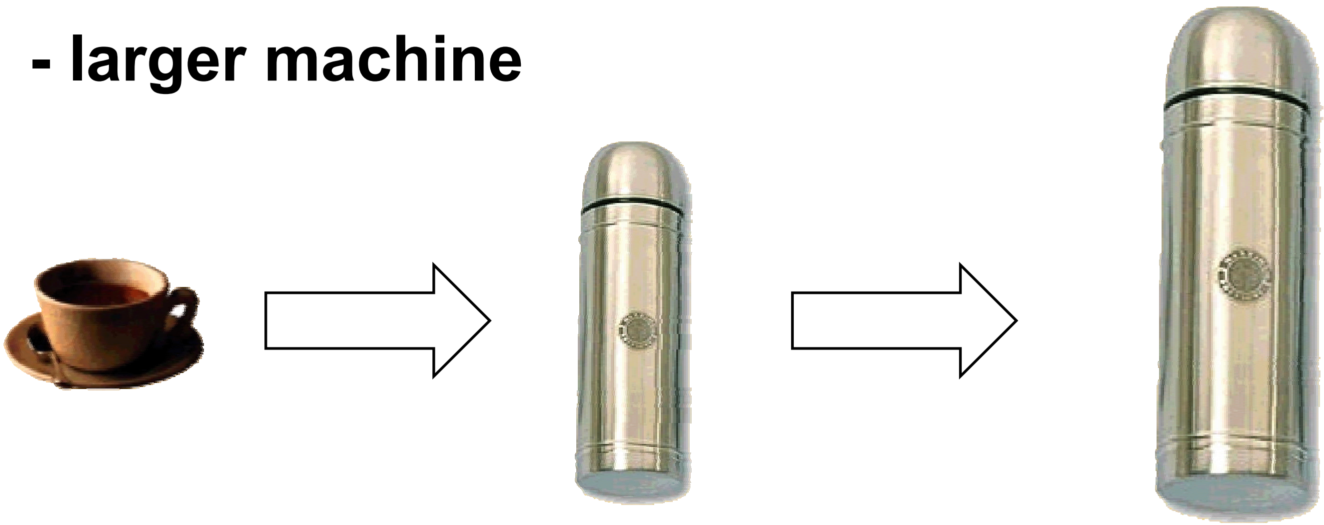
- for a **sustained** reaction : $n\,\tau_E > f(T)$
- we need a larger **confinement time**



thus

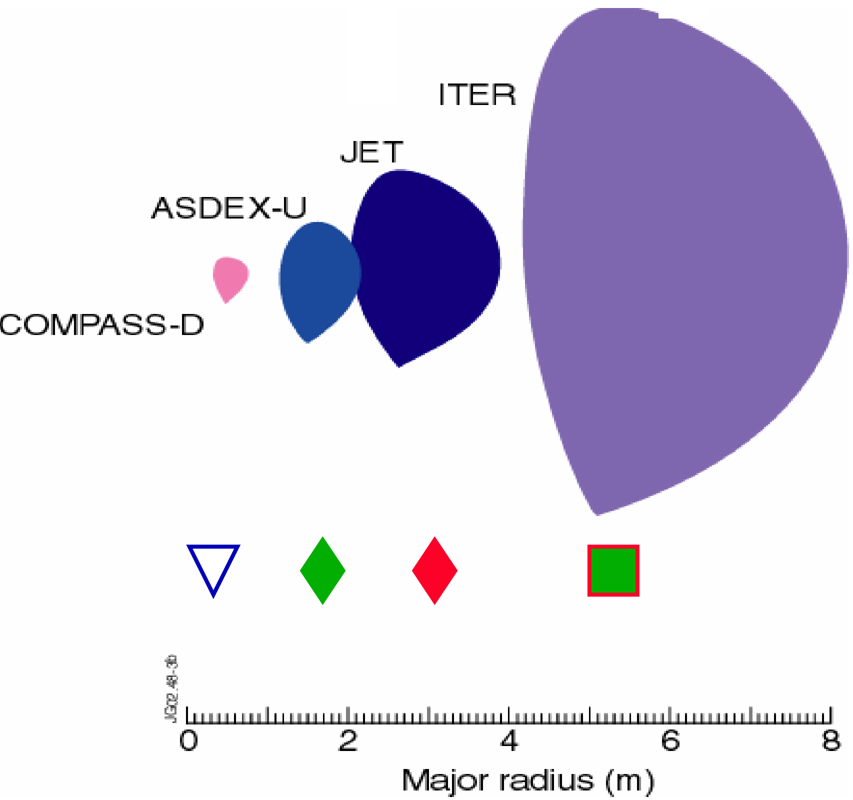
- better insulation

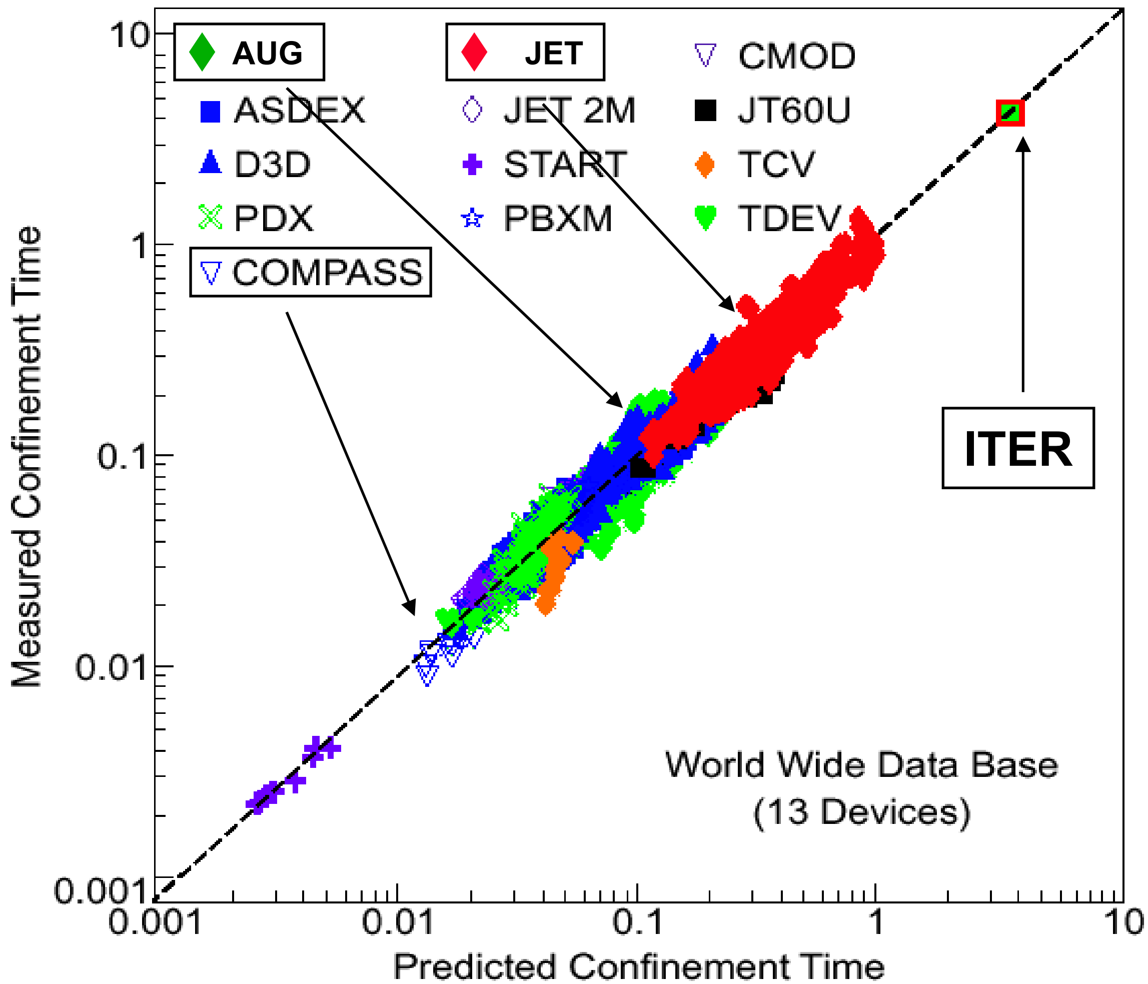
- larger machine



how much larger ?

