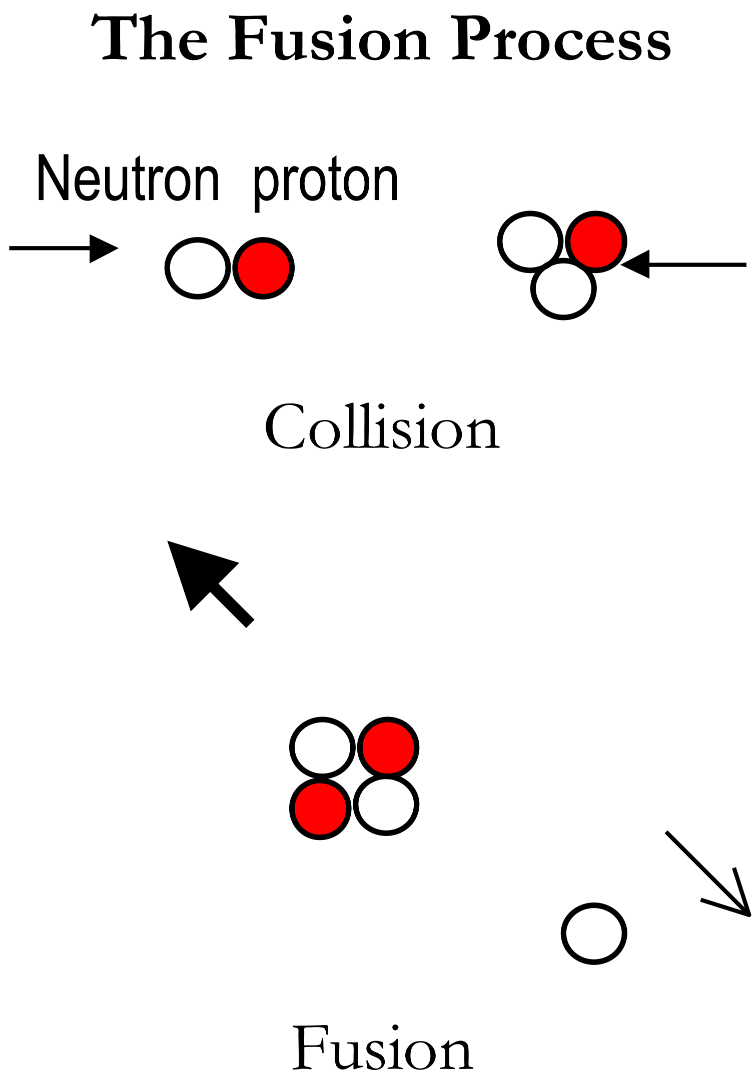
Nuclear Fusion Powers the Universe

Two nuclei combine into one nucleus plus a nucleon is called **nuclear fusion**, a nuclear reaction.

The picture here illustrates the fusion of

$$^{2}D + {}^{3}T \rightarrow {}^{4}He + n$$

that releases a lot of energy.

