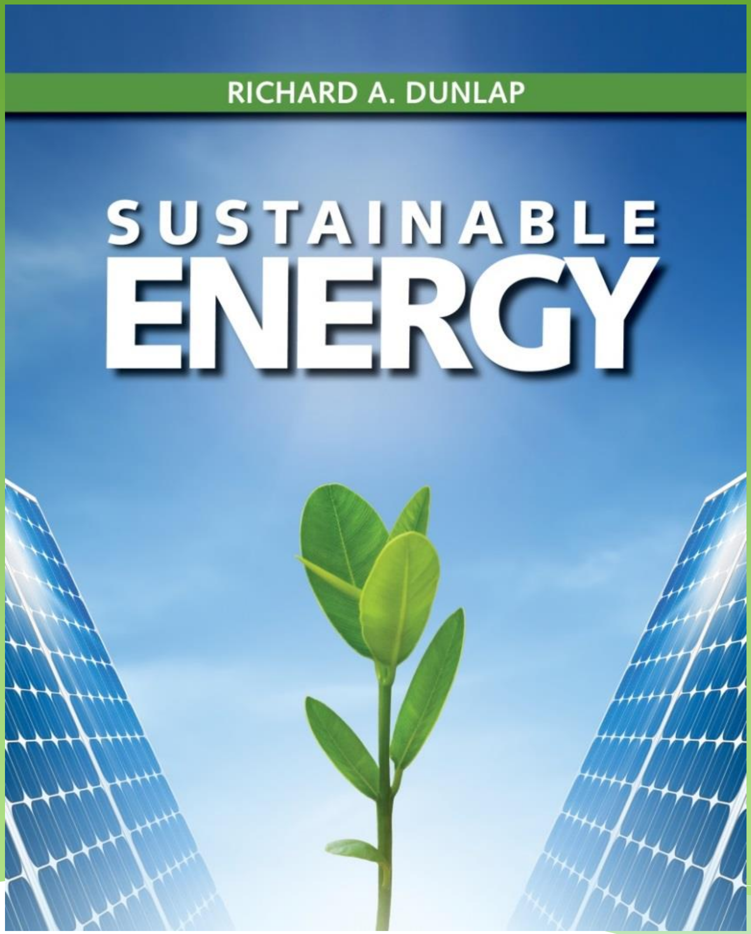
Sustainable Energy



Chapter 7

* Energy from Nuclear Fusion

Learning Objectives

- The properties of fusion reactions and the production of fusion energy.
- The design and operation of magnetic confinement reactors.
- The design and operation of inertial confinement reactors.
- The importance of the Lawson criterion.
- The design of a fusion power reactor.
- Progress toward a viable fusion reactor.

Advantages over nuclear fission

- Fusion processes are inherently more stable and can be readily stopped
- Utilizes inexpensive and plentiful fuel (maybe)
- Produces no hazardous waste products

Energy from nuclear fusion

Nuclear binding energy can be converted into kinetic energy by fusing together two light nuclei as shown by the binding energy per nucleon curve.