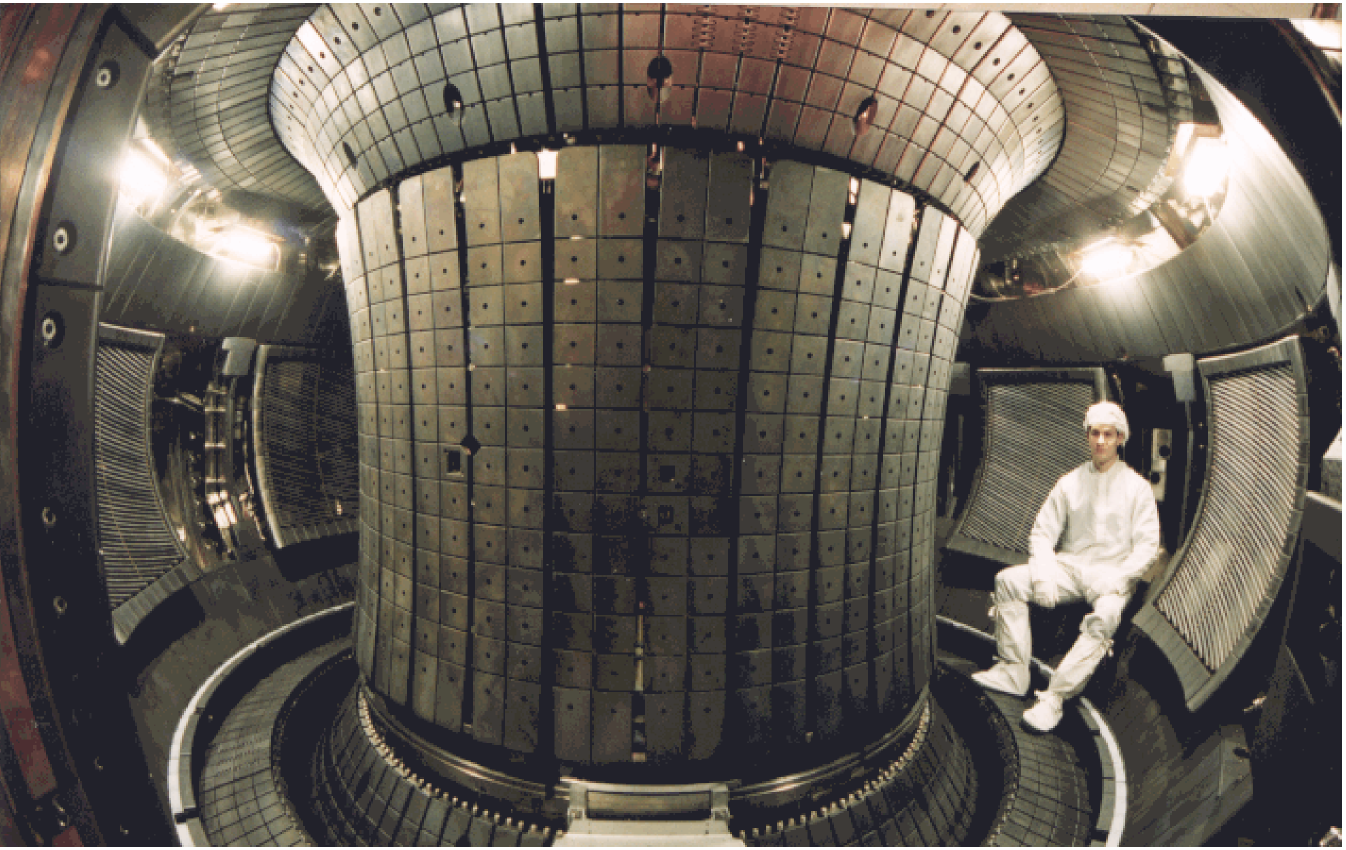
Size from scaling laws

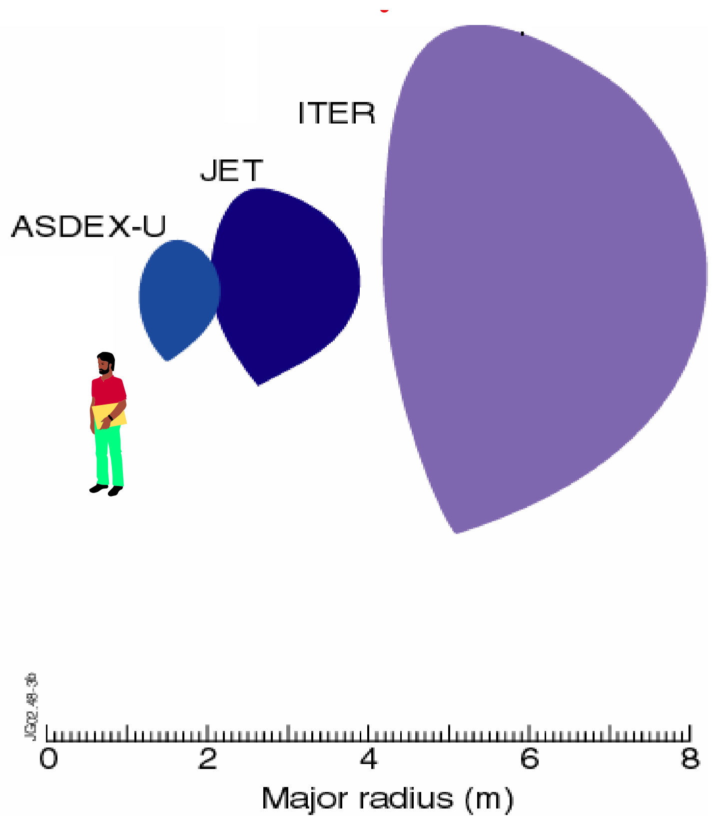




ASDEX Upgrade

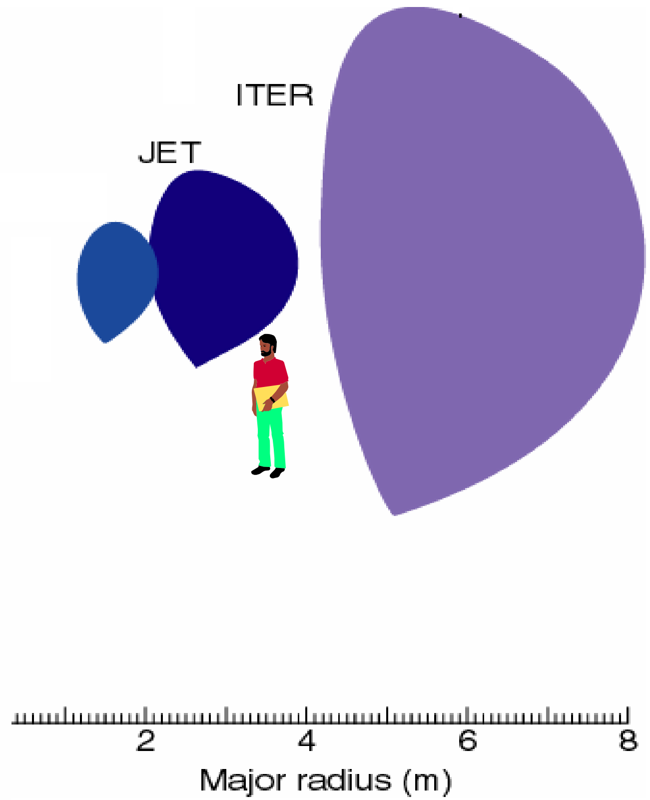
R = 1.65 m, a =0.5 m, τ_E = 0.1 s





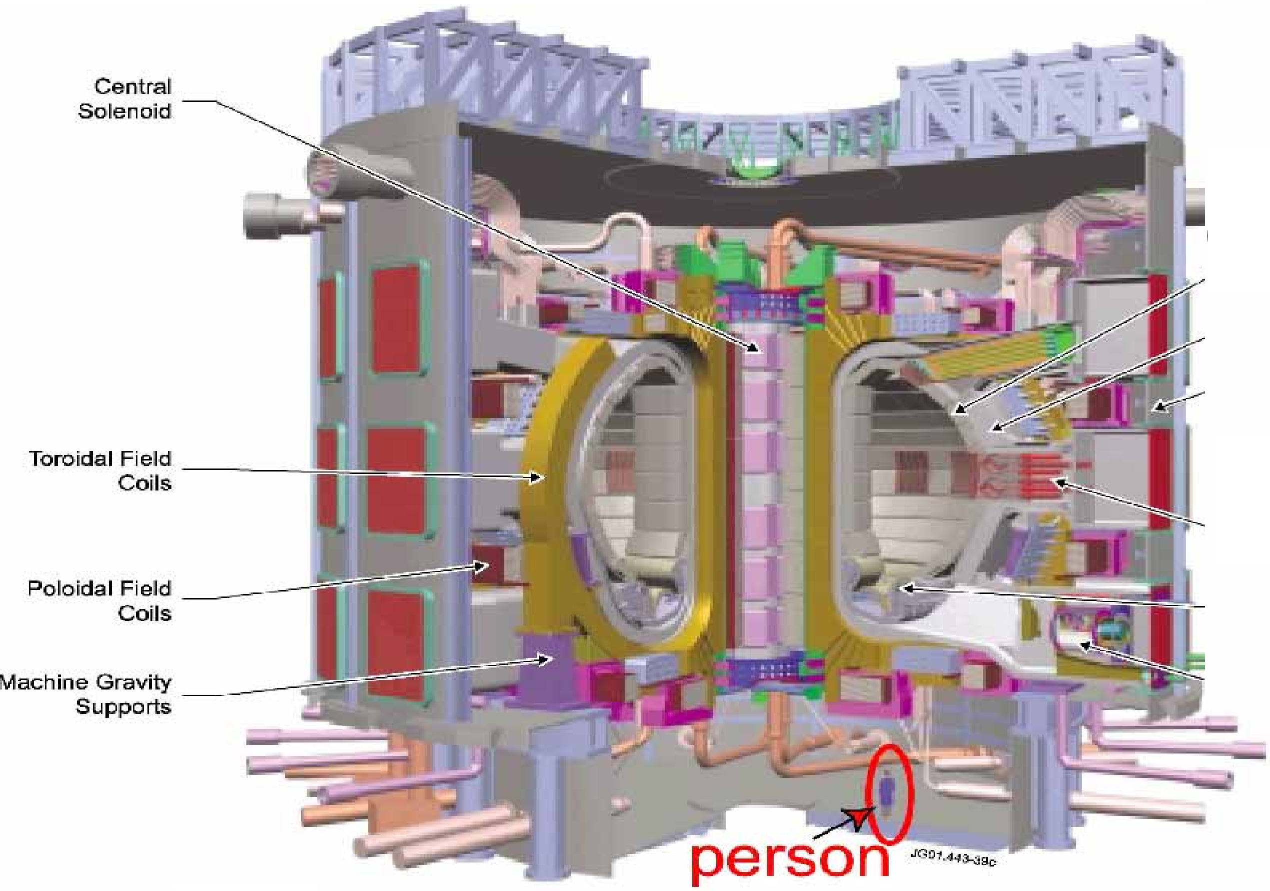
JET, without and with plasma

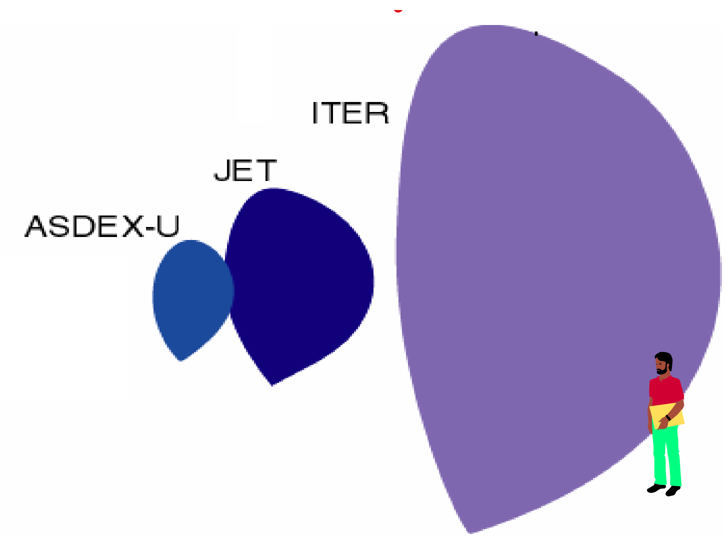