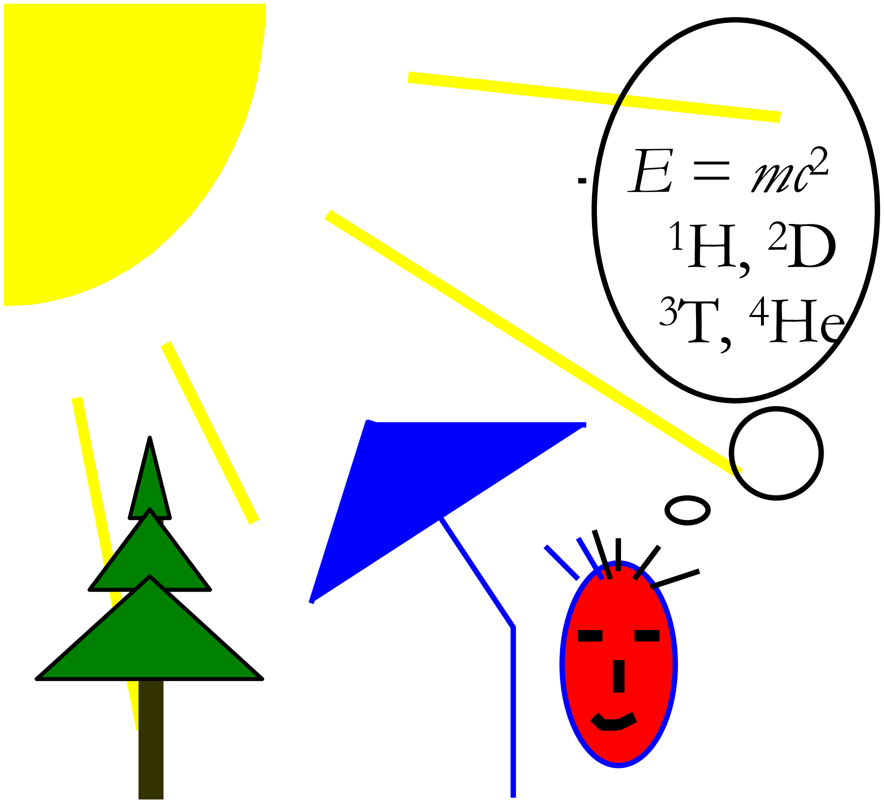


[The solar system](#)

Nuclear Fusion in Stars

[Solar system](#) NASA

These links may move



Stars are giant fusion reactors.

Nuclear fusion reactions provide energy in the Sun and other stars. Solar energy drives the weather and makes plants grow.

Energy stored in plants sustains animal lives, ours included.

The Sun

Core:

Radius = 0.25 R_{sun}

T = 15 Million K

Density = 150 g/cc

Envelope:

Radius = R_{sun} = 700,000 km

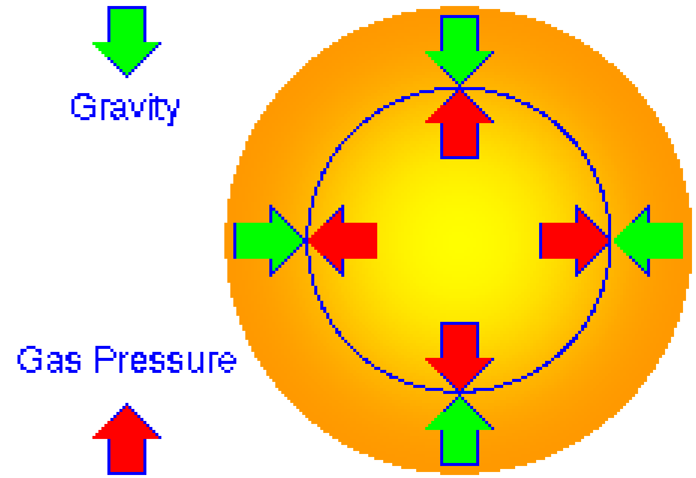
T = 5800 K

Density = 10^{-7} g

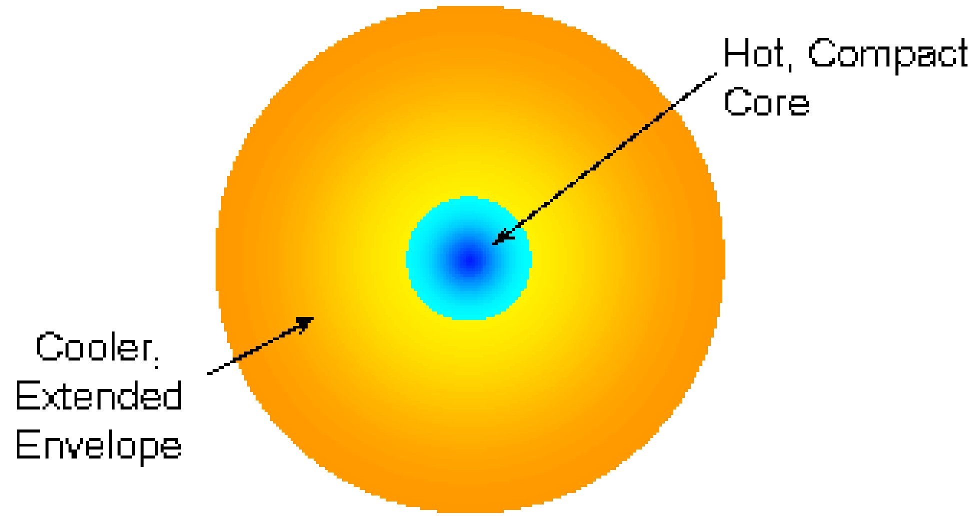
Life of Star:

tug-of-war between Gravity & Pressure

Hydrostatic Equilibrium



Core-Envelope Structure



Controlled Nuclear Fusion Energy for D-T Fusion

Estimate the fusion energy for $D + T \rightarrow {}^4He + n$

Estimate the fusion energy Q

The mass excess (MeV) are given below every species.

