EE80J: Introduction to Renewable Energy Sources

EE180J: Advanced Renewable Energy Sources

Lecture 12

read Goodstein. pg 101–end /

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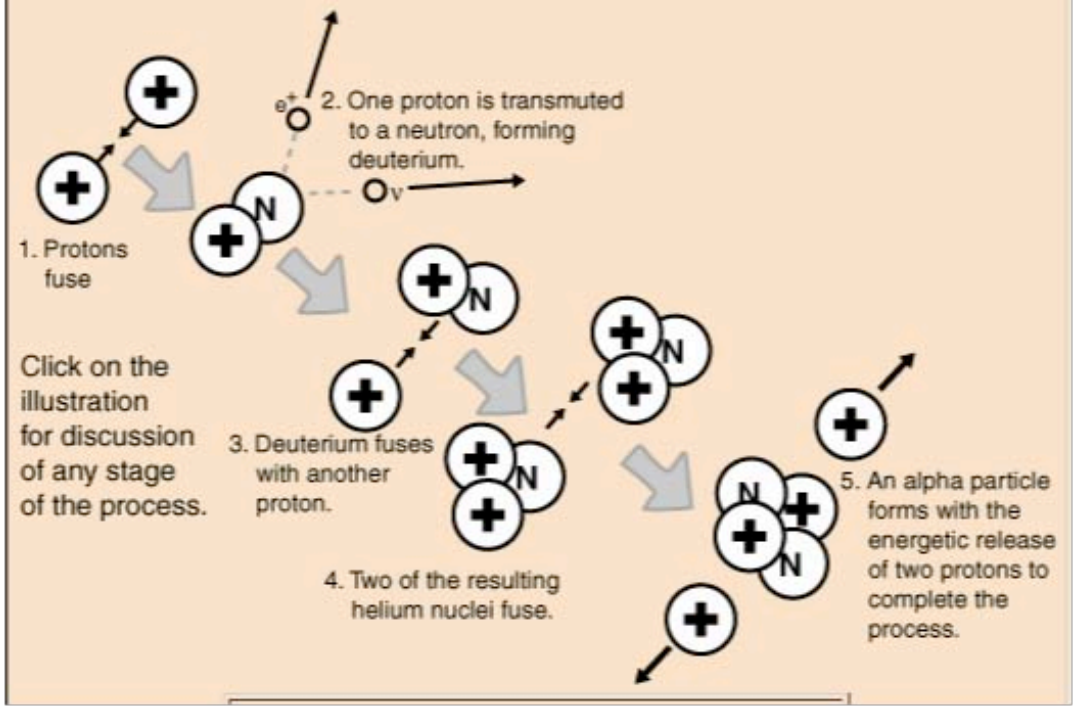
Proton-Proton Fusion

This is the nuclear fusion process which fuels the Sun and other stars which have core temperatures less than 15 million Kelvin. A reaction cycle yields about 25 MeV of energy.



http://hyperphysics.phy-astr.gsu.edu/hbase/astro/procyc.html

Nuclear Fusion

just opposite of nuclear fission!