R = 3 m, a = 1 m, τ_E = 0.5 s



ITER

$R = 6.2$ m, $a = 2$ m, $\tau_E = 3$ s





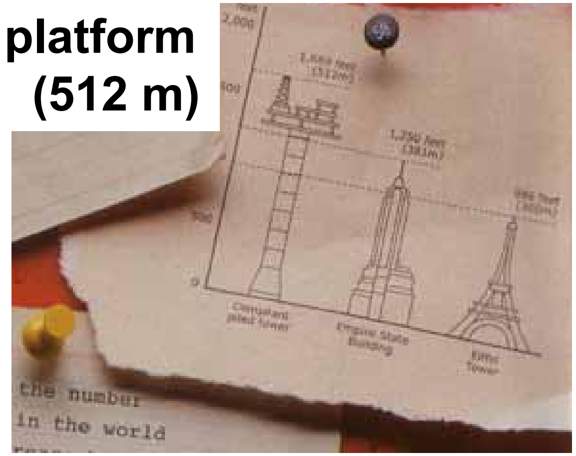
Volume	**850 m³**
Current	**15 MA**
Magnetic field	**5.3 T**
Fusion power	**400 MW**
Heating power	**40- 90 MW**
Q	**10**

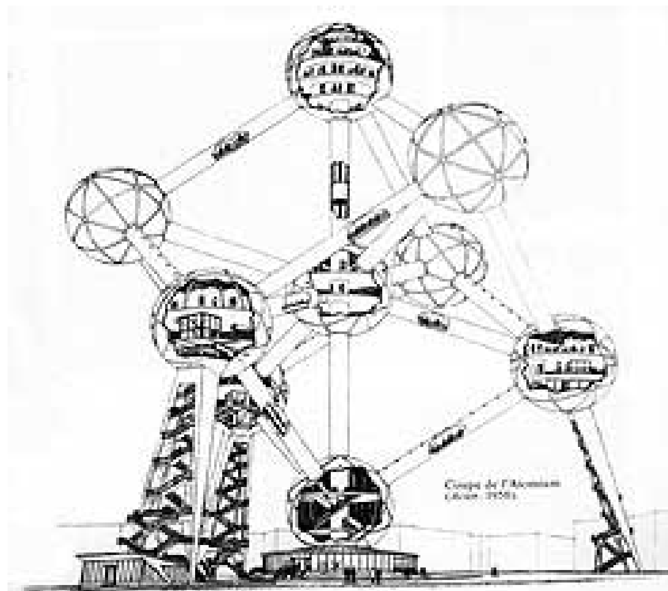
The overall dimension of the machine are H = 24 m, D = 28 m