$$D + T \rightarrow {}^4He + n + Q$$
$$13.136 + 14.950 = 2.425 + 8.070 + Q$$
$$Q = 17.6 \text{ MeV/fusion}$$

This amount is 3.5 MeV/amu compared to 0.8 MeV/amu for fission.

Estimating Q is an important skill. Mass and mass excess can be used, the latter is usually given to unstable nuclides.

Controlled Nuclear Fusion Energy for Fusion Reactions

Common fusion reactions and their *Q* values

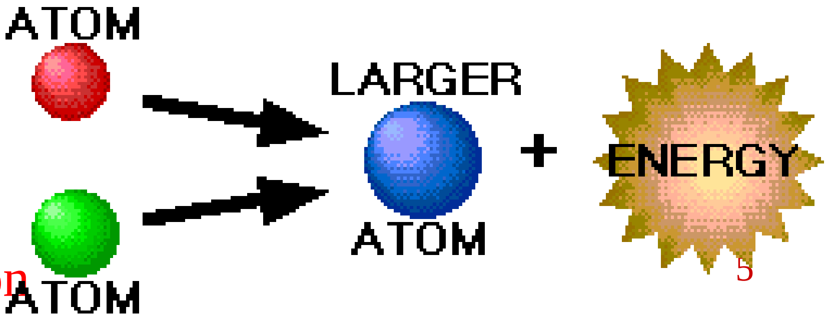
$$\mathrm{H} + \mathrm{H} \rightarrow \mathrm{D} + \beta^{+} + \nu + 1.44\ \mathrm{MeV}$$

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV}$$

$$\mathrm{D} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + \mathrm{p} + 18.4\ \mathrm{MeV}$$

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} + 3.3\ \mathrm{MeV}$$

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{T} + \mathrm{p} + 4.0\ \mathrm{MeV}$$



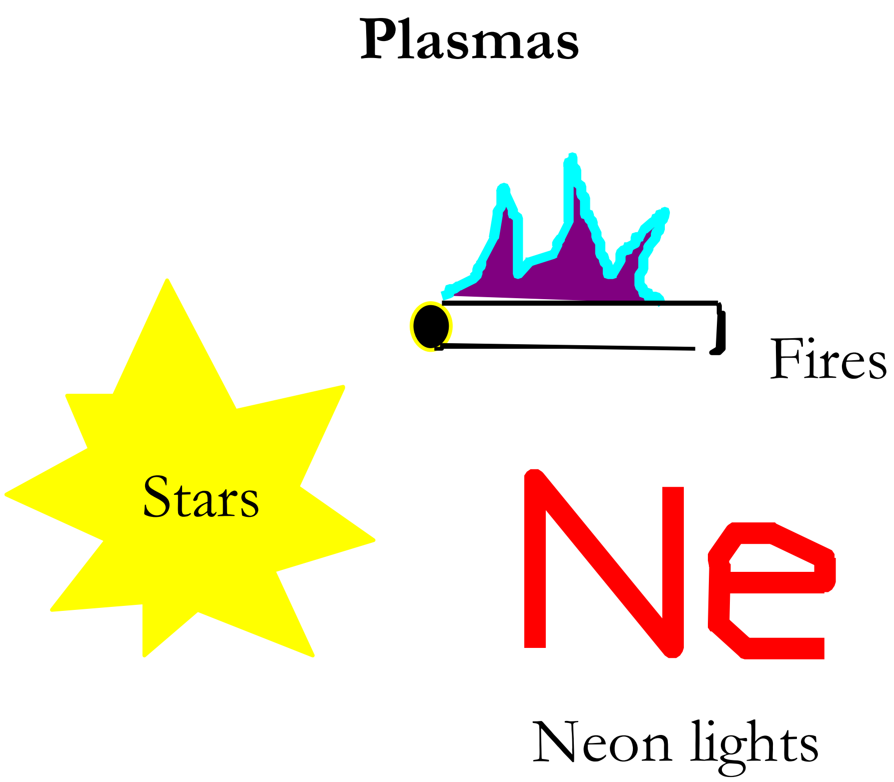
See ***Interactive Plasma Physics Education Experience*** : http:// ippex.pppl.gov/

