Controlled Nuclear Fusion, a Challenging Task with a Big Payoff

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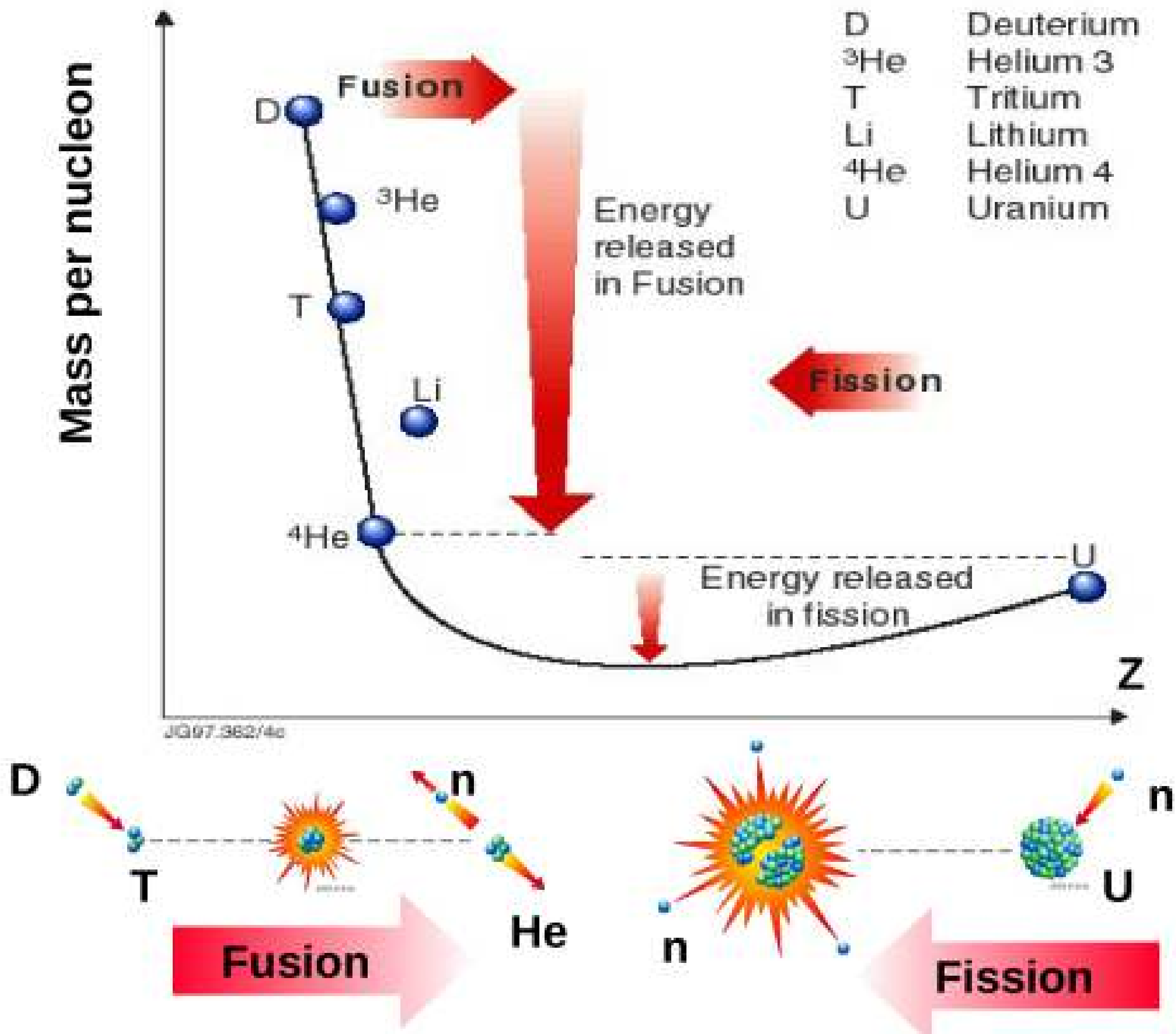
•basic principles
•experimental machines
•the next step ITER
•the future
•synergy of fission and fusion

Fusion and fission work along the same principle
$E = mc^2$



A number of reactions are possible

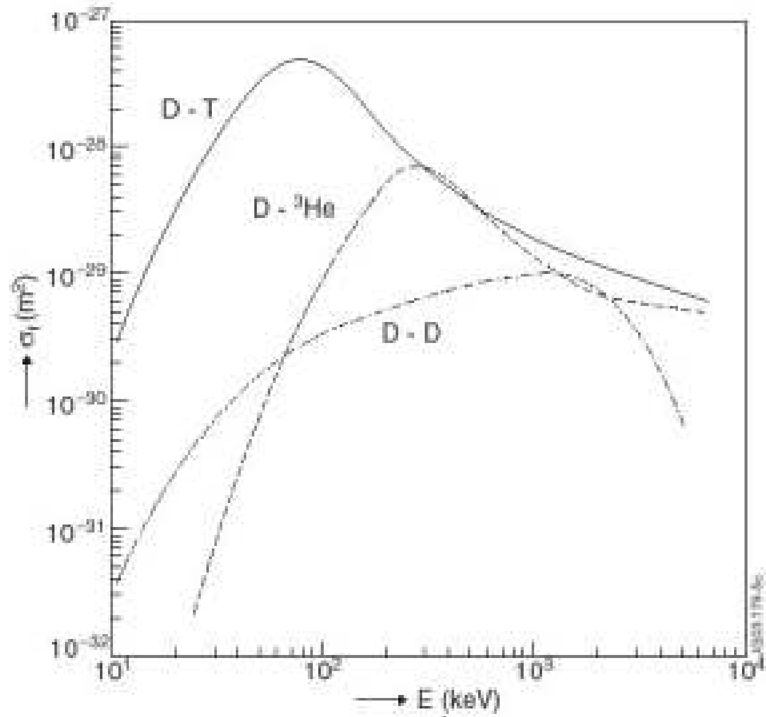
- D + D
- D + ^{3}He
- D + T
- "easiest": "largest" cross section at "lowest" temperature
- D + T