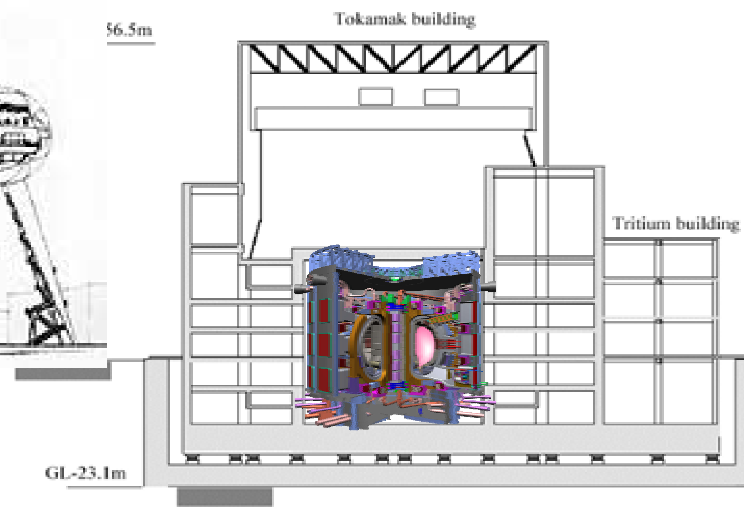
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

The reactor building (partially underground) will fit under the first level of the Eiffel tower (H = 58 m)

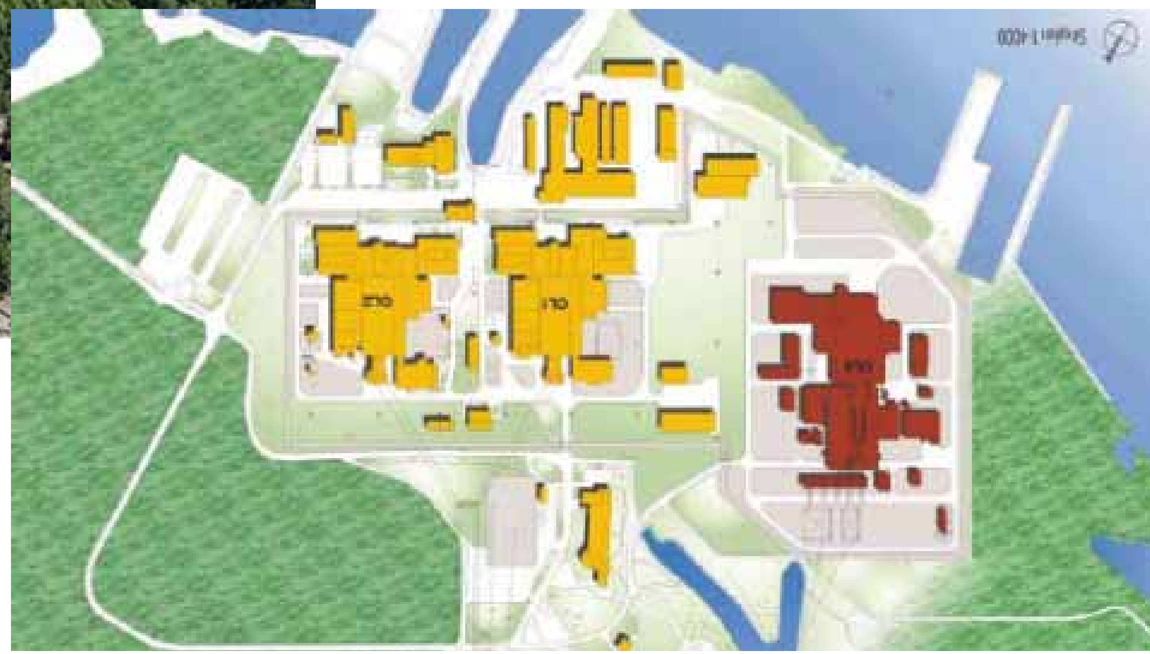
and is dwarfed by the size of an oil platform (512 m)