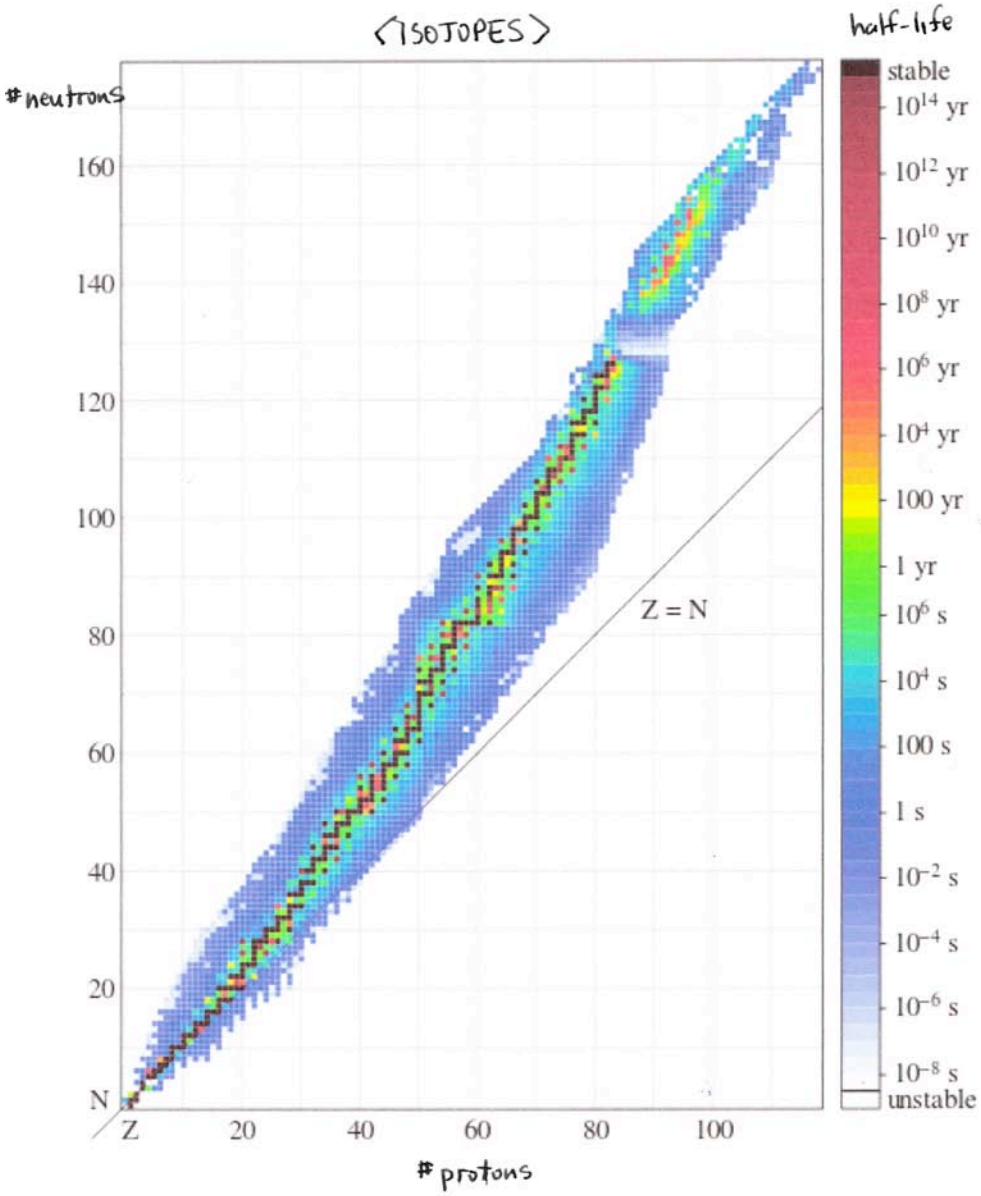
why the interest?

1. potentially plentiful supply of fuel

2. reactions easier to control ∴ less dangerous

3. minimal radioactive by products

BUT decades away from feasibility demo!


<ISOTOPES>
half-life
neutrons
160
140
120
100
80
60
40
20
N
Z
20
40
60
80
100
# protons
Z = N
stable
10^{14} yr
10^{12} yr
10^{10} yr
10^{8} yr
10^{6} yr
10^{4} yr
100 yr
1 yr
10^{6} s
10^{4} s
100 s
1 s
10^{-2} s
10^{-4} s
10^{-6} s
10^{-8} s
unstable

Nuclear Fusion. 1.

simplest / $p + p \rightarrow d + e^+ + \nu_e$ | $d = {}^2He$, nucleus of He or nucleus of D

DIFFICULT

energy / $E = Q = 2m_p - m_d - m_e$ $(m_{\nu_e} = 0)$

$Q = 0.42\ MeV$ produced.

generally:

$e^+ + e^- \rightarrow 2\gamma$ $(E = 1.02\ MeV)$

also can get $d + p \rightarrow {}^3He + \gamma$, $Q = 5.49\ MeV$

$d + d \rightarrow {}^4He + \gamma$, $Q = 23.8\ MeV$

not very likely.

and $d + d \rightarrow {}^3He + n$ $Q = 3.3\ MeV$

$\rightarrow {}^3H + p$ $= 4\ MeV$

or $d + {}^3H \rightarrow {}^4He + n$, $Q = 17.6\ MeV$ | more likely

t (${}^3H$ nucleus)

in SUN / ${}^3He + {}^3He \rightarrow {}^4He + 2\,{}^1H + \gamma$ $(Q = 12.86\ MeV)$

85% of energy from Sun!!

NOTE / d occurs naturally on earth

t does not / ½ life ~ 12 yrs!!

Nuclear Fusion. 2.

At present, most ^1H nuclei in Sun are <u>unreacted</u>!

Could we reproduce SUN in the lab?

in SUN $\sim 10^{57}$ p $\Longrightarrow \frac{E_T}{sec} \approx 3.8 \times 10^{26}$ watt
$\cong 3.8 \times 10^{26}$ Joule/sec !!

along with $p + p \rightarrow d + e^+ + \nu_e$
we have many reactions going on in Sun.

entire cycle is COMPLEX

but when one works out the entire cycle
one gets a $Q = 26.7$ MeV release
$= 4 \times 10^{-12}$ Joules !!

$\therefore$ # pp reactions cycles/sec

$$= \frac{3.8 \times 10^{26} \text{ Joule/sec}}{4 \times 10^{-12} \frac{\text{Joule}}{\text{cycle}}} \approx 10^{38} \text{ pp cycles/sec}$$

which corresponds to about
4×10^{38} protons fused/sec

Nuclear Fusion. 3

since 10^{57} p in the sun,

then

$$1 \text{ in } \frac{10^{57}}{4 \times 10^{38}} = 1 \text{ in } 2.5 \times 10^{18}$$ as fractions of proton fusing / sec!