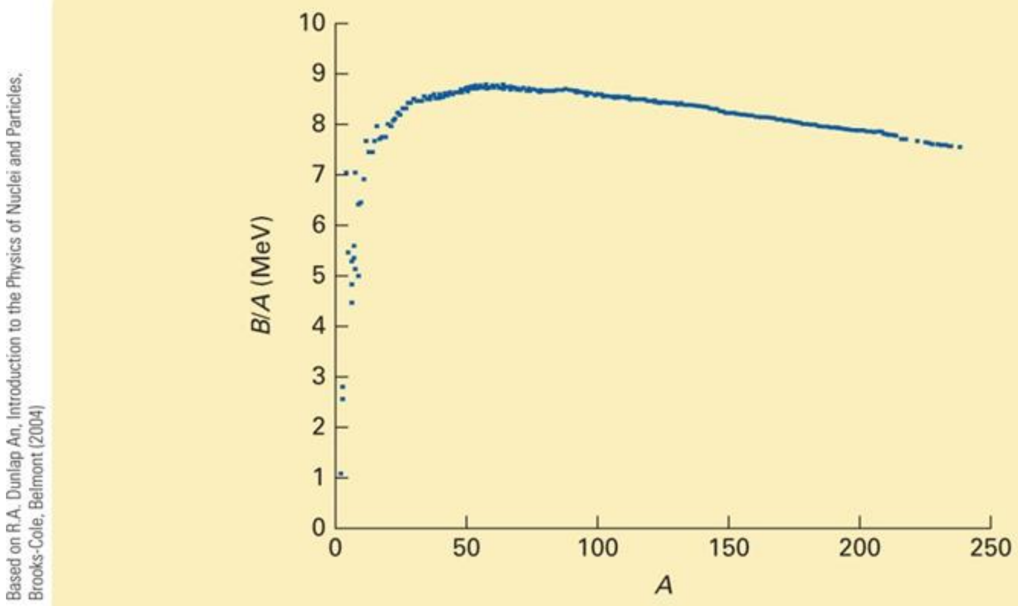


Figure 6.1: Average binding energy per nucleon as a function of the number of nucleons.

Proton-proton (p-p) fusion

The simplest fusion process is the binding together of two protons (or ^1H nuclei):

$$p + p \rightarrow d + e^+ + \nu_e \tag{7.1}$$

Because the positron and a neutrino are involved in this process it is dominated by the week interaction and proceeds very slowly.

Deuteron-deuteron (d-d) fusion

Two deuterons (^2H nuclei) can be fused without the need for the weak interaction by the processes

$$d + d \rightarrow {}^3He + n \qquad (Q = 3.3\ MeV) \qquad (7.4)$$

and

$$d + d \rightarrow {}^3H + p \qquad (Q = 4.0\ MeV) \qquad (7.5)$$

Deuteron-triton (d-t) fusion

A deuteron (^2H nucleus) and a triton (^3H nucleus) can also be fused by the process

$$d + t \rightarrow {}^4He + n \qquad (Q = 17.6 \text{ MeV}) \qquad \textbf{(7.6)}$$

Cross sections for d-d and d-t fusion

Cross sections show that d-t fusion will be easier to achieve than d-d fusion

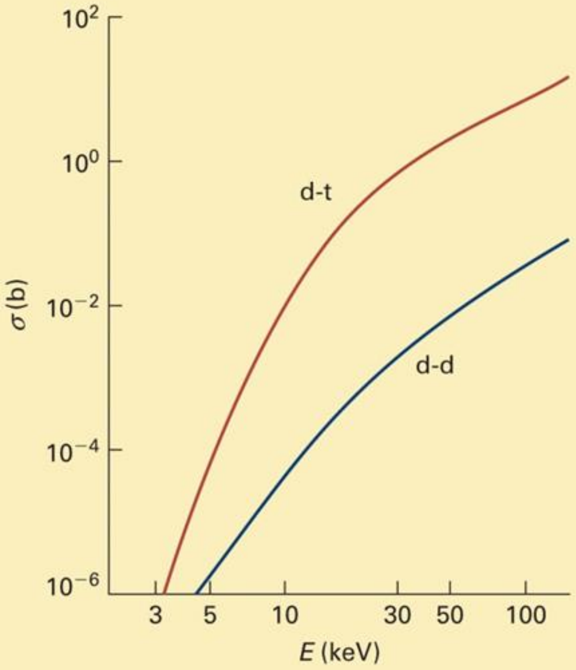


Figure 7.1: Fusion cross sections as a function of energy for d-d and d-t reactions. (b = barns; 1 b = 10^{-28} m^2)

Based on R.A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks-Cole, Belmont (2004).

Coulomb barrier

In order to fuse two nuclei together it is necessary to overcome the Coulombic repulsion of the positively charged protons.