- **D + T -> ^{4}He + n + ΔE**

n + ^{6}Li -> ^{4}He + T

n + ^{7}Li -> ^{4}He + T + n

D + Li -> ^{4}He + 100 x 10^{6} kWh/ kg

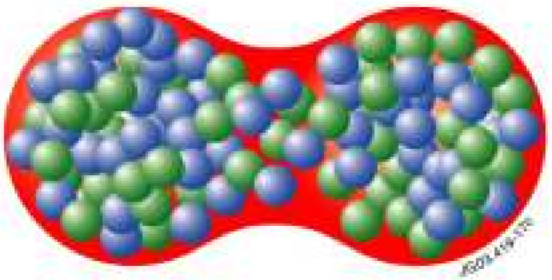


keV

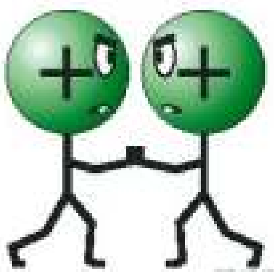
1 eV = 10^{4} K

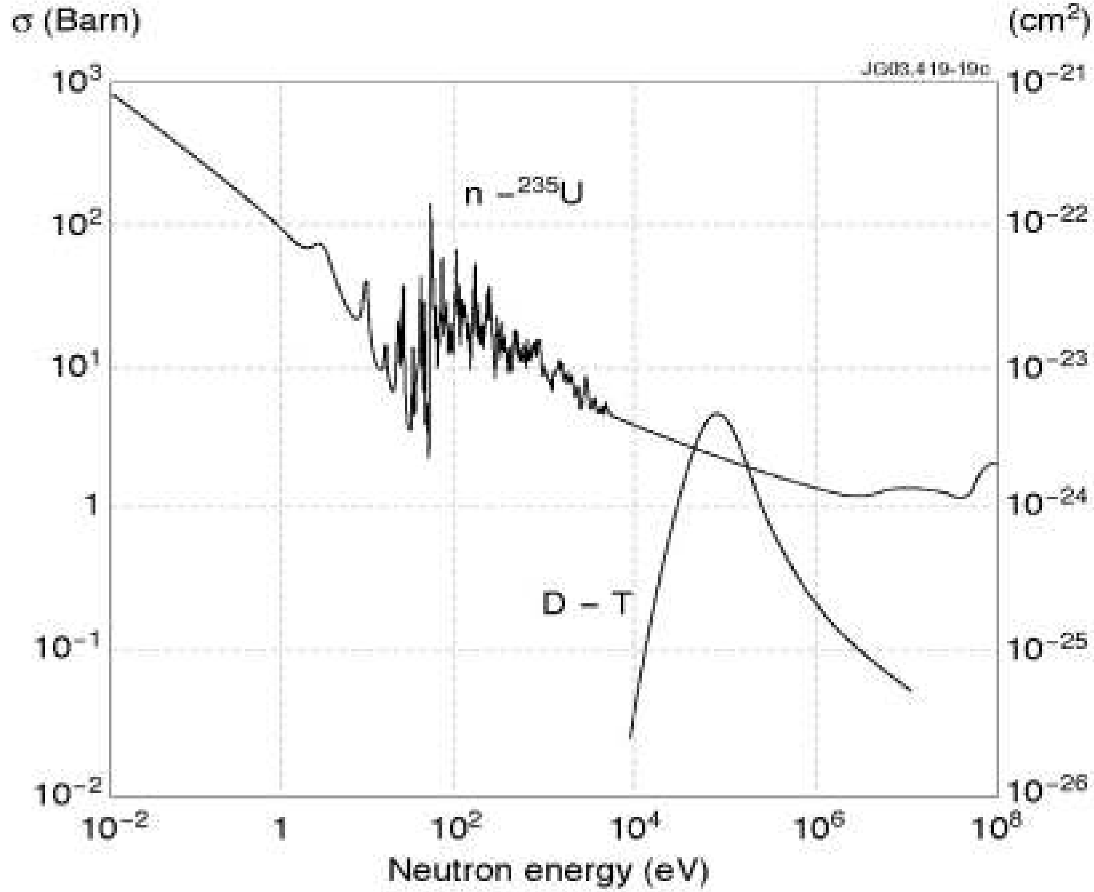
Conditions to achieve the reaction

Fission



Fusion

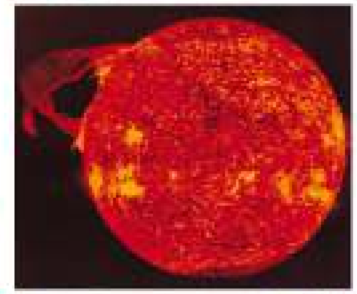


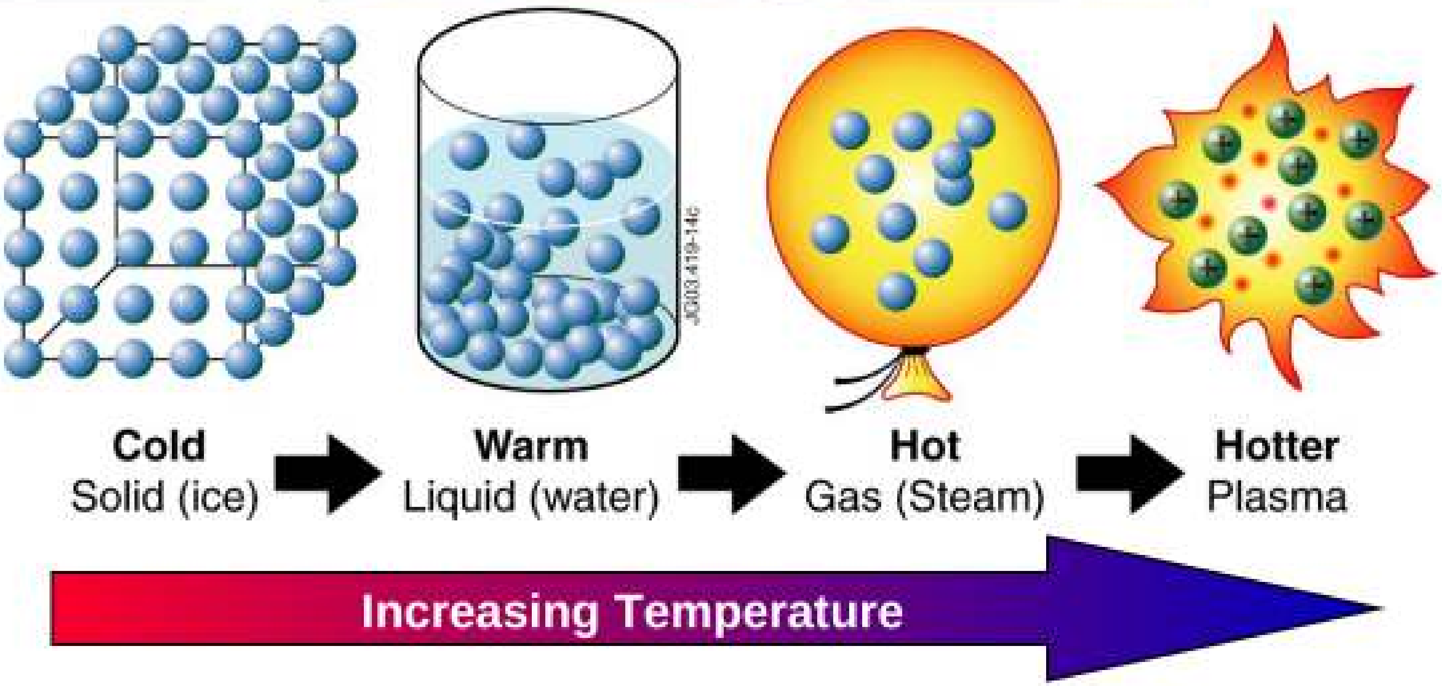


conditions to achieve fusion reaction:

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

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

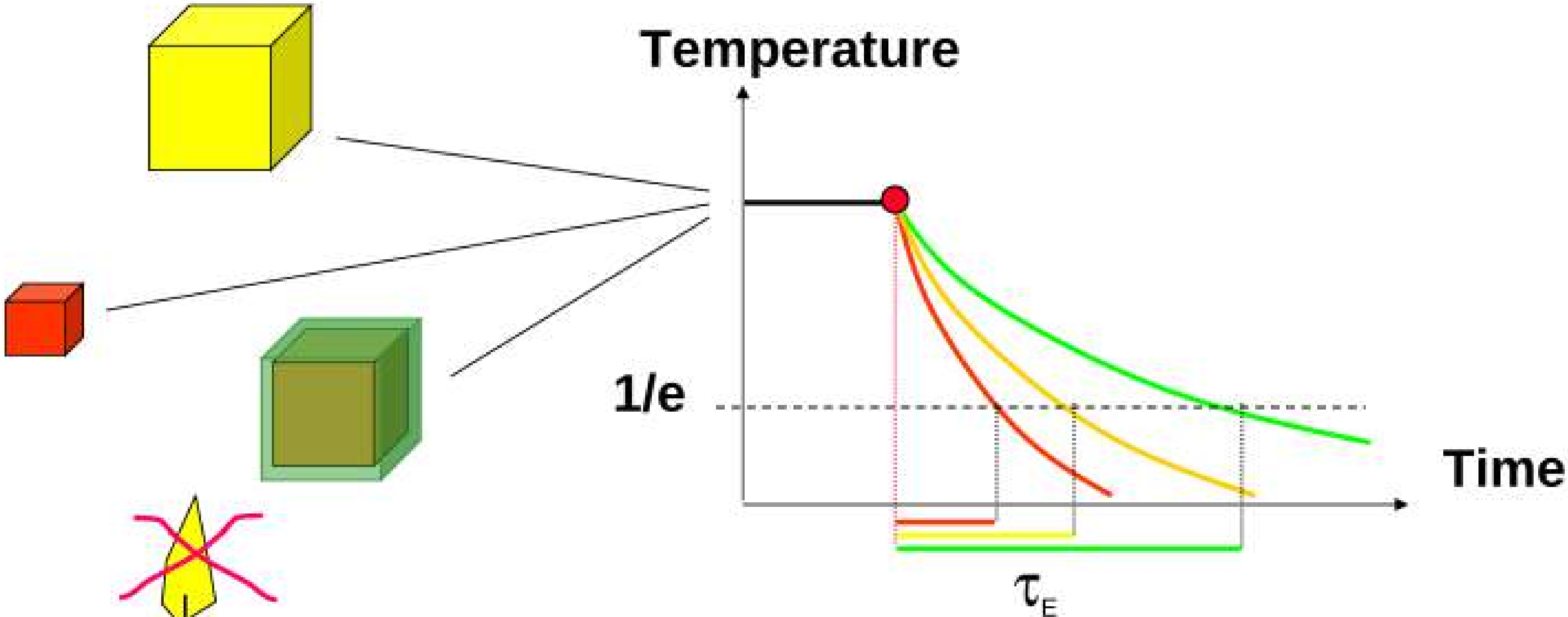
radiation losses $n^2 T^{1/2}$

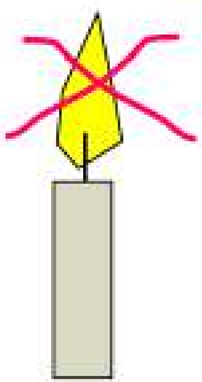
convection and conduction $n T / \tau_E$

n (density) x τ_E (confinement time) > function of T (Temperature)

Lawson Criterium

What is the meaning of the confinement time τ_E?