∴ if sun produced energy at constant rate it would exist for 2.5×10^{18} sec before it burnt up — 80B years!

∴ it would take 80B years to extract all the energy //

SO we need to look at other reactions or lasts all

Feasibility of a d-d reactor

deuterium occurs naturally

atomic % = 0.0156 % / wt % = .000312 since $A_d = 2A_H$ atomic

mass of water in oceans is:

$$m = (1.3 \times 10^9 \, km^3) \times (10^9 \, m^3/km^3) \times (10^6 \, g/m^3)$$

$$= 1.3 \times 10^{24} \text{ gms } (H_2O)$$

$$\therefore m_H = \underbrace{\frac{2}{2+16}}_{\frac{H}{H_2O}} \times m = 1.44 \times 10^{23} \text{ gm Hydrogen!}$$

$$\therefore m_d = 1.44 \times 10^{23} \text{ gm} \times .000312$$

$$= 4.49 \times 10^{19} \text{ g deuterium}$$

$$= 1.35 \times 10^{43} \text{ atoms of deuterium in ocean}$$

each fusion gives 3.3, 4.0 MeV of energy

take avg = 3.6 MeV / fusion

each fusion takes 2 deuterium atoms

$$\therefore \frac{1.35 \times 10^{43}}{2} = 6.76 \times 10^{42} \text{ fusions available}$$

$$= 6.76 \times 10^{42} \times 3.6 \frac{\text{MeV}}{\text{fusion}} \times \frac{1.6 \times 10^{-13} \text{ J}}{\text{MeV}}$$

$$= 3.9 \times 10^{30} \text{ J available from ocean!}$$

current energy use $\approx 5.7 \times 10^{20}$ J/yr $\Longrightarrow$

$\therefore$ energy contents will last 6.8×10^9 years!

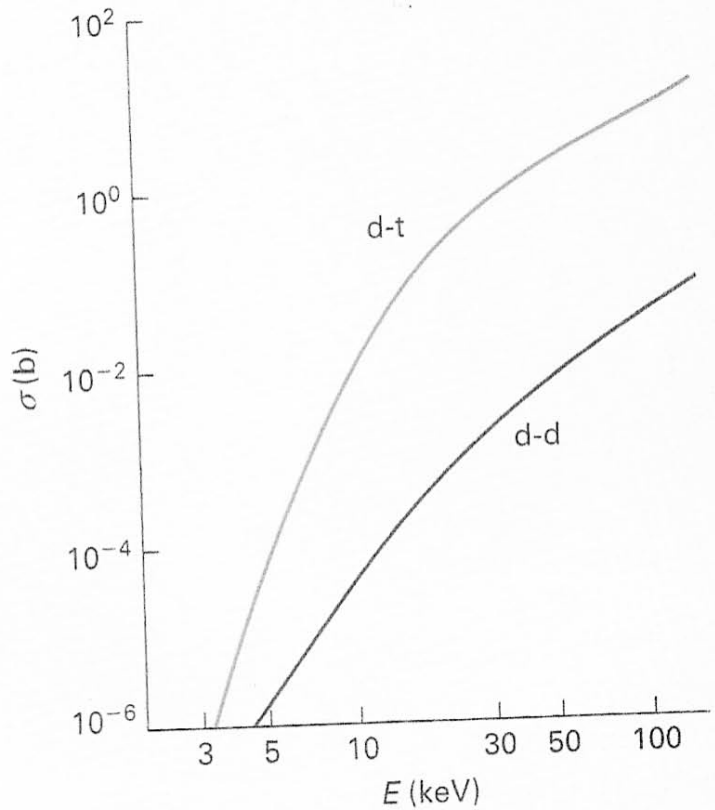


Figure 7.1: Fusion cross sections as a function of energy for d-d and d-t reactio
(b = barns; 1 b = 10^{-28} m^2)

Nuclear Fusion 4.

dt reactions ~ 10x more probable than dd —

∴ look at such reactions as candidates for a lab fusion reactor

NOTE / as T rises, so does the KE of the particles AND probability of reaction

(think of cold vs hot water)

to get appreciable probability of fusion need energy of about 10 keV

this corresponds to $T \approx 10^8$ °K !!!

how to achieve this?

magnetic OR inertial confinement!

DECADES for construction —

MUST get $E_{OUT} > E_{IN}$

ITER goals 500 MW out / 50 MW in

Nuclear Fusion 4.

dt reactions ~ 10x more probable than dd —

∴ look at 1mb reactions as candidates for a lab fusion reactor

NOTE / as T rises, so does the KE of the particles AND probability of reaction

(think of cold vs hot water)

to get appreciable probability of fusion need energy of about 10 keV

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how to achieve this?