Nuclear Fusion and Plasma

D and T mixtures have to be heated to 10 million degrees. At these temperatures, the mixture is a plasma.

A plasma is a macroscopically neutral collection of charged particles.

Ions (bare nuclei) at high temperature have high kinetic energy and they approach each other within 1 fm, a distance strong force being effective to cause fusion.



Nuclear Fusion and Plasma

the next problem: here on Earth, one has to achieve confinement in a much smaller space and much shorter time than in stars. As mentioned above, using a fusion reaction for an energy-producing system requires a huge number of such fusion reactions per second. This means one has to keep the nuclei relatively close together and prevent the plasma from flying apart by confining it long enough that a sufficient number of fusion reactions can take place.

How much energy can be produced in such a confined plasma? The energy produced per time τ *depends on the kinetic energy Q of the reaction*

How much energy can be produced in such a confined plasma?

energy produced per time τ *depends on the kinetic energy Q of the reaction*

$$E = W\tau Q = \frac{n^2}{4}\langle v\sigma\rangle \tau Q$$

Nuclear Fusion and Plasma

where Q is given in MeV. The ultimate aim in ICF research is an energy-producing reactor. Therefore the energy obtained from the fusion processes has to be greater than the energy to heat the plasma to such high temperatures. Or in other words, energy will be gained from an ignited DT-plasma only if this energy is larger than the total kinetic energy of all the particles. Because the kinetic energy E_{kin} of the nuclei and electrons is $E_{kin} = 3nk_BT$, it follows that only if

$$3nk_BT < \frac{n^2}{4}\langle v\sigma\rangle\tau Q,$$

the fusion reactions actually release more energy than is required to produce the plasma of such temperature and density. Re-expressed as

$$n\tau > \frac{12k_BT}{\langle v\sigma\rangle Q}, \tag{1.10}$$

this relation is called *Lawson criterion* (Lawson, 1957), which is one of the fundamental relations of confinement fusion.

In addition to the problem of confinement, the fusion particles have to have enough kinetic energy for a sufficient number of fusion reactions to take place. For DT fuel this implies a temperature of approximately 5 keV. In the case of a DT reaction with $Q = 17.6$ MeV and an operating temperature of the reactor of about 5–10 keV, the Lawson criterion becomes

$$n\tau \simeq 10^{14} - 10^{15}\ \text{s cm}^{-3}, \tag{1.11}$$

where n is the number of particles per cm^3 and τ the confinement time.

Nuclear Fusion and Plasma

1.3 The Two Approaches — Magnetic vs. Inertial Confinement

As stated before, for enough fusion reactions to take place: the plasma must be kept together at a high temperature for a sufficiently long time. Essentially two methods have been pursued in the quest for a viable fusion reactor — *magnetic confinement* (MCF) and *inertial confinement* (ICF), which aim to fulfill the Lawson criterion in two different ways. MCF tries to confine the plasma at low densities for the relatively long times of several seconds — whereas ICF yields to achieve extremely high densities for a very short time. Table 1.2 gives a comparison of the confinement times and densities in the two approaches.

Table 1.2. Confinement parameters in MCF and ICF.

	MCF	ICF
Particle density n_e/cm^{-3}	10^{14}	10^{26}
Confinement time τ/s	10	10^{-11}
Lawson criterion $n_e\tau/\mathrm{s\ cm}^{-3}$	10^{15}	10^{15}

Magnetic Fusion

Because of the required high temperature of the plasma, it cannot simply be confined in a material vessel since any contact with the walls would lead to rapid cooling. As its name implies, MCF is based on the fact that plasma can in principle be confined by applying a suitable magnetic field. This is only possible because the particles in the high temperature plasma are all charged. Magnetic fields force the charged particles of the plasma into helical orbits which follow the field lines (see Fig. 1.4). Particle movement perpendicular to the field lines is restricted while the particle moves freely in the longitudinal direction. In this way contact with the walls can be largely avoided. Because charged particles follow curved trajectories, the idea is that a suitable configuration of magnetic fields can be found so that the particles stay on closed orbits and never escape.