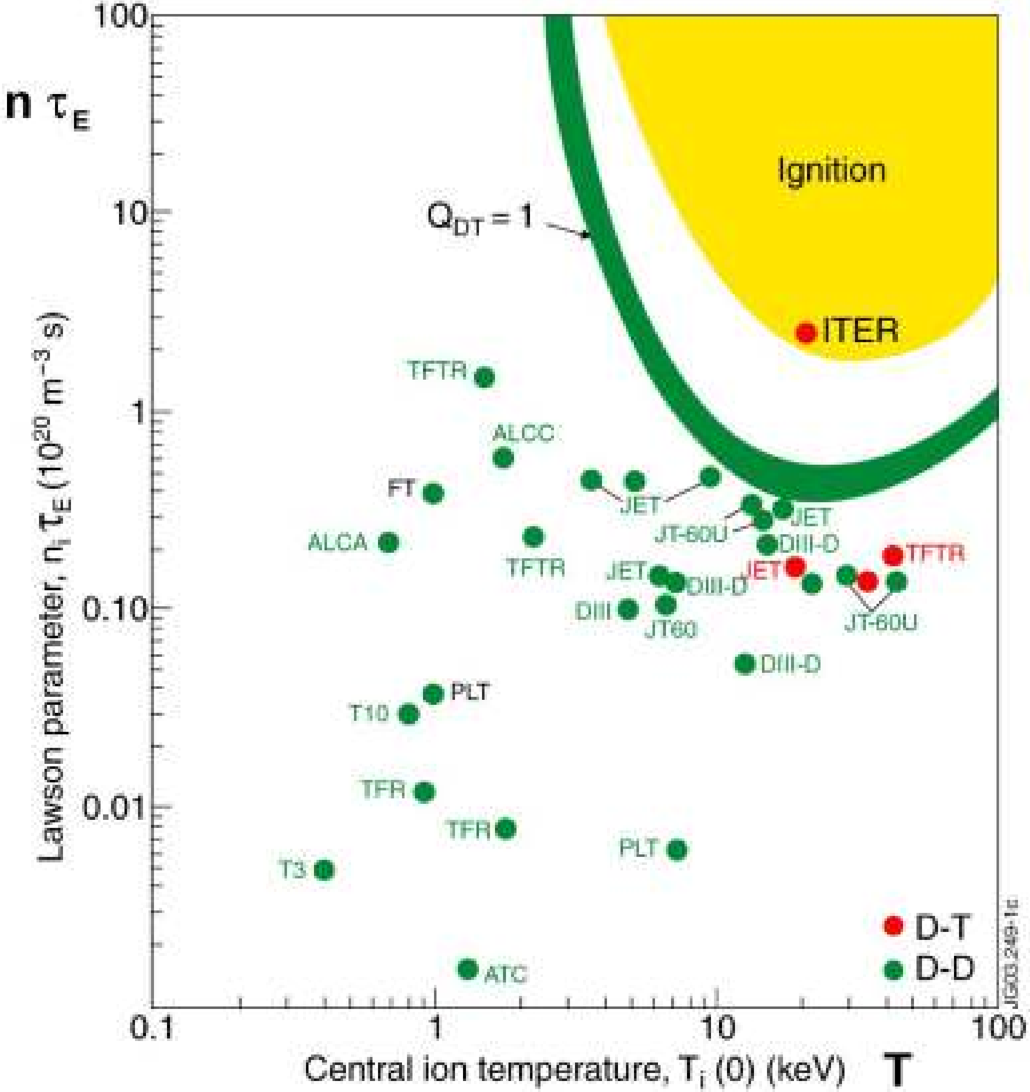




τ_E is a measure of how fast the plasma looses its energy

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

Lawson Criterium



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

(external power = 0)

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

(external power = 0)

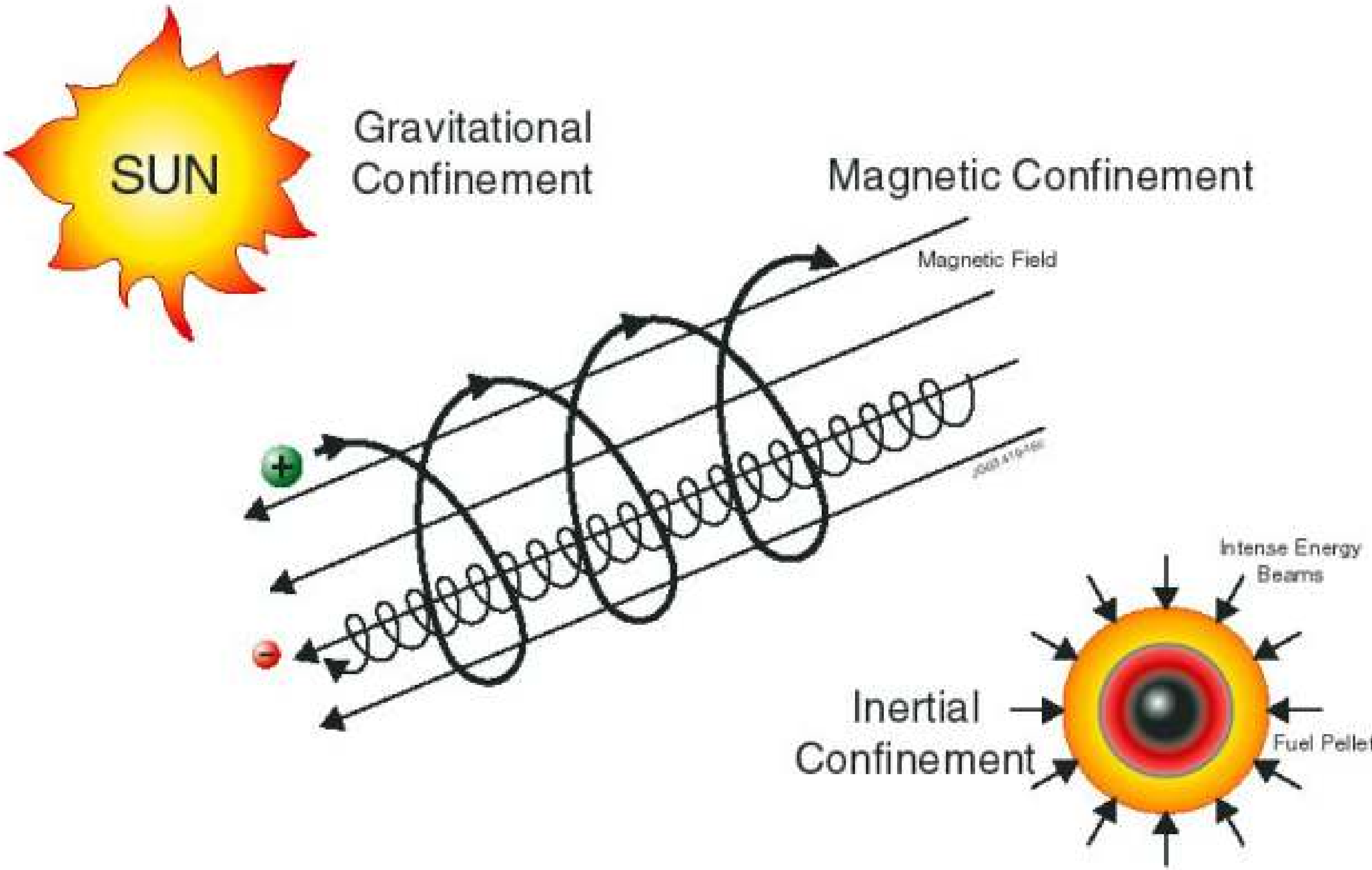
$n \times \tau_E > f(T)$

sometimes
also transformed into

(taking into account temperature dependence near minimum)