It is necessary that the nuclei are at high enough energy and are kept close enough together for long enough that fusion will occur.

The Lawson criterion for density and confinement time must be satisfied

$$n\tau > 10^{20} \quad s \cdot m^{-3} \qquad (7.9)$$

Approaches to fusion

Two approaches can be used to achieve fusion

- Magnetic confinement
- Inertial confinement
  (sometimes called laser fusion)

Magnetic confinement

At high temperature all gas atoms are ionized creating a plasma.

The charged particles of the plasma can be controlled by electromagnetic fields.

The Tokamak, which uses a toroidal field geometry is the cost common.

Confinement of plasma in a toroidal field geometry

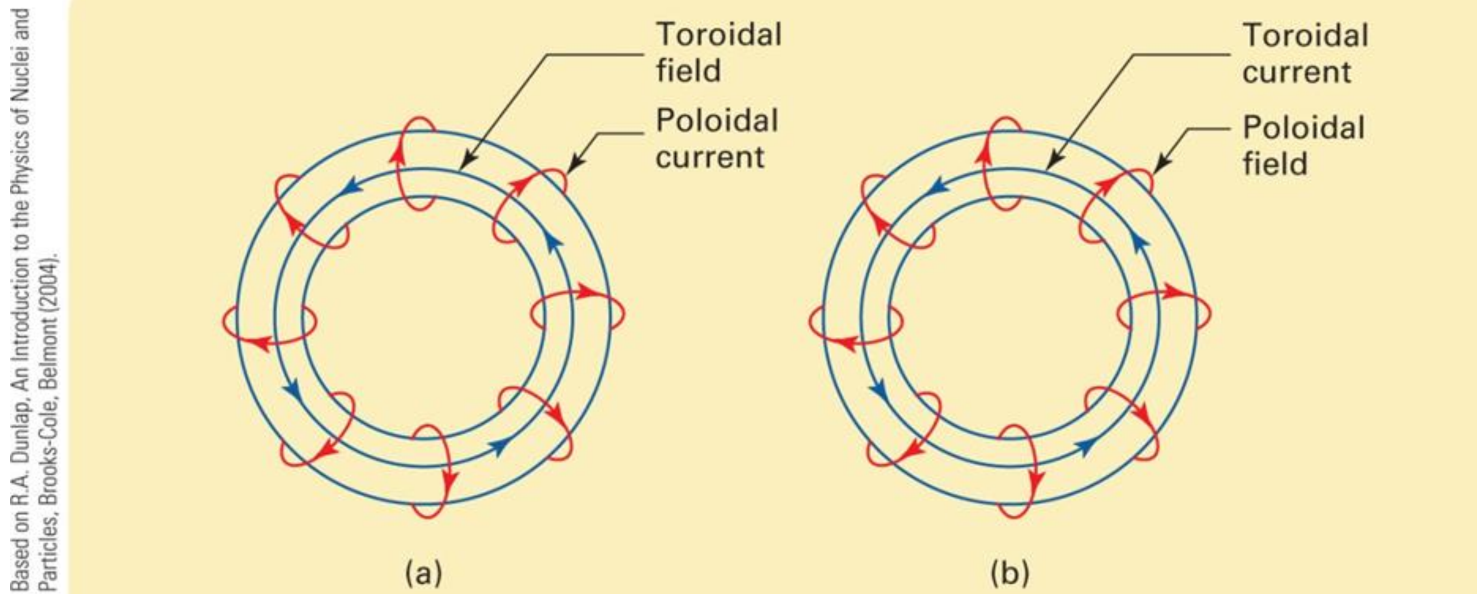
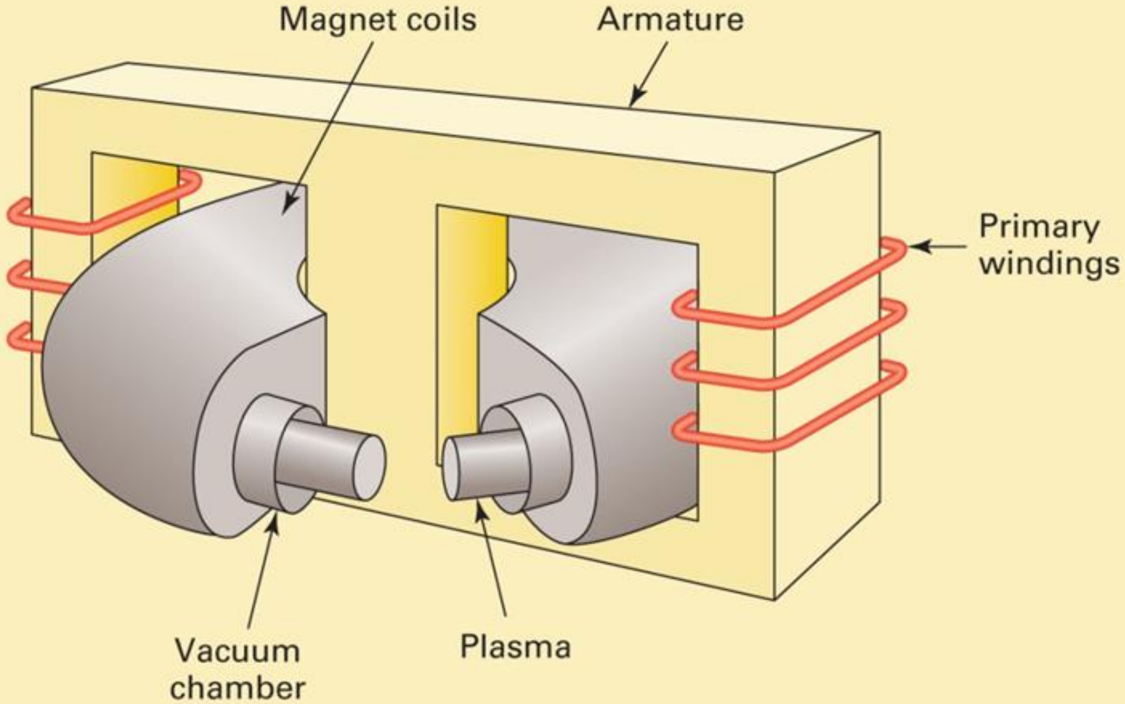