The objective of a closed orbit is most easily fulfilled by ring-shaped magnetic fields. However, in such a configuration, the field strength decreases with radius, which leads to a radial velocity component and a drift of the particles towards the outside. To confine the plasma for a long time,

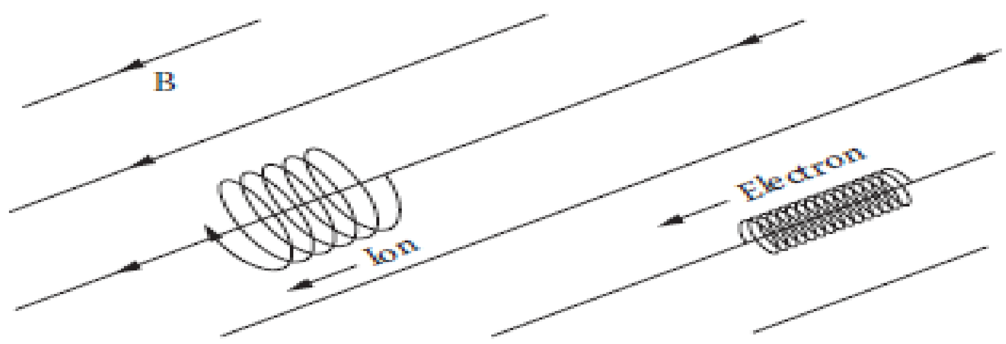
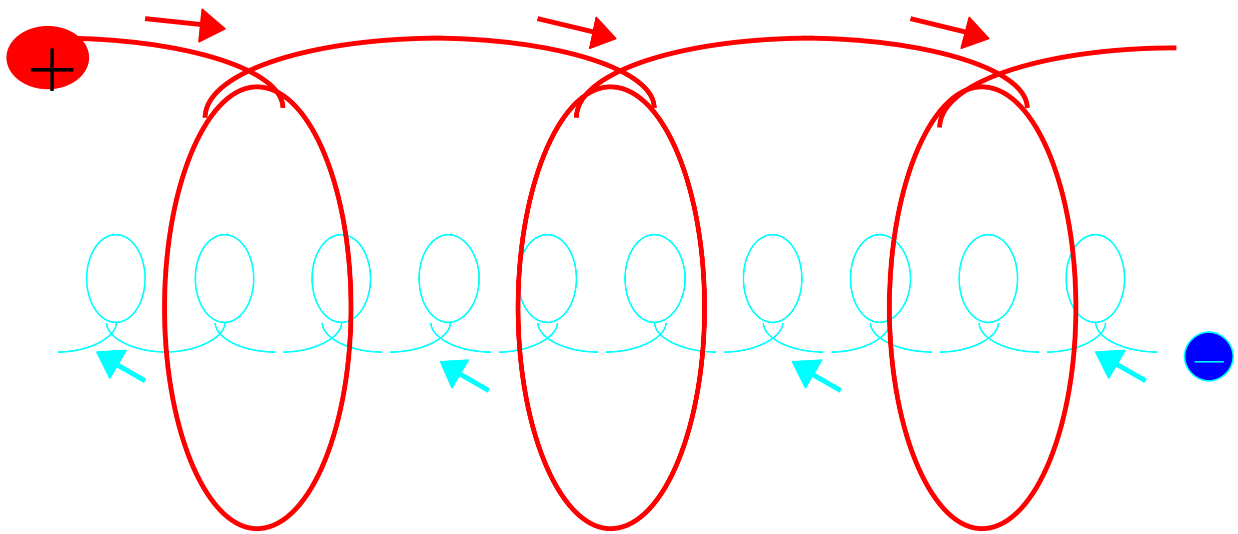


Figure 1.4. Helical movement of electrons and ions along magnetic field lines.