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

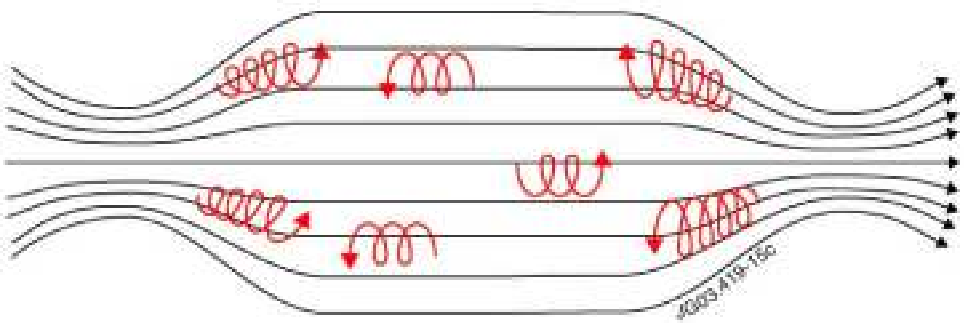
How can a plasma be confined ?



Magnetic confinement

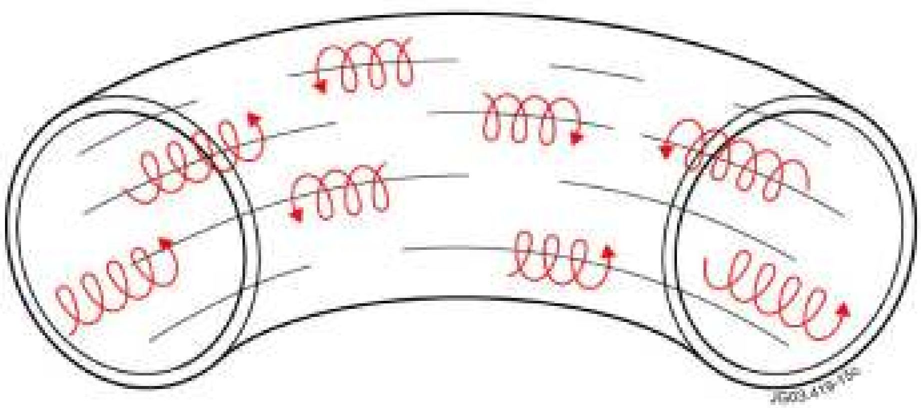
Particles move freely along field lines: how stop the losses in that direction ?

two solutions



- pinching the field lines at the end -> reflection (“mirror”)

-> linear arrangement



- closing the field lines on themselves

-> toroidal confinement

- however: a pure toroidal field does not work

- need a helical field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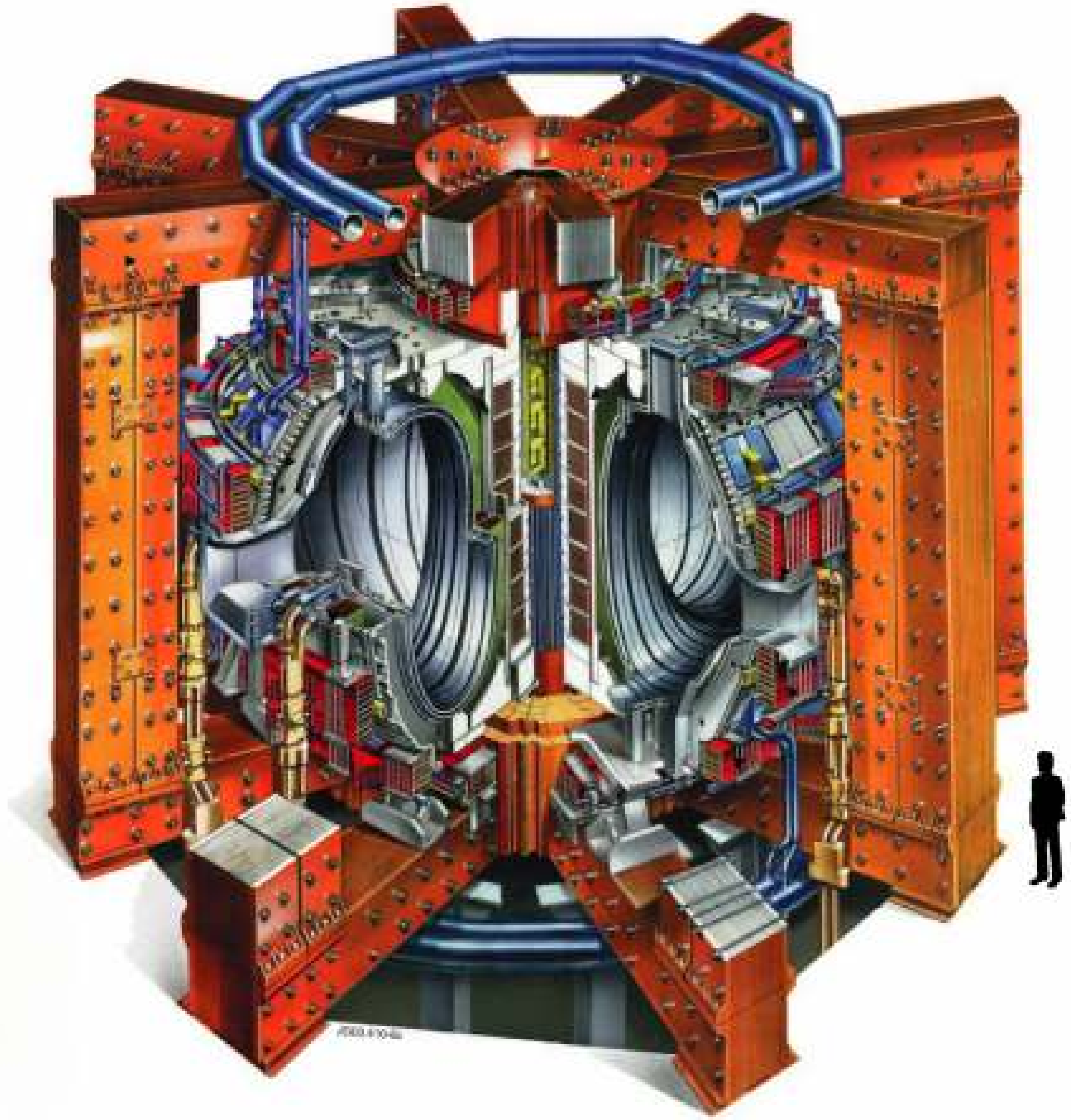
JET: the European Tokamak