Figure 7.2: Geometry of currents and magnetic field lines in a toroidal reactor: (a) toroidal field produced by poloidal currents; (b) poloidal field produced by a toroidal current.

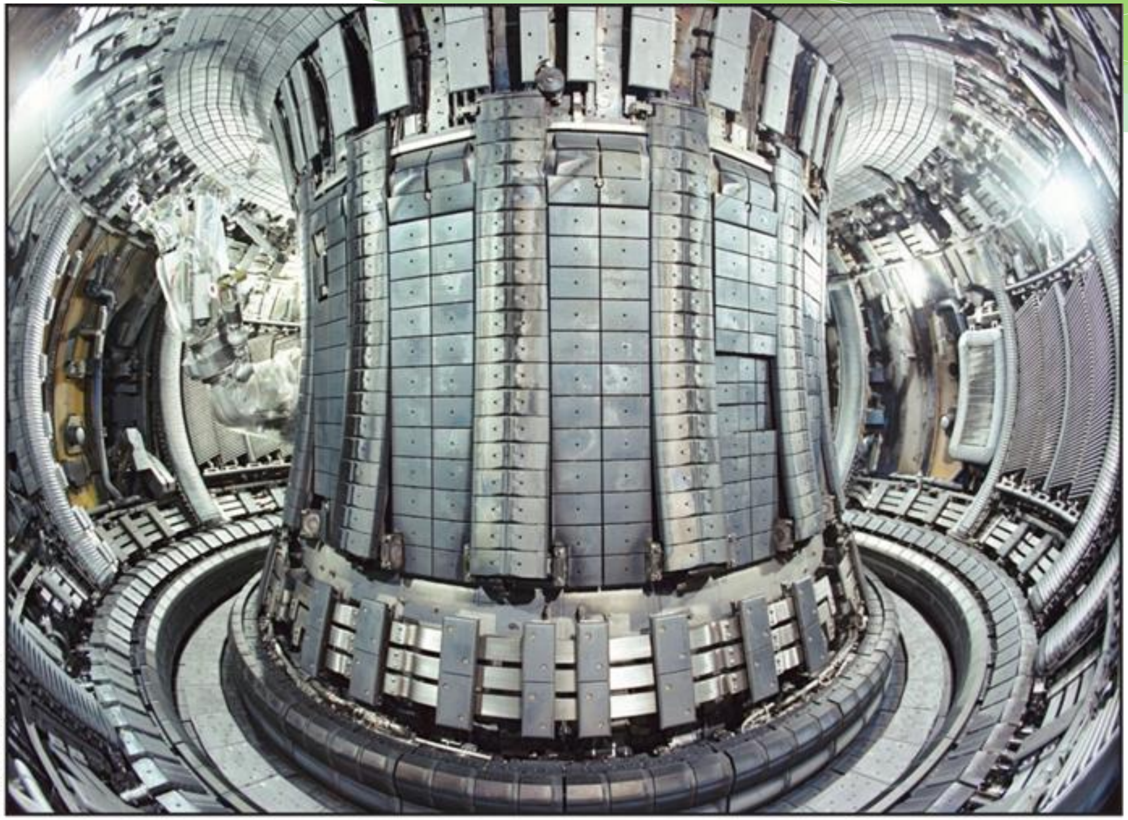
Basic Tokamak design



Based on R.A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks-Cole, Belmont (2004).

Figure 7.3: Schematic diagram of a tokamak.

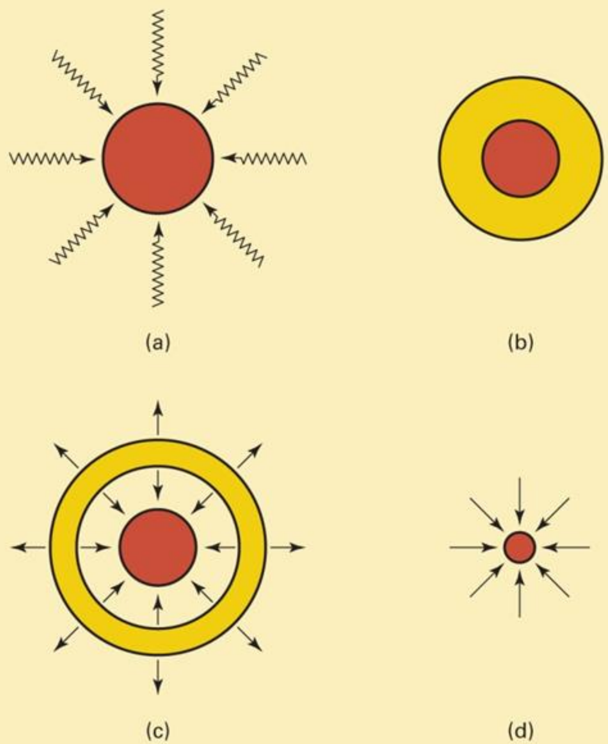
Interior of a "spherical" Tokamak



EFDA-JET/Science Source

Figure 7.4: Interior of the Joint European Torus (JET), a tokamak located in Culham, Oxfordshire, England.

Inertial confinement fusion



Based on R.A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks-Cole, Belmont (2004).

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.