The magnetic device contains a vacuum into which a mixture of deuterium and tritium is injected. The magnetic field is produced by passing an electric current through coils wound around the torus. The plasma current creates a poloidal magnetic field and the two fields combine to provide

Until ignition is achieved the plasma has to be heated externally. There are three different heating mechanisms used: ohmic heating, heating by high-frequency waves, and by the injection of beams of neutral particles.

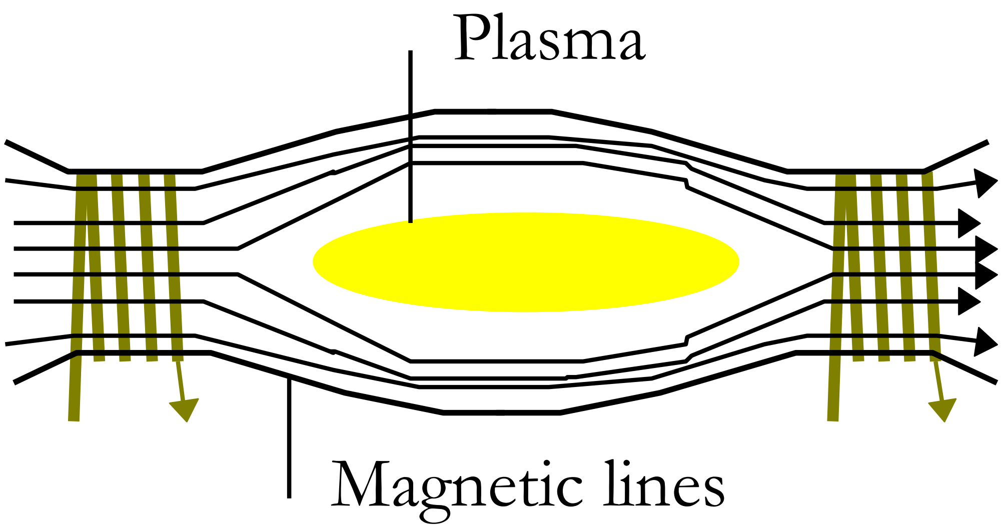
Motion of Nuclei and Electrons in a Magnetic Field



Charged particles avoid crossing magnetic lines.