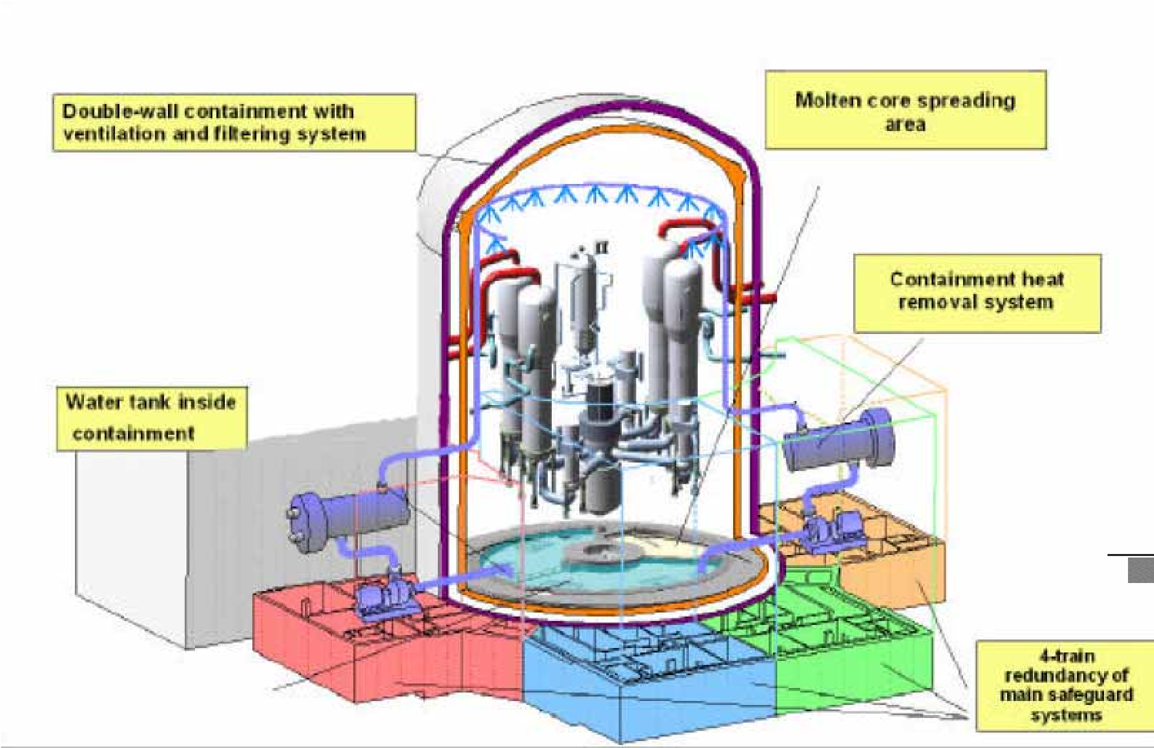


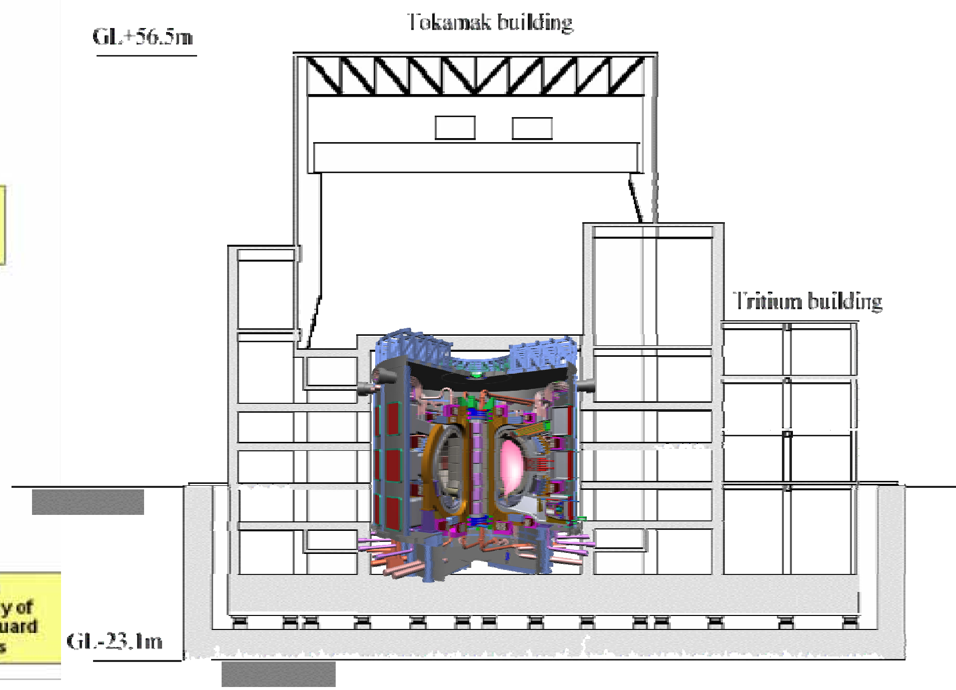
Fission reactor
Olkiluoto 3, in Finland



EPR and ITER buildings

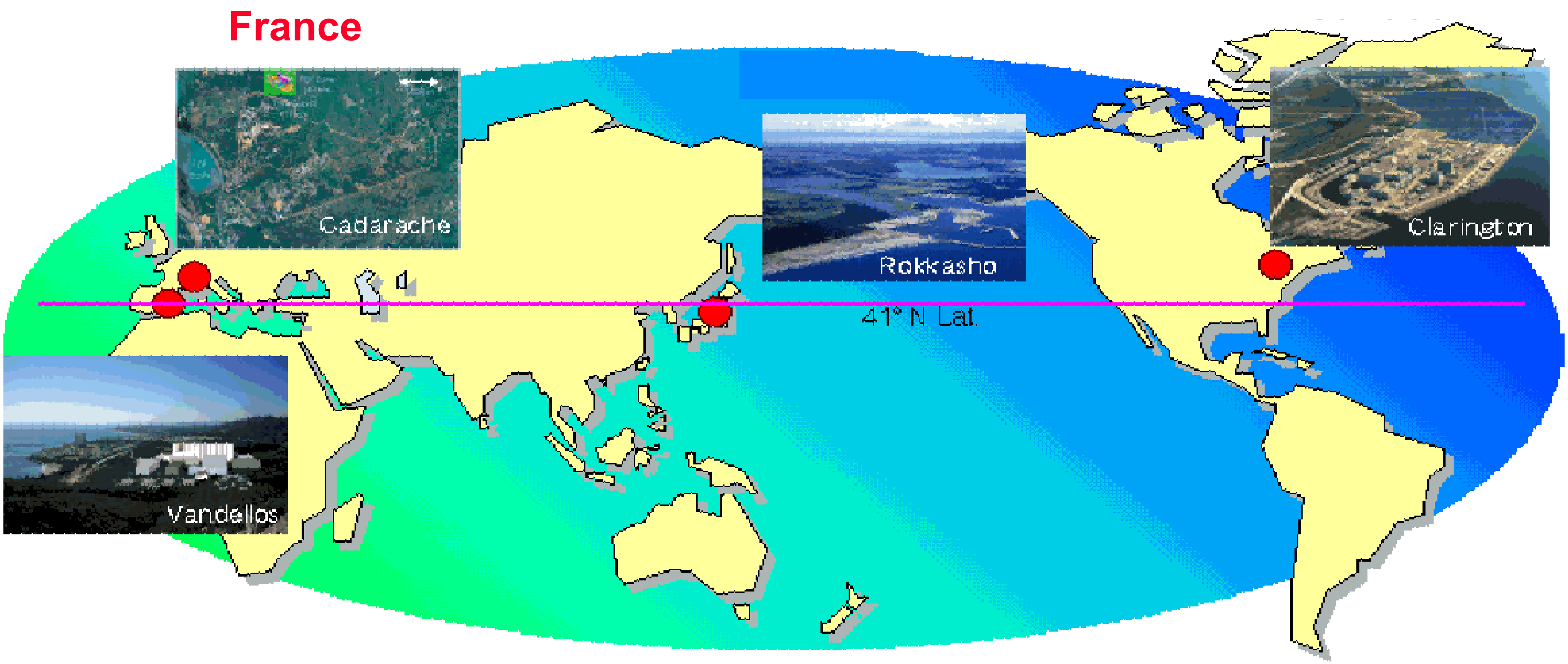
both approximately 60 m high



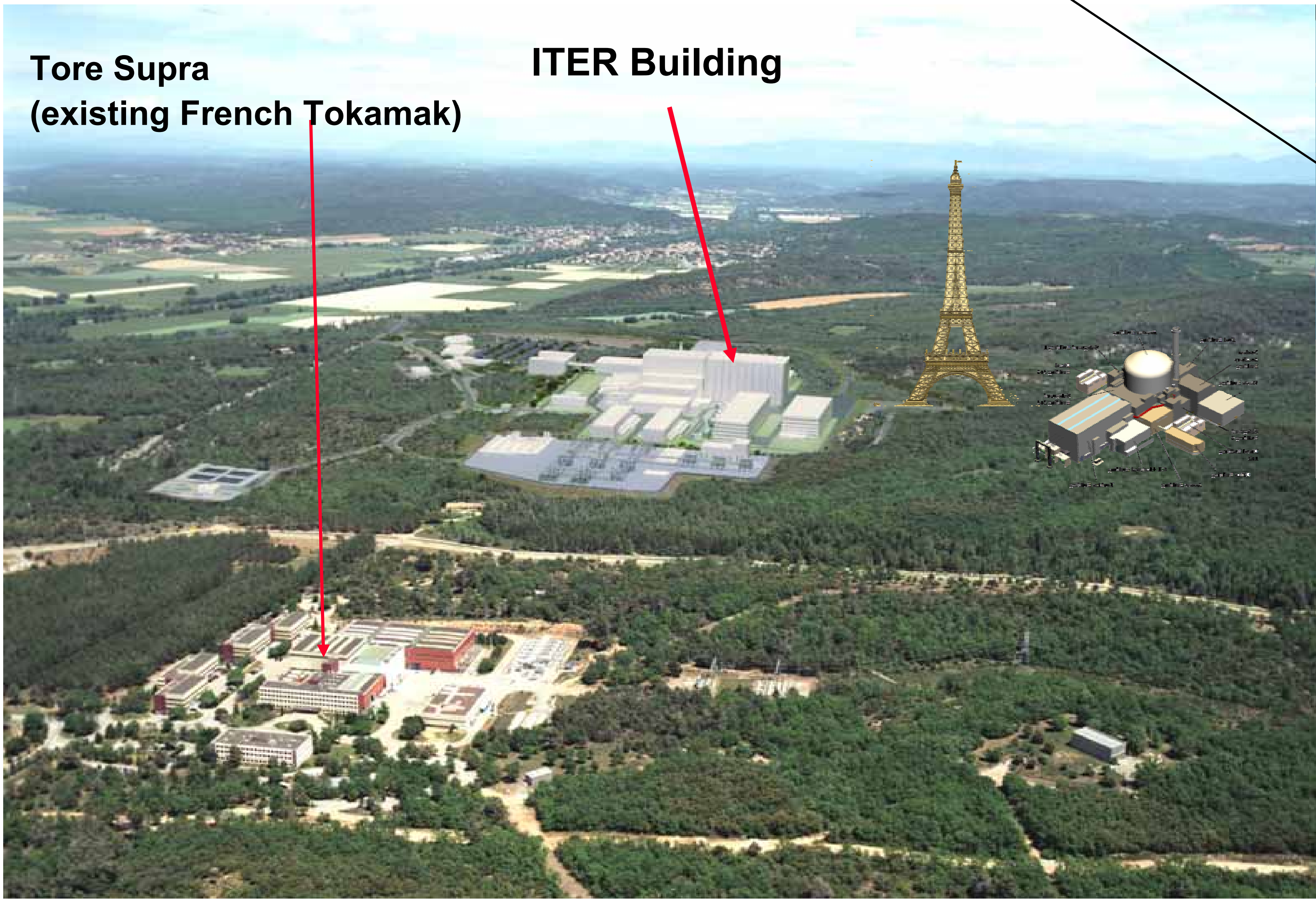


A site was recently chosen

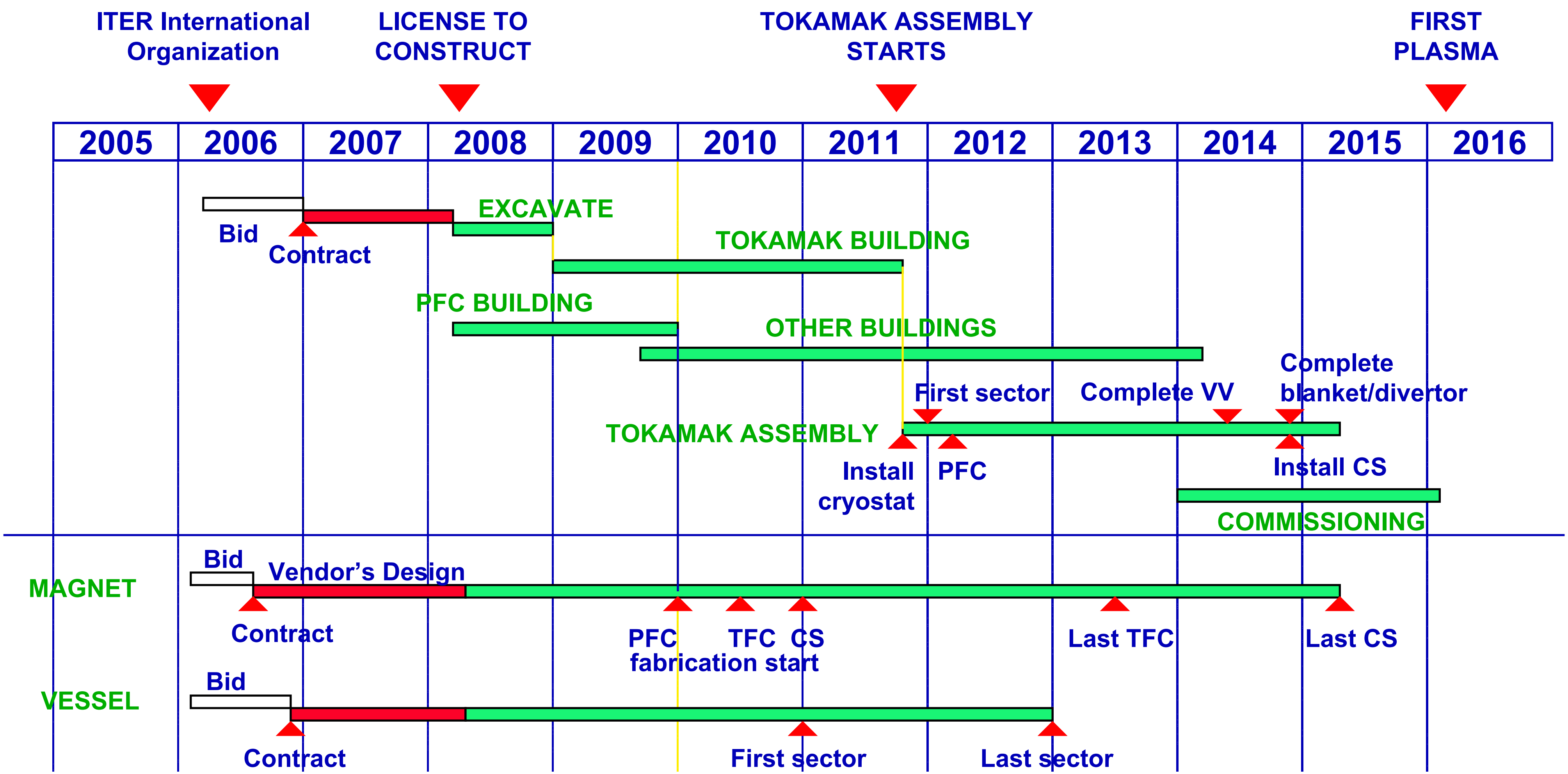
- there were originally 4 candidate sites
- then 2
- at the end of June 2005: decision for Cadarache



Cadarache, near Aix en Provence



Construction schedule: 10 years




• basic principles