Steps to Laser fusion

(a) irradiation of fuel pellet with Laser
(b)Heating of outer portion of pellet
(c) Ablation of outer portion of pellet
(d) Compression of core by inertial forces

Lawrence Livermore Laser fusion experiment

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 fusion experimental conditions

d-t fuel pellet - typically 1 mg

Laser power - 750 TW
(50 times total average world power consumption)

Laser pulse duration - 2.4 ns

Energy per laser pulse -

$$(750\ \text{TW})\times(2.4\ \text{ns}) = 1.8\ \text{MJ}$$

density - confinement time relationships for different fusion experiments

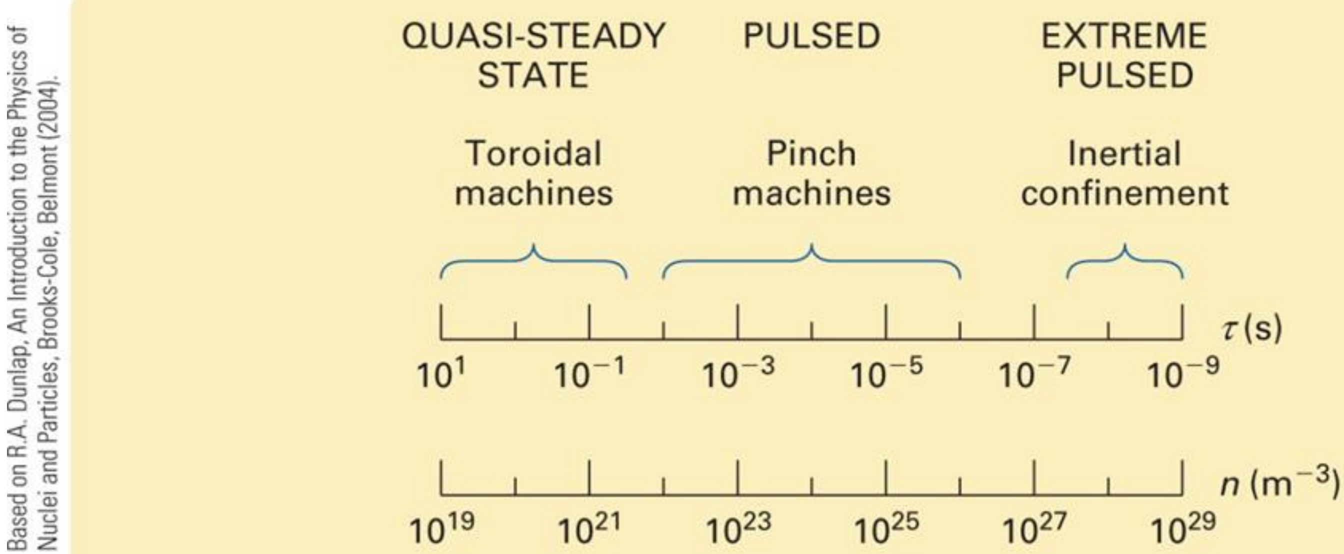


Figure 7.8: Relationship of the quantities in the Lawson parameter for different types of fusion reactors that are necessary to meet the Lawson criterion.

Progress towards fusion energy (Magnetic Confinement Reactors)