- plasma volume
- magn. field.
- plasma current

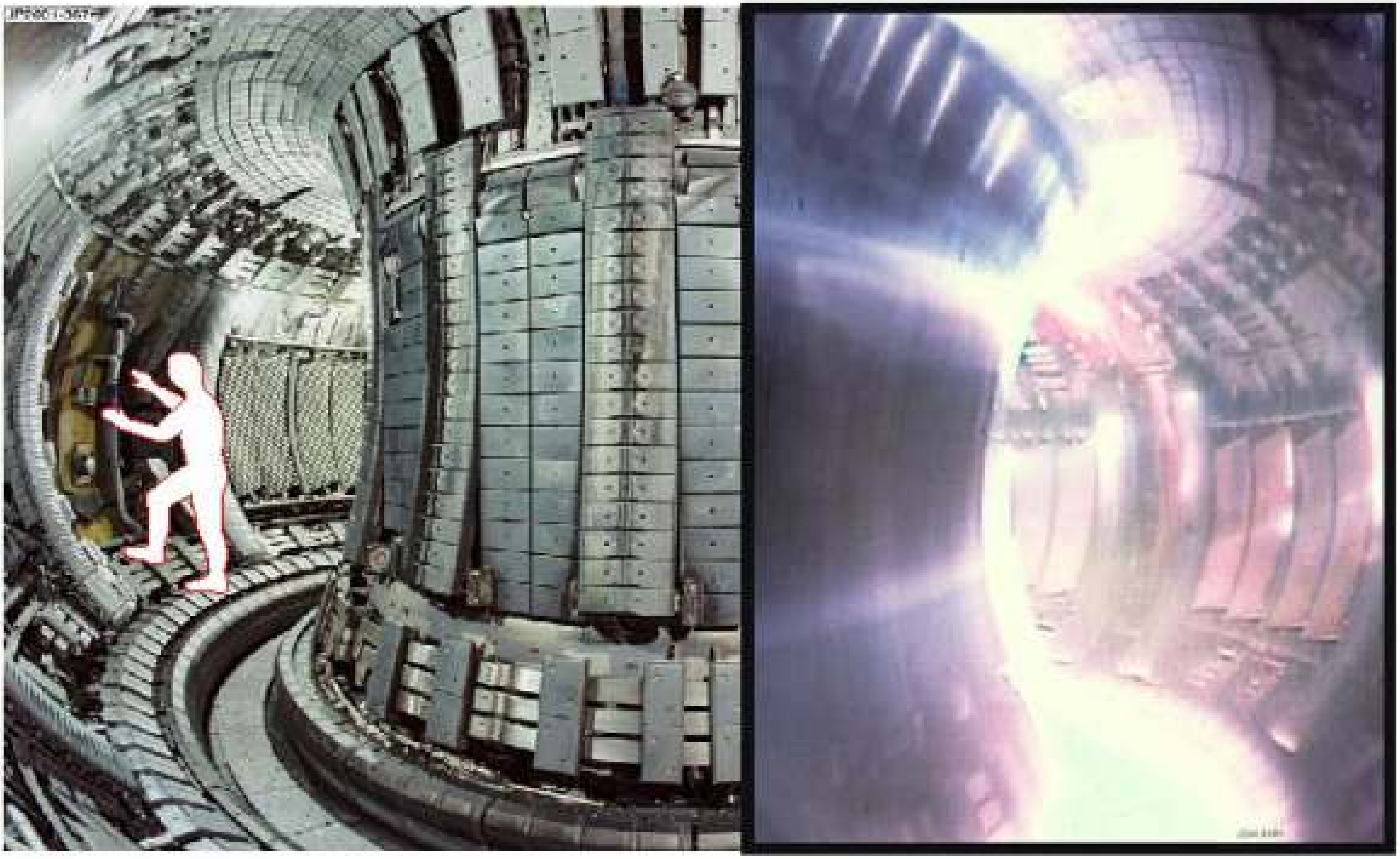


- 60 m^3
- up to 4 T
- up to 5 MA

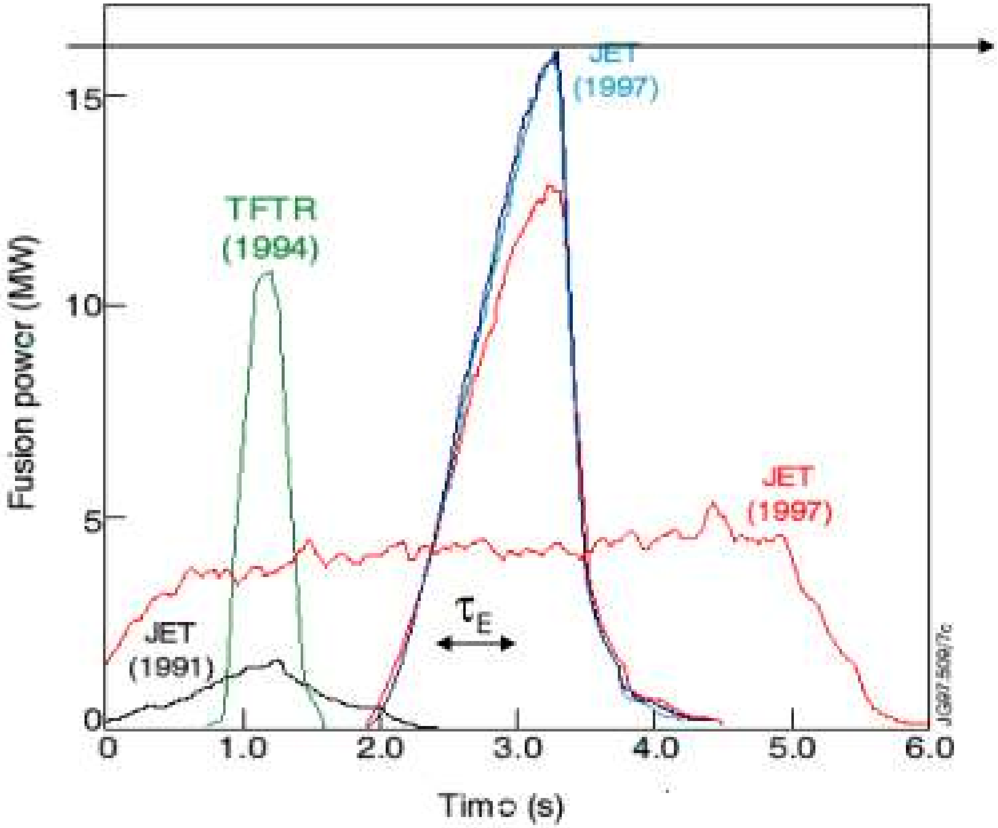
A vacuum vessel octant

The transformer yoke

Inside of JET without and with plasma



What has been achieved ?