Nuclear Fusion using Magnetic Plasma Confinement

Magnetic Mirror Confinement



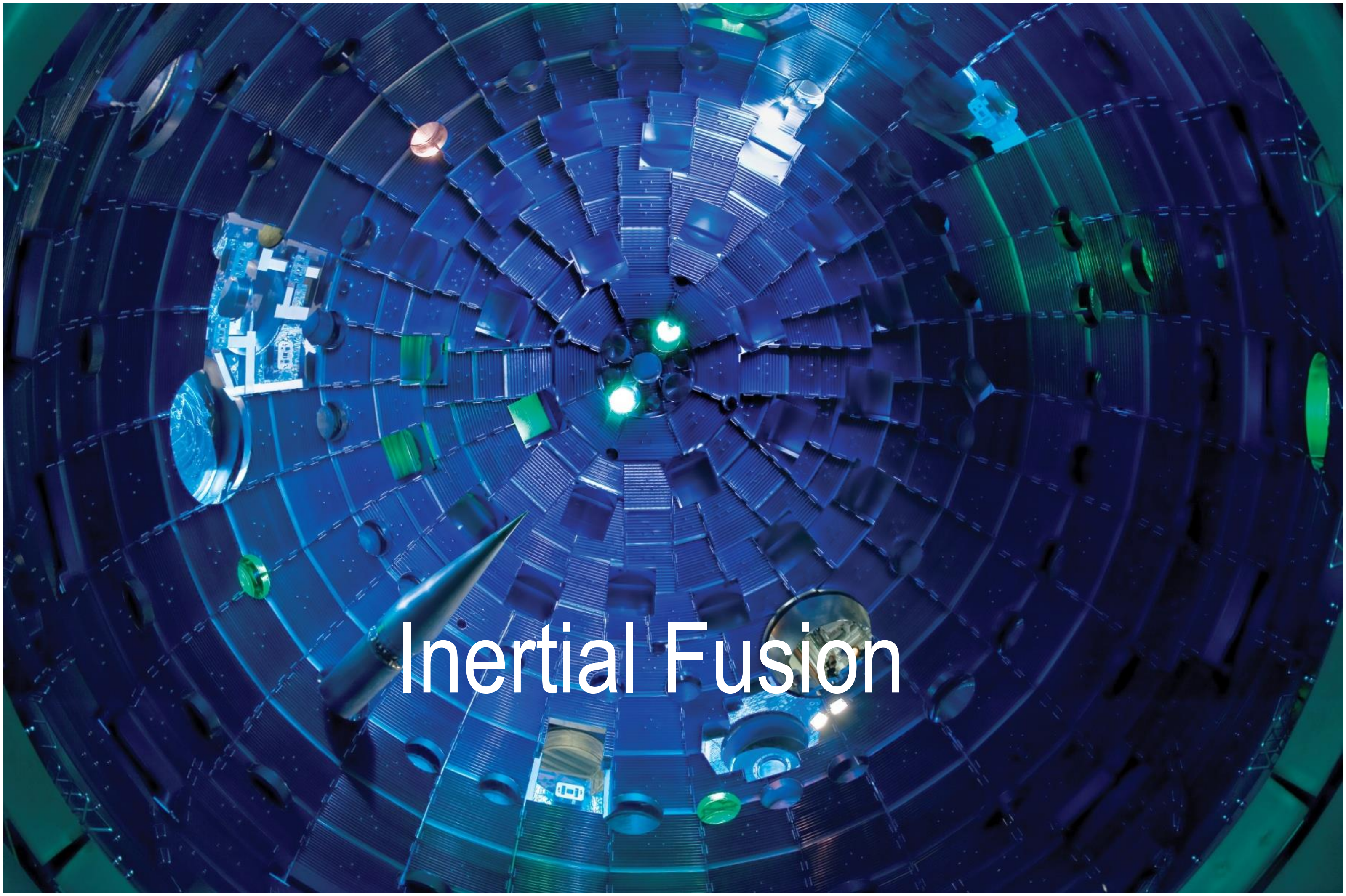
A Magnetic Bottle for Plasma Confinement

A plasma distorts magnetic field or bends magnetic lines.

magnetic confinement device, : to trap high temperature plasma using magnetic fields. In a magnetic mirror a specially shaped electromagnet creates a configuration of magnetic field lines which reflects charged particles from a high density magnetic field region to a low density magnetic field region.

Large experimental magnetic mirror machines have been developed to confine hot deuterium plasma as a possible approach to fusion power, since the plasma is too hot for any solid container.

A charged particle moving within a region of magnetic field experiences a Lorentz force that causes it to move in a helical (corkscrew) path along a magnetic field line. The radius of the circle that the particle describes is called the radius of gyration or gyro-radius.
If it enters a region of denser magnetic field lines, a field gradient, the combination of the radial component of the fields and the azimuthal motion of the particle results in a force pointed against the gradient, in the direction of lower magnetic field. It is this force that can reflect the particle, causing it to decelerate and reverse direction