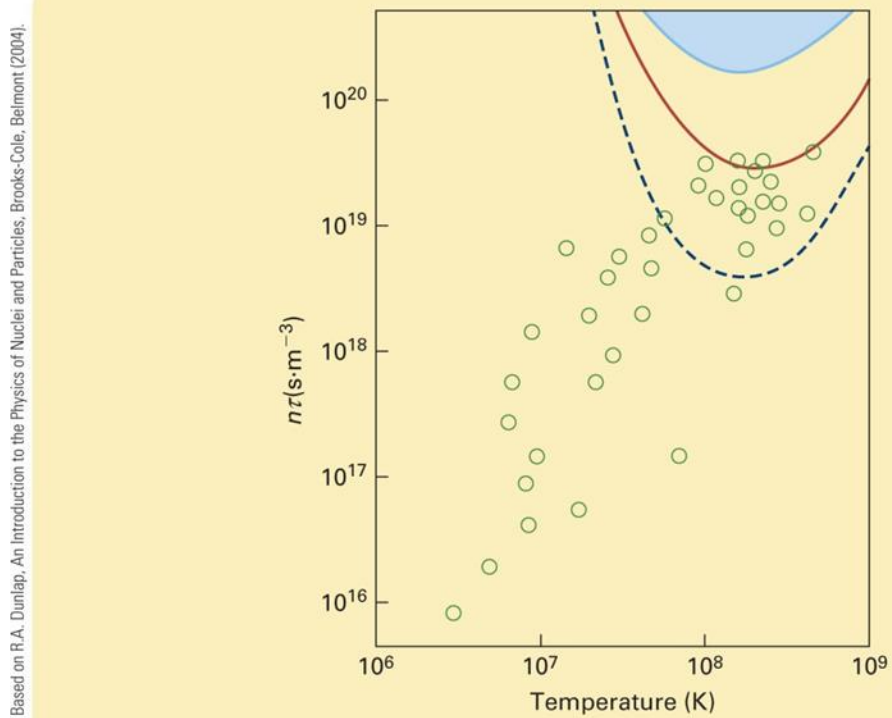
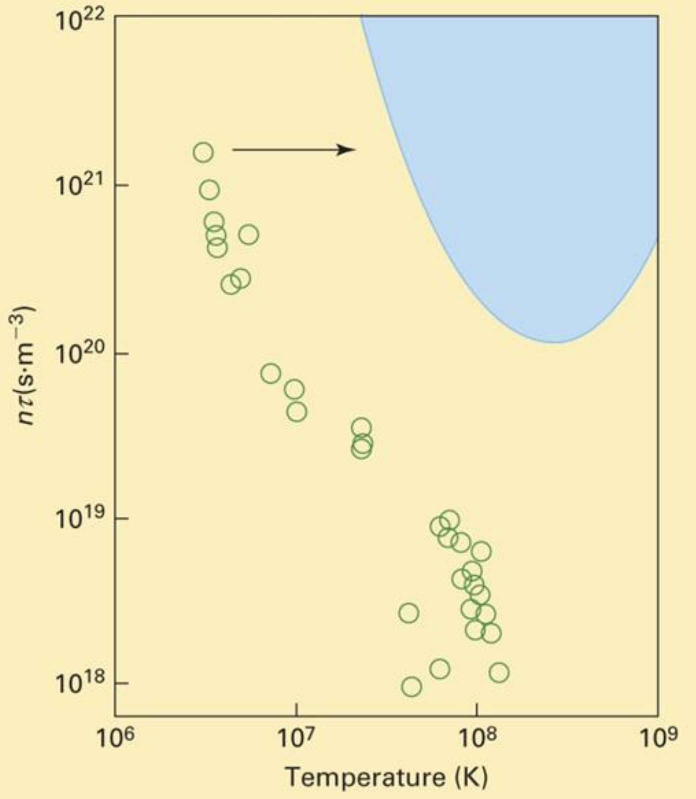


Figure 7.9: Progress toward ignition for magnetic confinement fusion reactors. The broken blue line is the breakeven point if additional energetic particles are injected into the plasma and the red line is breakeven without particle injection.

Progress towards fusion energy (Inertial Confinement Reactors)



Based on R.A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks-Cole, Belmont (2004).

Figure 7.10: Progress toward ignition for inertial confinement fusion reactors.

Where does fuel come from?

d-d fusion is much more difficult than d-t fusion so current experiments focus on d-t fusion.