16 MW

in a D-T plasma,

with 20 MW input

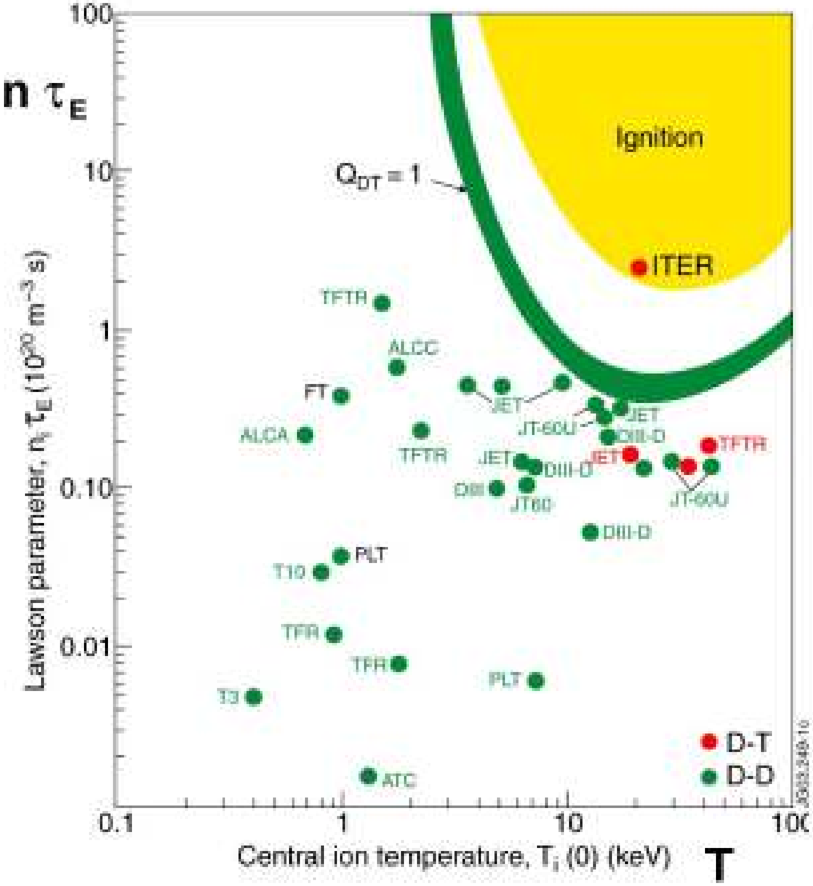
into the plasma

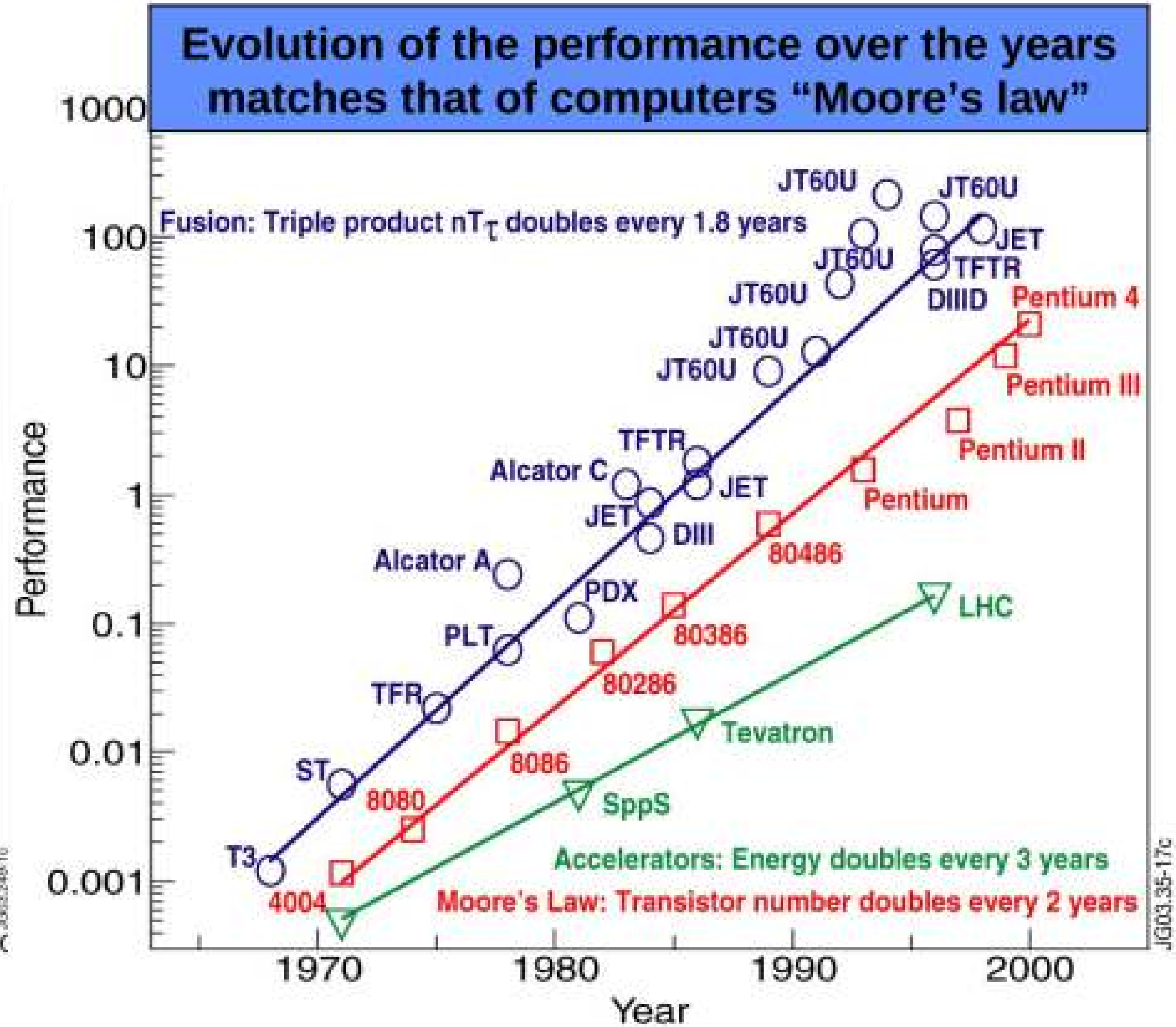
total output : max 16 MW

record (Q = 0.8) but

not yet self sustaining !

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



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ITER ИТЭР

INTERNATIONAL
THERMONUCLEAR
EXPERIMENTAL
REACTOR

国 際 熱 核 融 合
実 験 炉

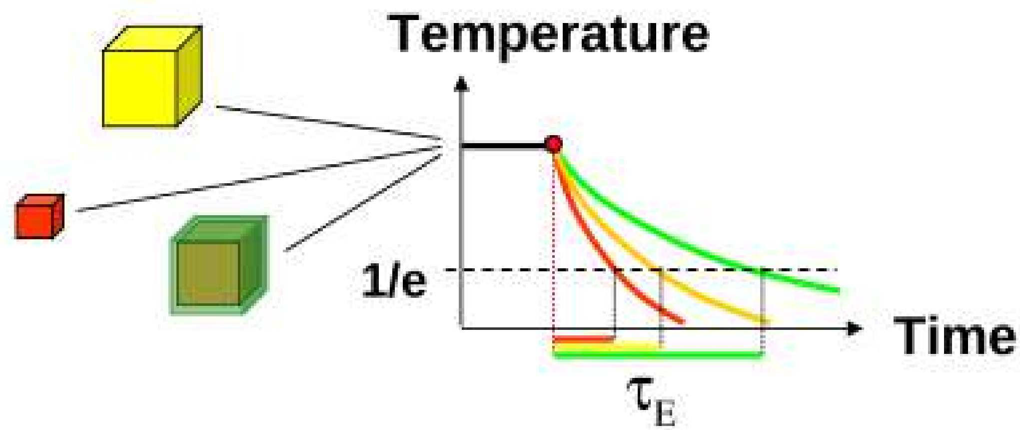
МЕЖДУНАРОДНЫЙ
ТЕРМОЯДЕРНЫЙ
ЭКСПЕРИМЕНТАЛЬНЫЙ
РЕАКТОР