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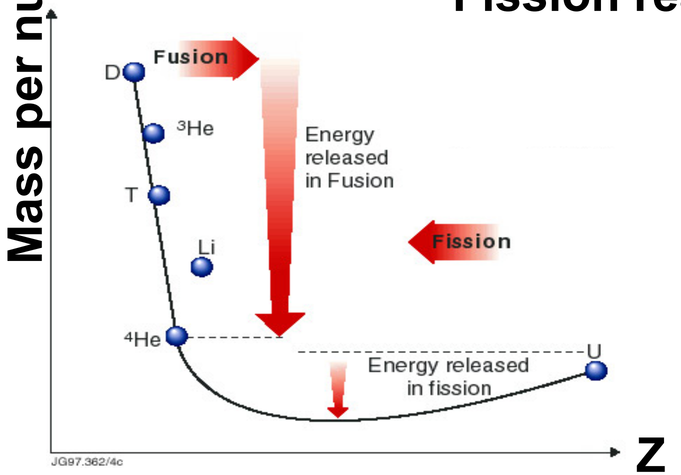
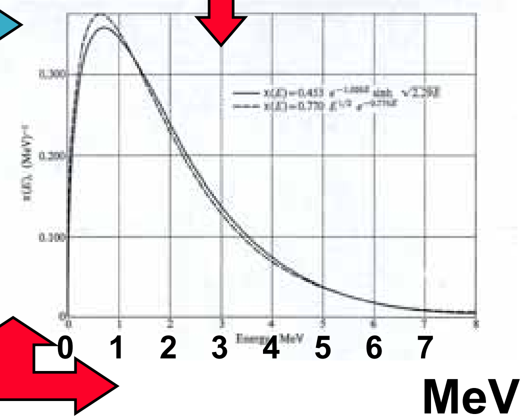
Both nuclear, but there are differences

Fusion reaction: $^2D + ^3T \rightarrow ^4He + n$ + Energy

Fission reaction: $^{235}U + ^1n \rightarrow x.\ n + Y + Z$ + Energy



	Mass input	Energy output	Neutron output	Neutron energy	Products
Fusion	5	17.6	1	14.1	^{4}He
Fission	236	200	≈ 2		radioactive



for the same power :

fuel mass smaller by factor approx 4
(amount of fuel in reactor at any time much smaller)