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Nuclear Fusion 4.

dt reactions ~ 10x more probable than dd —

∴ look at light reactions as candidates for a lab fusion reactor

NOTE / as T rises, so does the KE of the particles AND probability of reaction

(think of cold vs hot water)

to get appreciable probability of fusion need energy of about 10 keV

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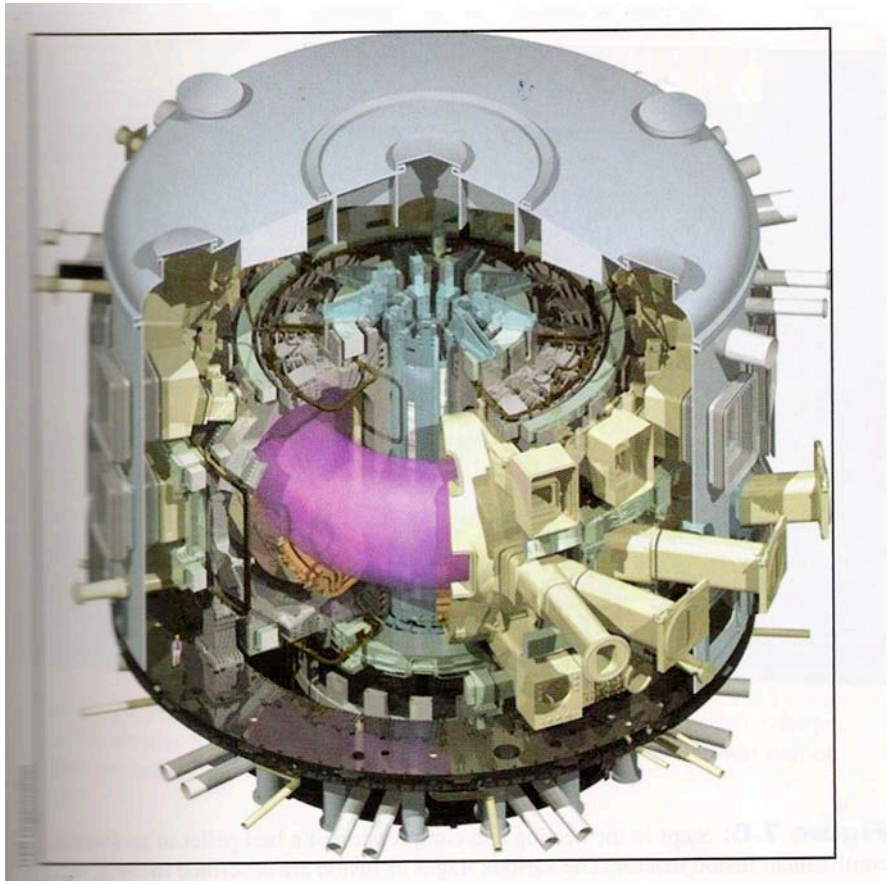