We need a larger machine

- for a sustained reaction : $n\,\tau_E > f\,(T)$

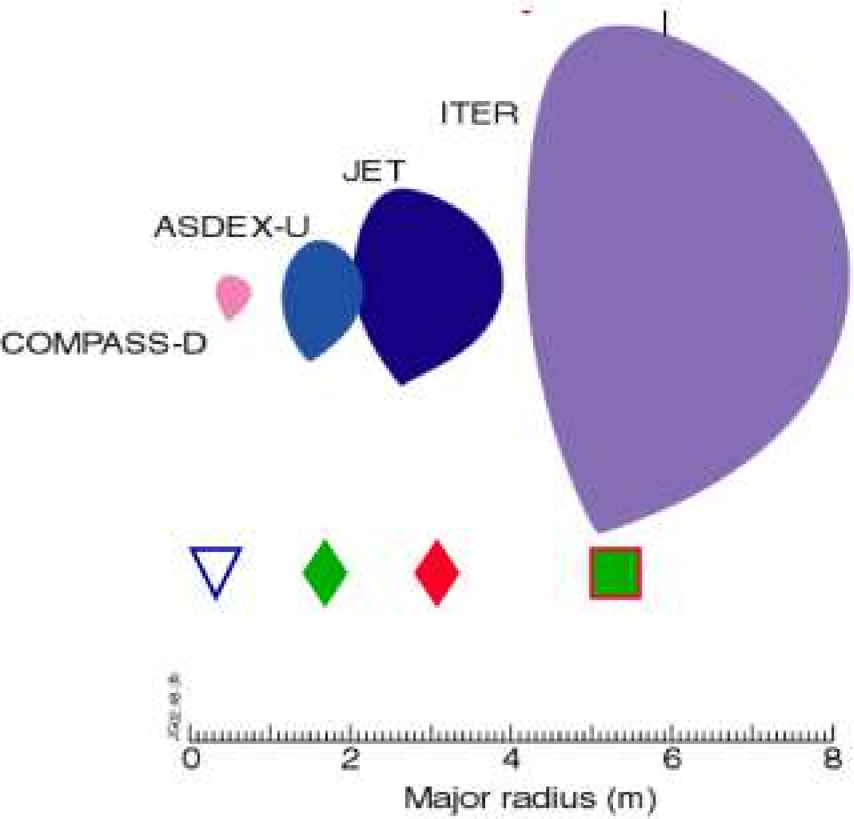
we need a larger confinement time

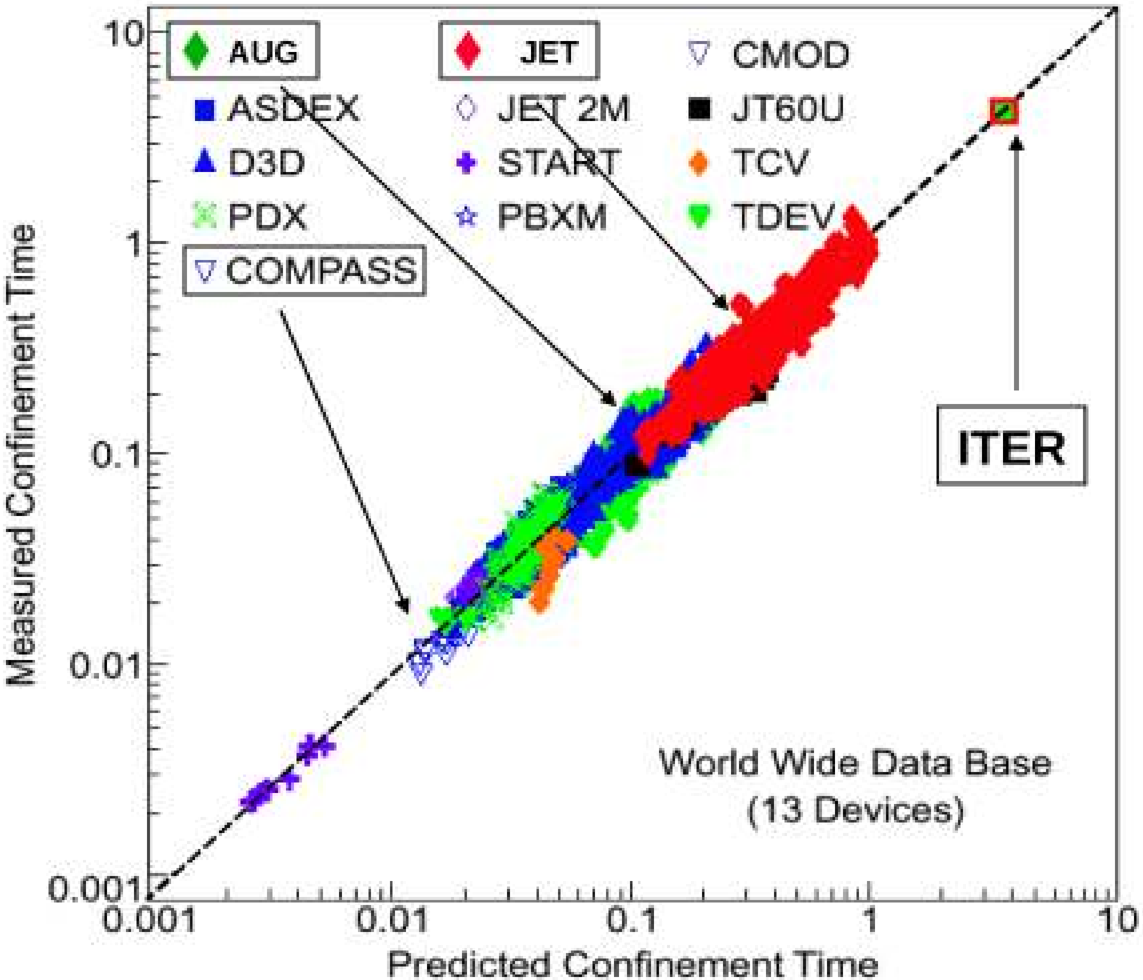
thus
- better insulation
- larger machine



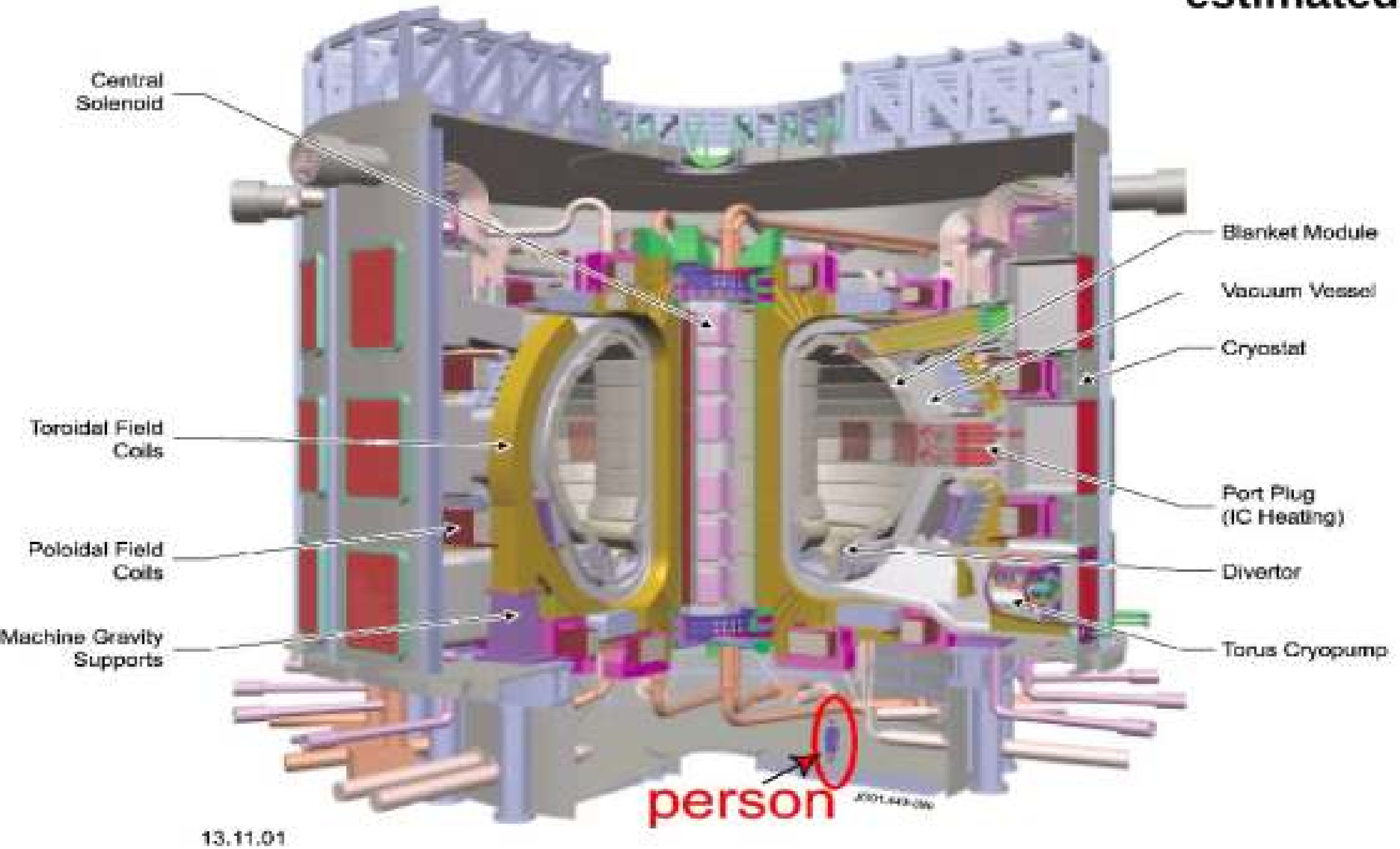
how much larger ?

Size from scaling laws





ITER



estimated cost :