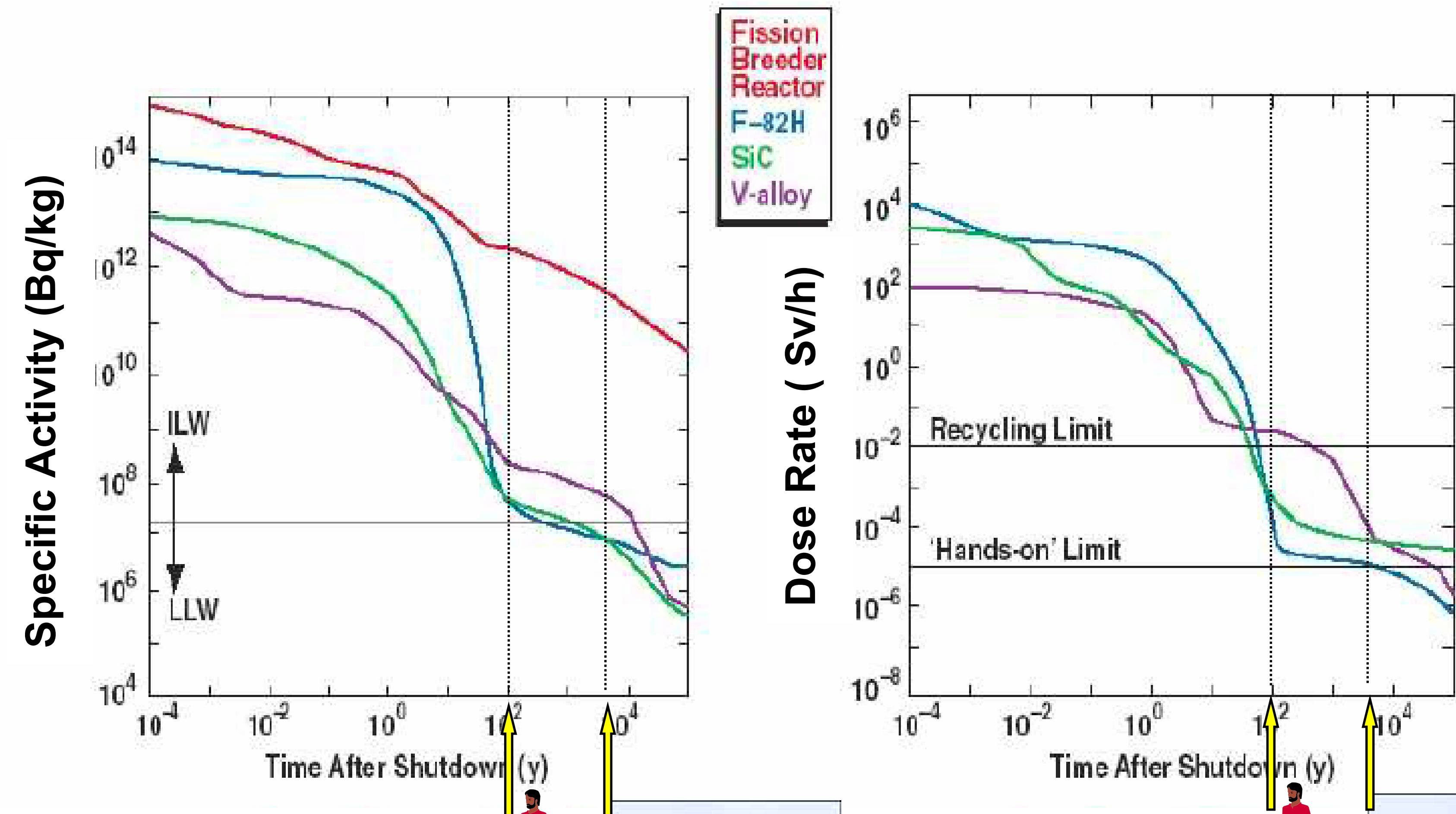
approx. 5 x more neutrons

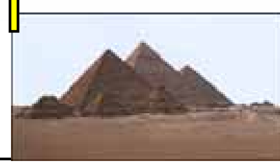
with higher energy

dpa: 10 vs 150

no radioactive products, but structure becomes activated

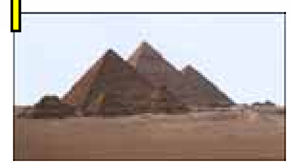
Fusion material



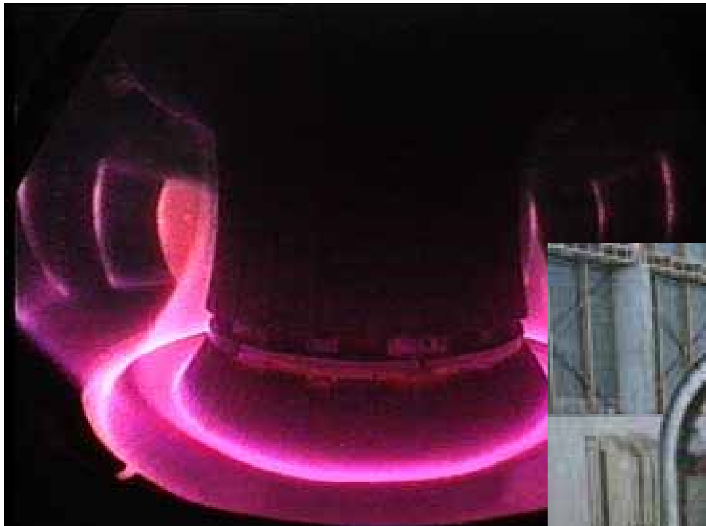


after 2.5 y irradiation
with averaged neutron wall load of 2 MW/m²

Forthy and Taylor
Euromat96 Conf.

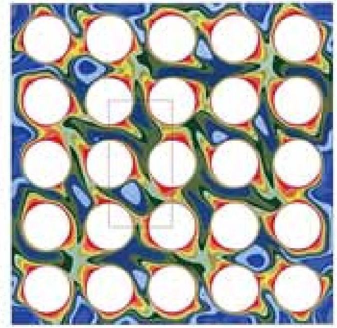


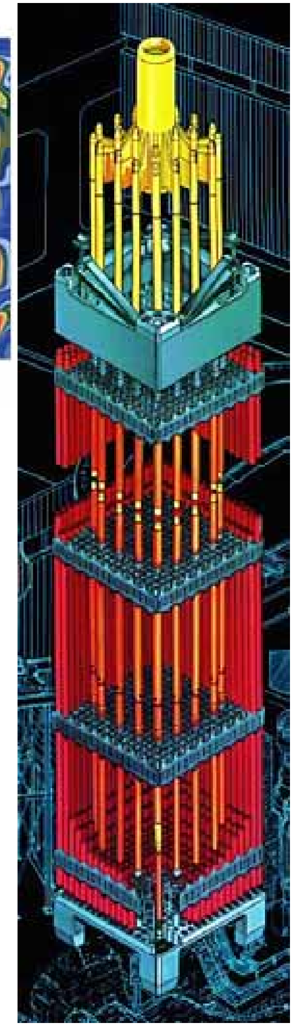
Strong demands on materials
Power per unit area : ITER vs PWR