ITER Reactor,

South of France

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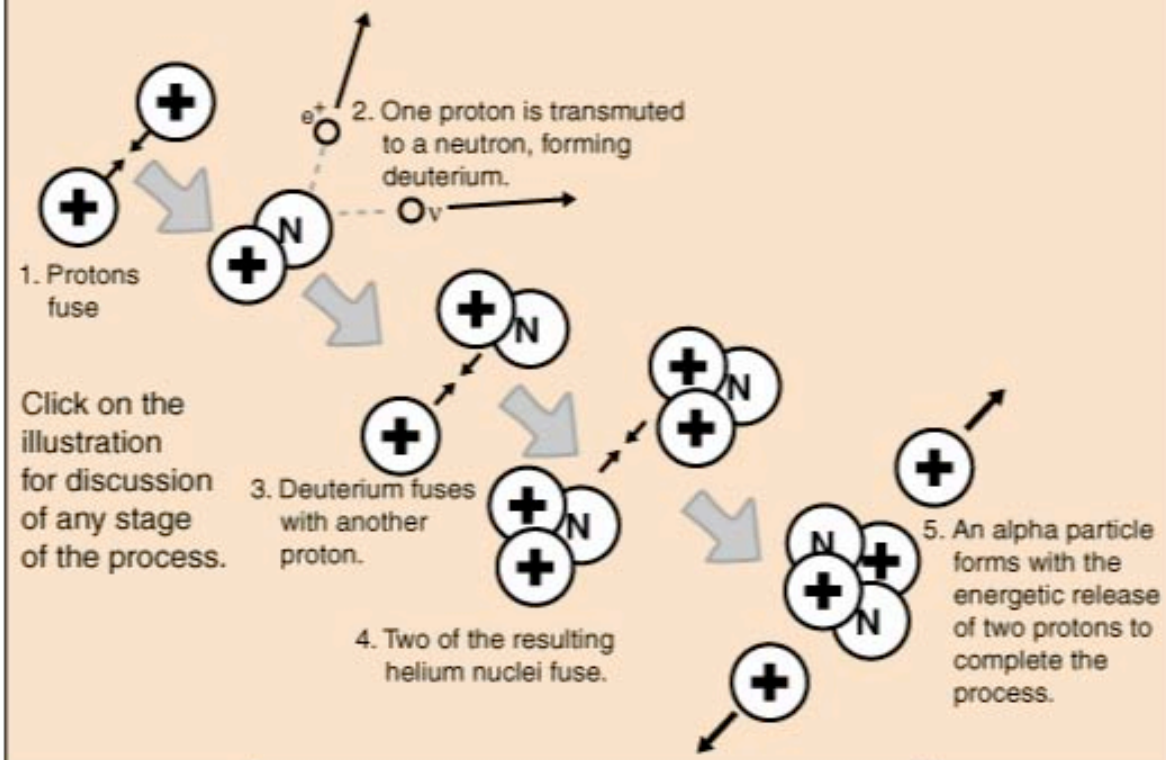
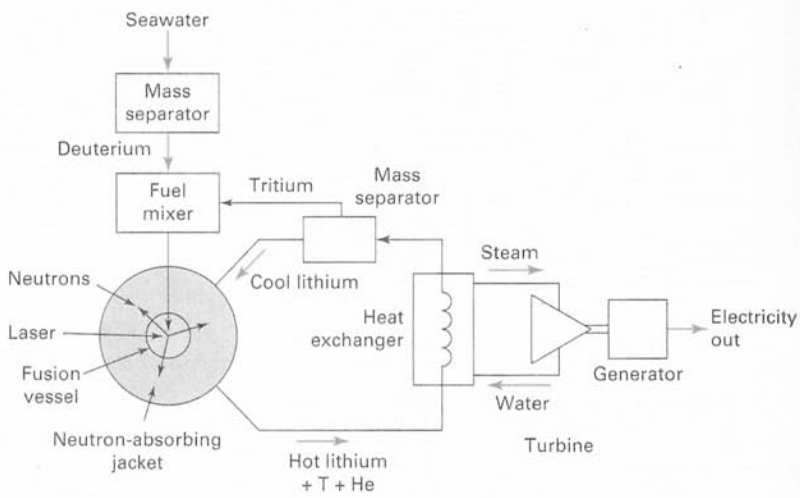




Belmont (2004).

Figure 7.11: Proposed inertial confinement fusion reactor for the production of electricity.