4 000 Million Euro

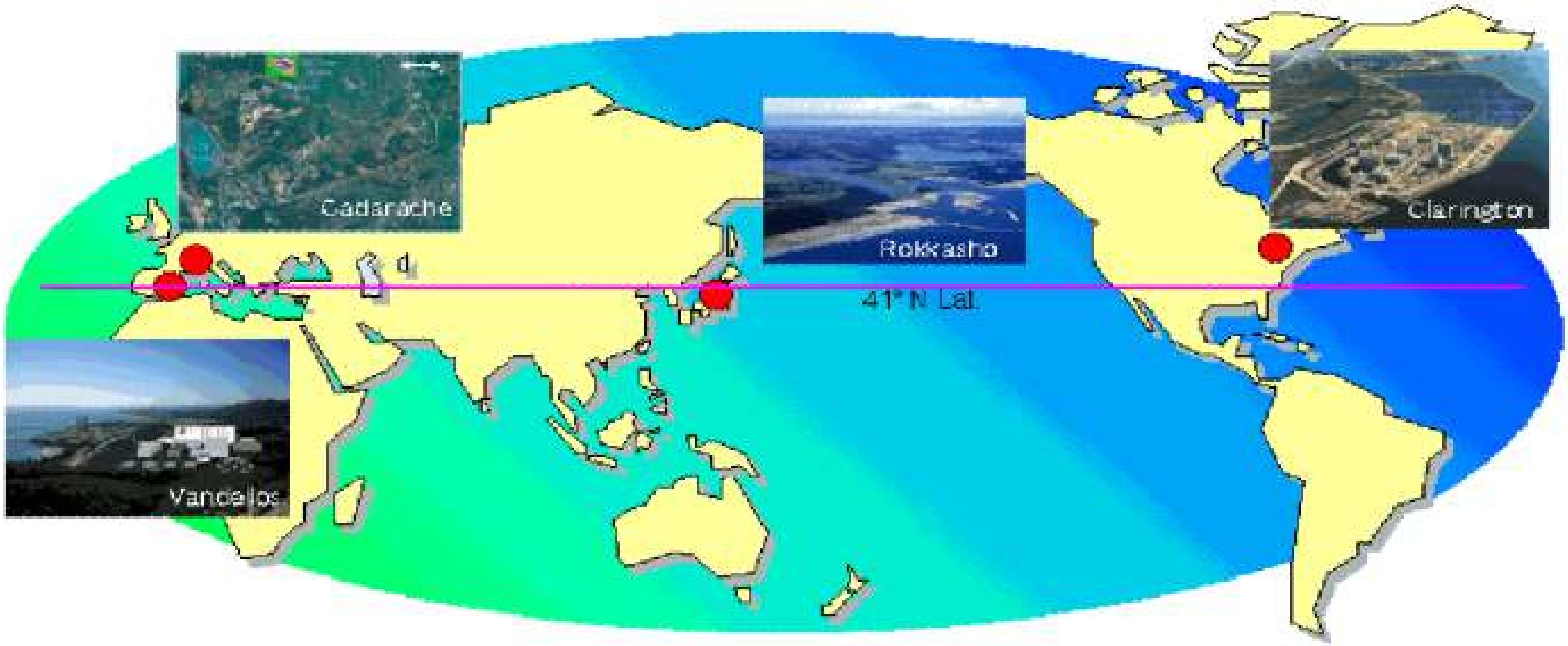
R (m)	6.2
a (m)	2
V_p (m^3)	850
I_p (MA)	15(17)
B_t (T)	5.3
δ,κ	0.5, 1.85
P_{aux} (MW)	40-90
P_α (MW)	80+
Q (P_{fus}/P_{in})	10
β_T, β_P	2.5%, 0.7

ITER will be a nuclear machine: 1.5×10^{20} neutrons/s

Status

- international negotiations for a choice of the site
- and the legal framework for setting up this enterprise

4 candidate sites

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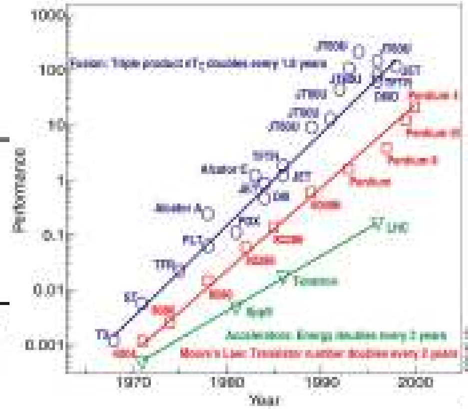
Timeline



Fermi Nobel Prize (radioactivity)	1938
Fisson: Hahn, Meitner & Strassmannn	1939
Chicago Pile	1942
Atomic Bomb	1945
First US Nuclear Electricity	1951
First USSR Nuclear Electricity	1954
Commercial exploitation	1956
Realisation that fusion powers the stars (Eddington)	1920
Reaction Rate Calculated (Bethe)	1938
Ware Pinch (Thoneman and Thomson)	1947
Thernonuclear Bomb Test	1952
Geneva Conf. Declassification	1958
Bethe Nobel Prize	1967
T3 Results	1968
JET Joint Undertaking	1997
JET- EFDA	2000-2005 - ?
ITER Contruction	? 2004 - 2014
ITER Life	? 2014 -2030
Fusion Reactor	? 2030 -

Today

More than 400 Reactors built

6 % of Total World Energy

1 keV temperature achieved

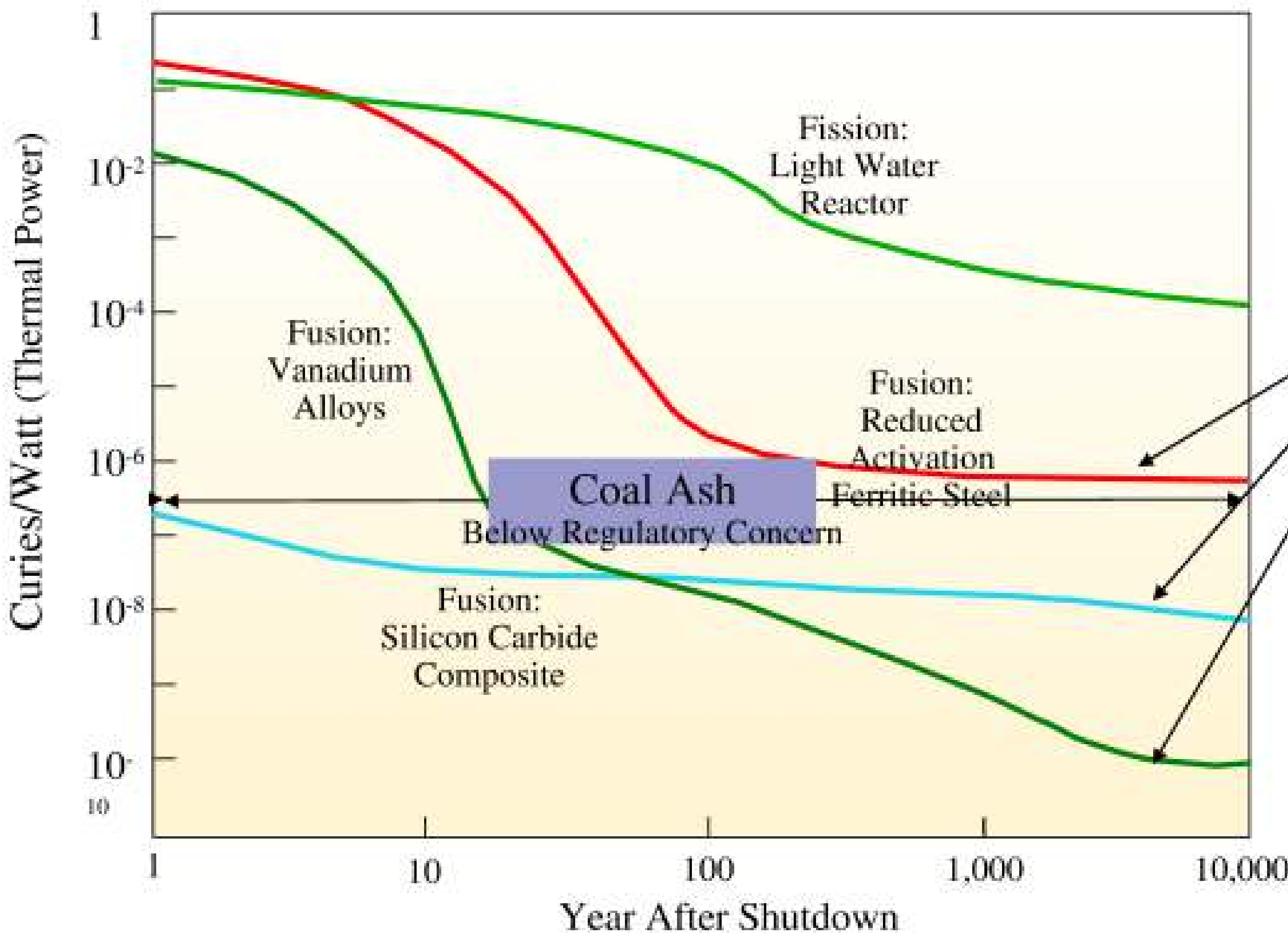
1997 16 MW of Fusion Power

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 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

Choice of Material for Fusion



- **Radioactive waste not inherent to the reaction**
- **several choices possible**

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Synergy of Fission and Fusion

- nuclear fusion is a nuclear process and you have the expertise
- fission and fusion will only be accepted if public opinion becomes more positive towards nuclear energy
- for public acceptance: critical issue is waste management
- long term fission requires reprocessing and breeders
- fusion could in the long term take over from fission
- thus fission can work for the next decades

with a one through cycle and no reprocessing -> better acceptance

To Remember

- nuclear fusion has made substantial progress
- we are ready to make the next step: ITER
- ITER will be a nuclear machine, we will need your experience
- the prospect of fusion as a long term energy option could influence positively the further development of fission