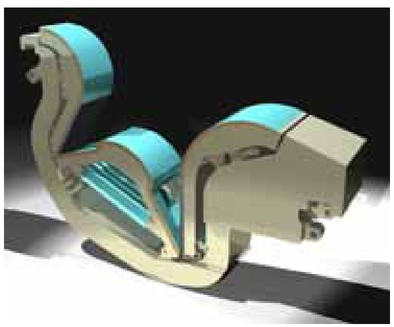


Average Power/Area:
approx. same 0.5 MW/m^2

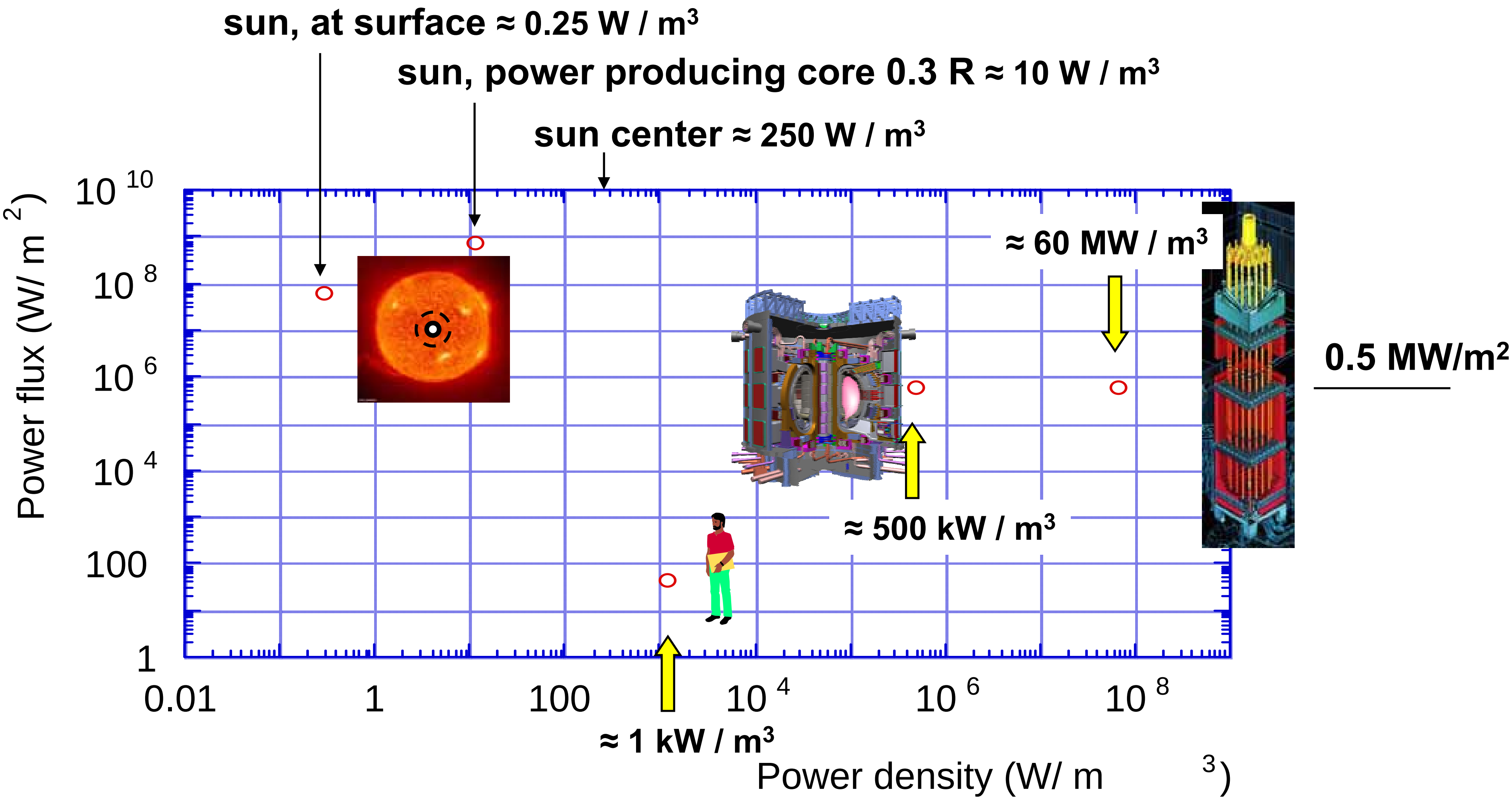
Peaking factor: 10 vs. 2





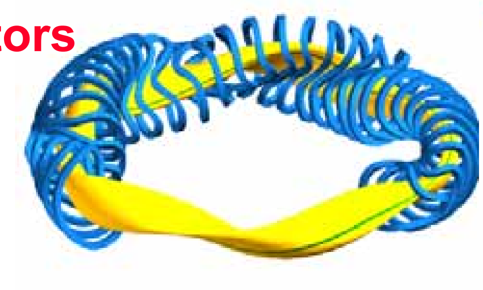


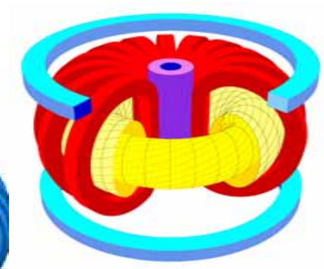
Power flux vs power density



The Fusion Reactor

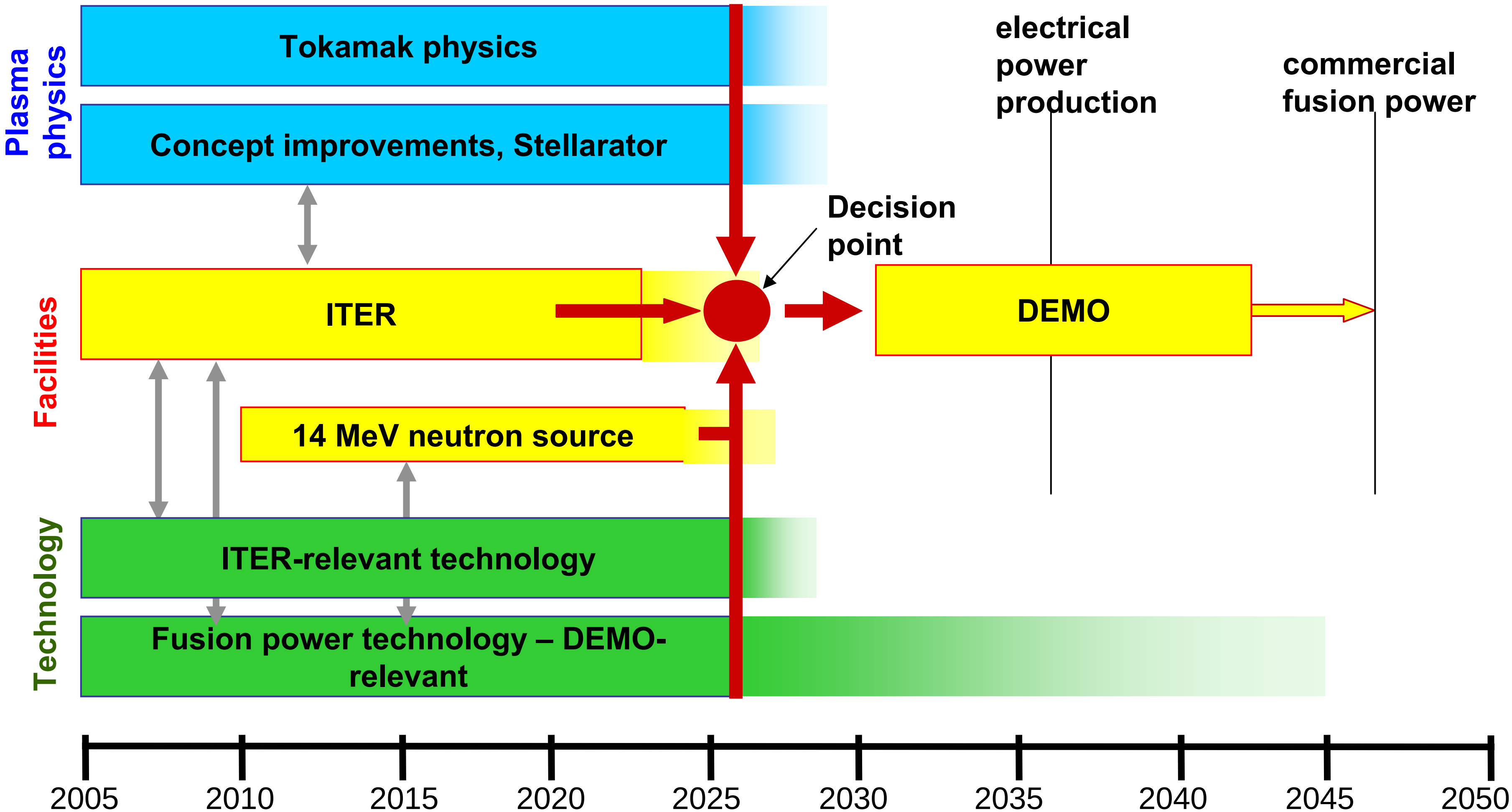
- a reactor may or may not be based on the tokamak concept
  - tokamak presently the best to achieve the fusion conditions
  - other concepts may have advantages as reactors





- fusion has some definite positive points
  - D and Li readily available and not geographically localized
  - about 1 truck load /year necessary for a power plant
  - reaction cannot run away (conditions, fuel inventory a few seconds)
  - largest conceivable accident will not require evacuation
  - no direct emissions (CO_2)
  - final products of the reaction are not radioactive
  - material will be activated by neutrons, but some choices possible

Towards commercial power




• basic principles
• hurdles and achievements
• ITER
• nuclear aspects
• synergy of fission and fusion

Synergy of Fission and Fusion

- nuclear fusion is a nuclear process and will need nuclear engineers
- fission and fusion will only be accepted
  if the public opinion becomes more positive towards nuclear energy
- for public acceptance: critical issues are waste management and safety
- long term fission requires reprocessing and breeders
- fusion could in the long term take over from fission
- for the next decades, there is a strong role for fission
  thereby a one through cycle, without reprocessing would suffice
- this could lead to better acceptance

To Remember

- nuclear fusion has made substantial progress
- we are embarking on the next step: ITER
- ITER will be a nuclear machine
- the prospect of fusion as a long term energy option

  could influence positively the further development of fission