natural Li
vs 7% ^6Li, 93% ^7Li

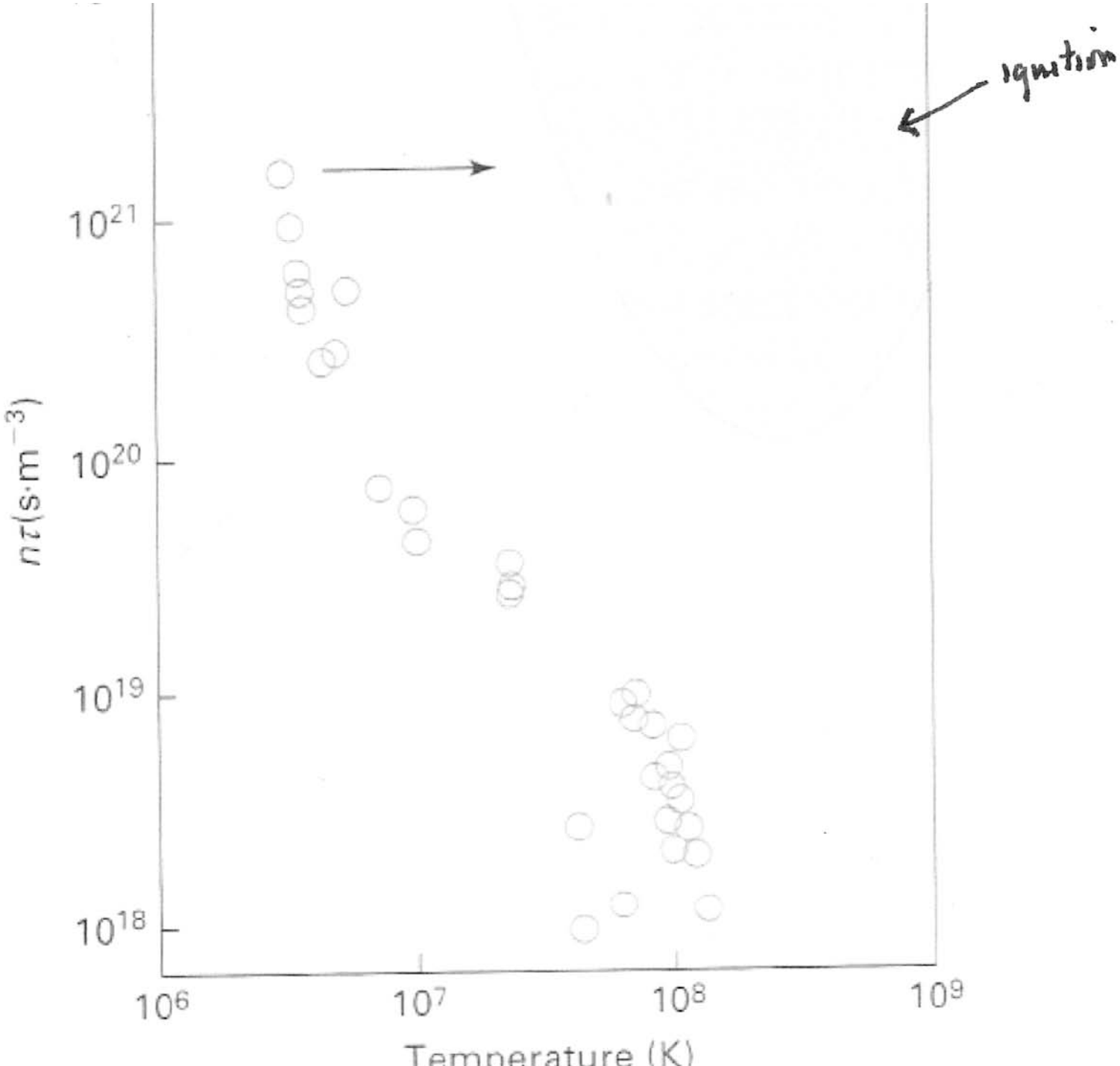
$^6Li + n \rightarrow {}^3H + {}^4He$

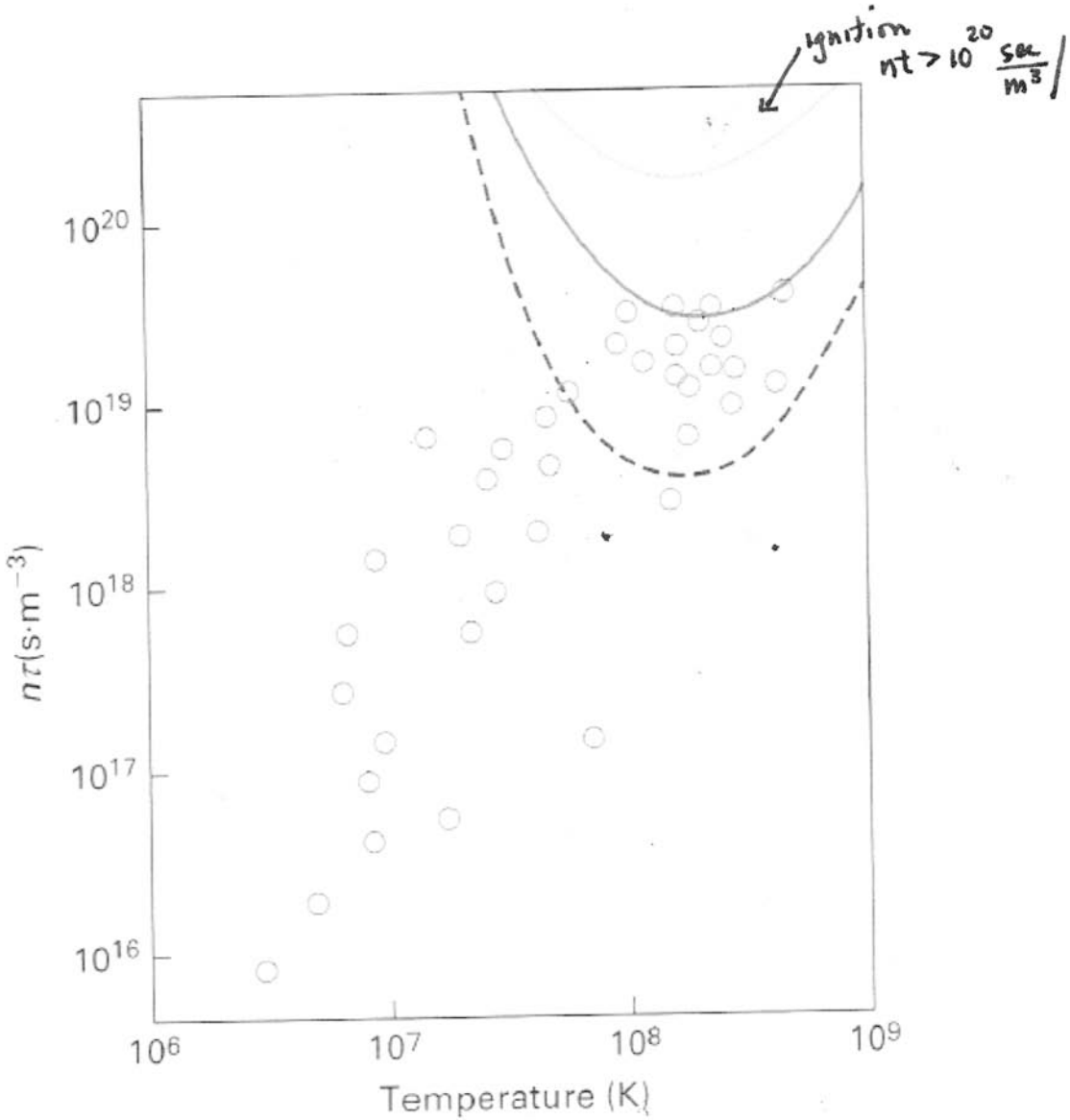
$Q = 4.78\,MeV$

produces tritium T (^3H)

inertial confinement

fuel confined by inertial forces