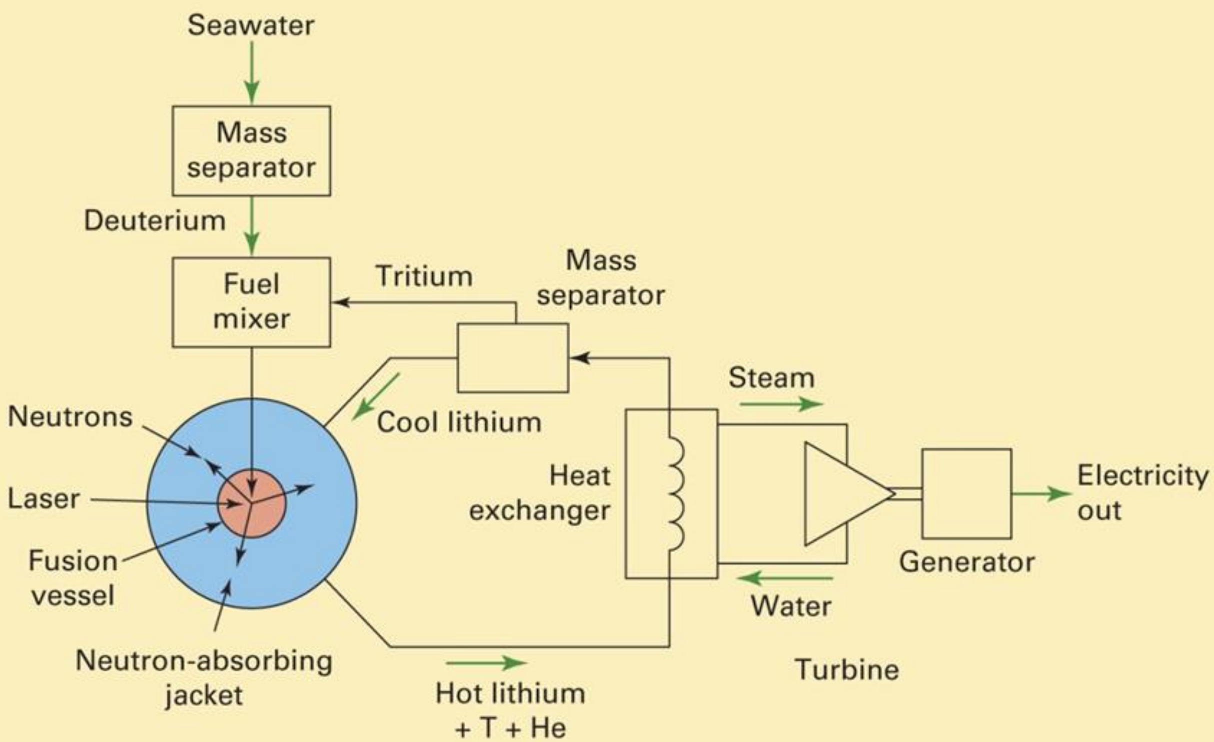
Deuterium from sea water - one hydrogen out of 6410 is deuterium - more or less unlimited

Tritium is unstable (half life = 12 years) and must be made artificially by the reaction

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow {}^{3}\mathrm{H} + {}^{4}\mathrm{He} \qquad (Q = 4.78\ \mathrm{MeV}) \qquad \textbf{(7.10)}$$

Limited by the world's supply of lithium

Basic design of a fusion reactor



Based on R.A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks-Cole, Belmont (2004).

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

Challenges to fusion energy

- Need to achieve net energy gain
- Need to account for Carnot efficiency of electricity generation
- Need to make energy economically competitive
- Need to consider fuel availability
  (if tritium is used, lithium supply might last 500 - 1000 years)
- Need to consider competition for lithium supplies
  (for rechargeable batteries)

Summary

- Nuclear binding energy can be released during the fusing together of light nuclei
- Safer and more environmentally conscious than fission
- d-t fusion most likely to be feasible
- Two basic approaches -
  - Magnetic confinement and
  - Inertial confinement (Laser fusion)
- Needs to be energetically and economically viable
- d-t fusion requires lithium to breed fuel