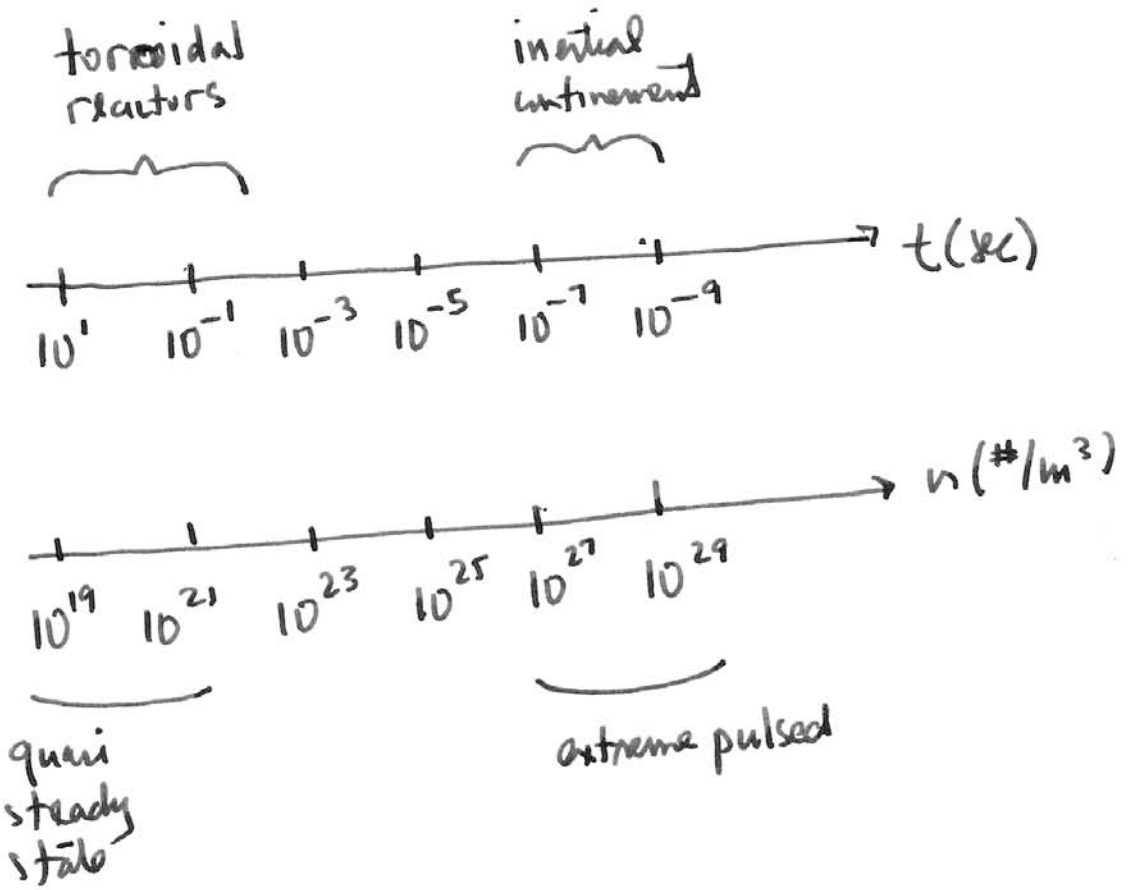

ignition
10^{21}
10^{20}
10^{19}
10^{18}
$n\tau(\mathrm{s \cdot m^{-3}})$
10^6
10^7
10^8
10^9
Temperature (K)



magnetic confinement reactors

$nt > 10^{20}$ sec/m^3

to sustain a fusion reaction.



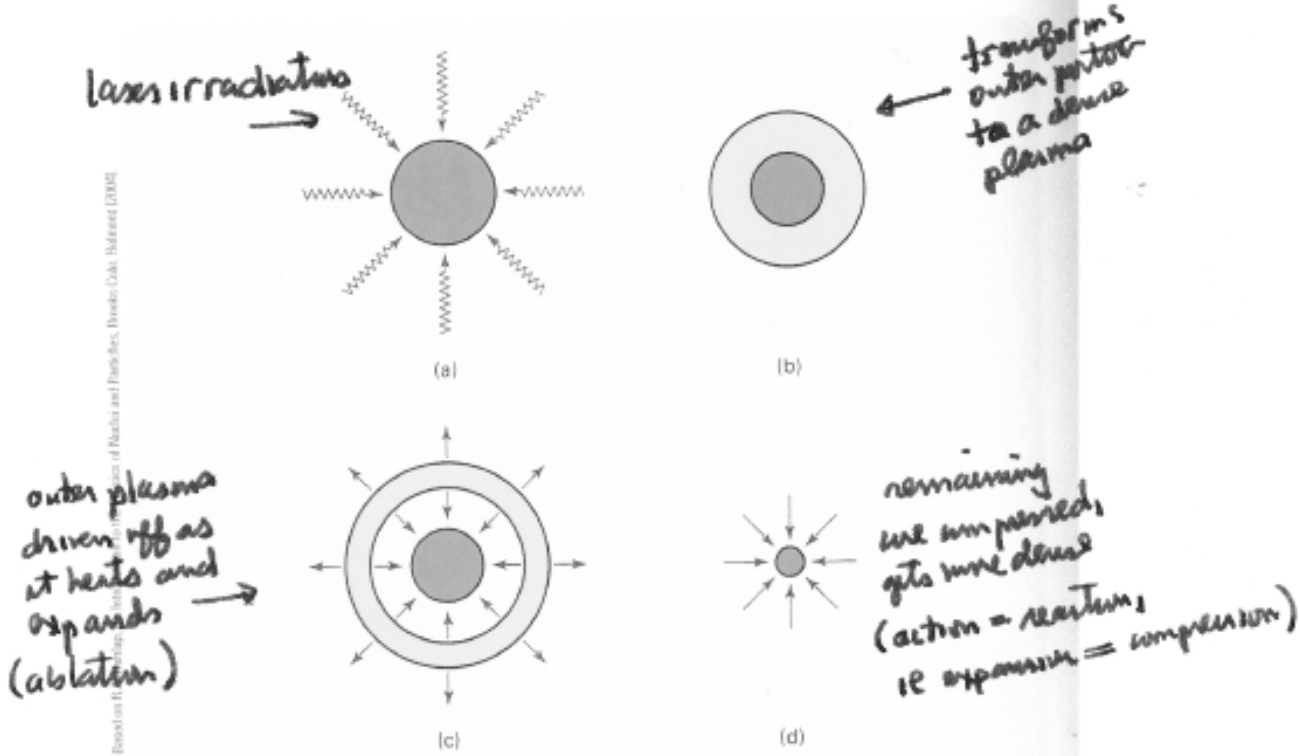


Figure 7.6: Steps in the heating and compression of a fuel pellet in an inertial confinement fusion reactor. The various stages of fusion are described in the text.

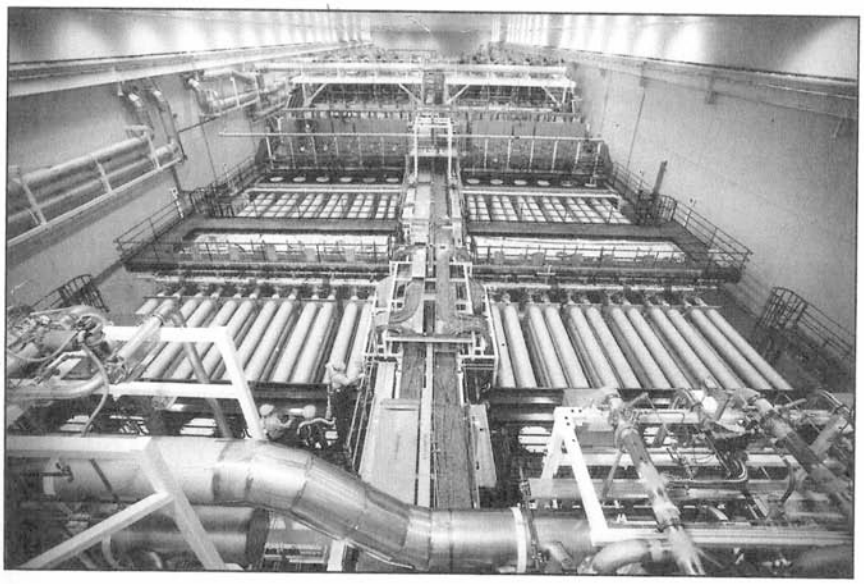


Figure 7.7: Photograph of the laser fusion (inertial confinement fusion) system at Lawrence Livermore National Laboratory (California). Note workers in lower part of photograph for scale.

Laser power output = 750 T watts / pulse = 2.4 nsec long

P_{avg} (worldwide) $\approx$ 15 T watts!

↓

1.8 M joules / energy to move automobile few 100 m!