Inertial Fusion

Plasma Conditions During ICF

- **Before compression and ignition**

  Density: solid DT pallet at 0.225 g/cm^3 and gas
  Temperature: few Kelvin

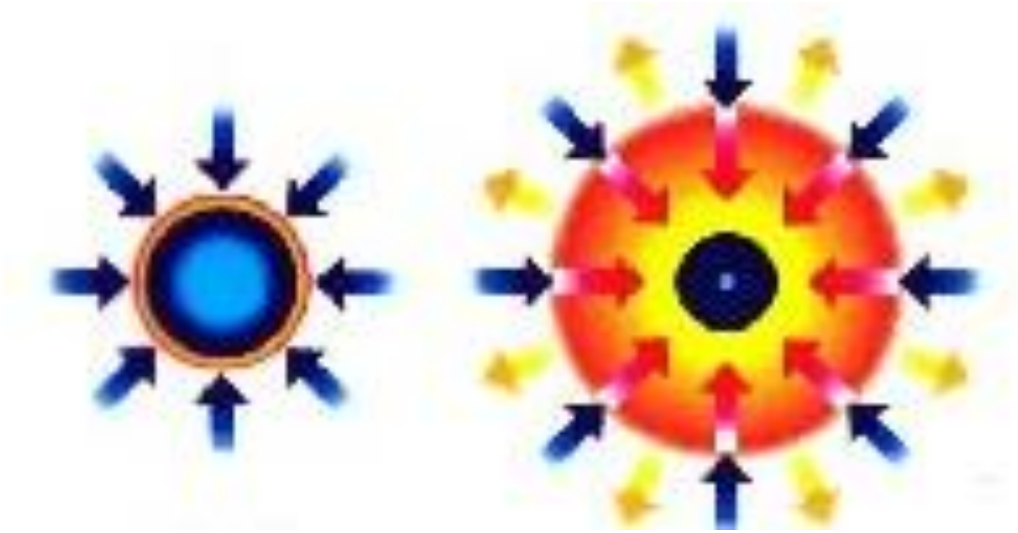
- **During the burn phase**

  Density: 300 to 1000 times solid density
  300 to 1000 $g/cm^3 \approx 10^{26}\ cm^{-3}$
  Temperature: around 10.000.000 K or 10 keV
  Pressure: around 10^{12} bar

- **Confinement time needed**: around 200 ps

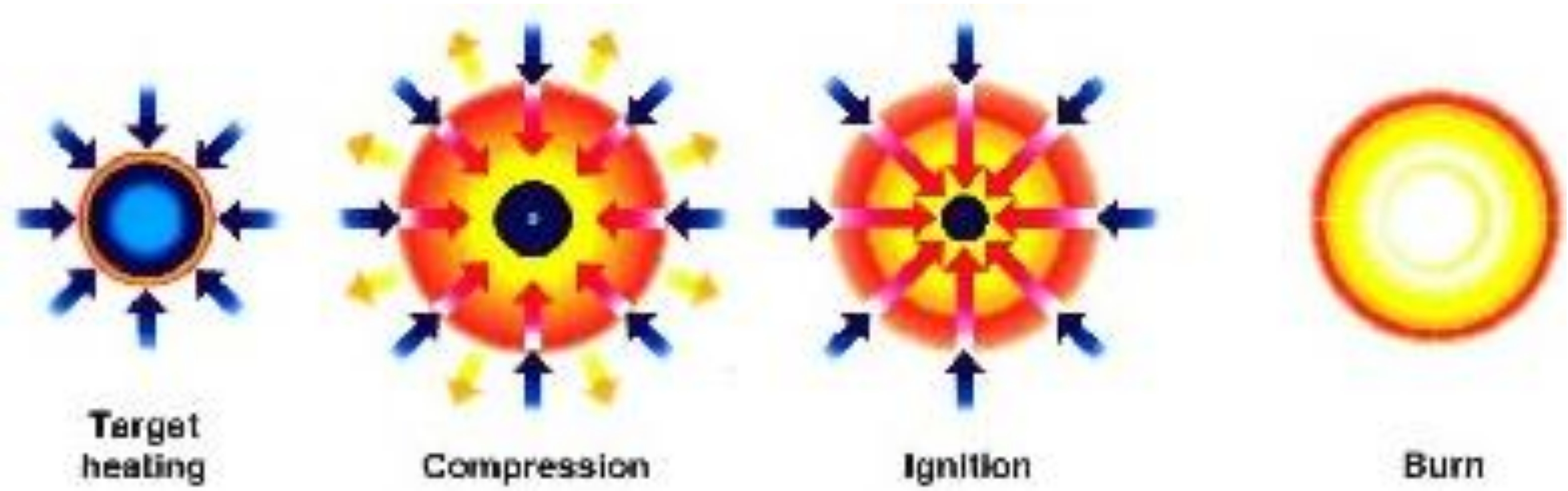
Achieving High Densities

- A hollow sphere ~ mm in diameter is compressed by heating the outside to produce an expanding plasma that acts like a rocket propelling the shell inwards
  - The inside must remain degenerate in order to minimize the pressure (~ 790 eV at 300 g cm^{-3} giving ~ 30 Gbar)
  - Compression time ~ 10^{-8} s
  - Minimum absorbed energy ~ 100 kJ

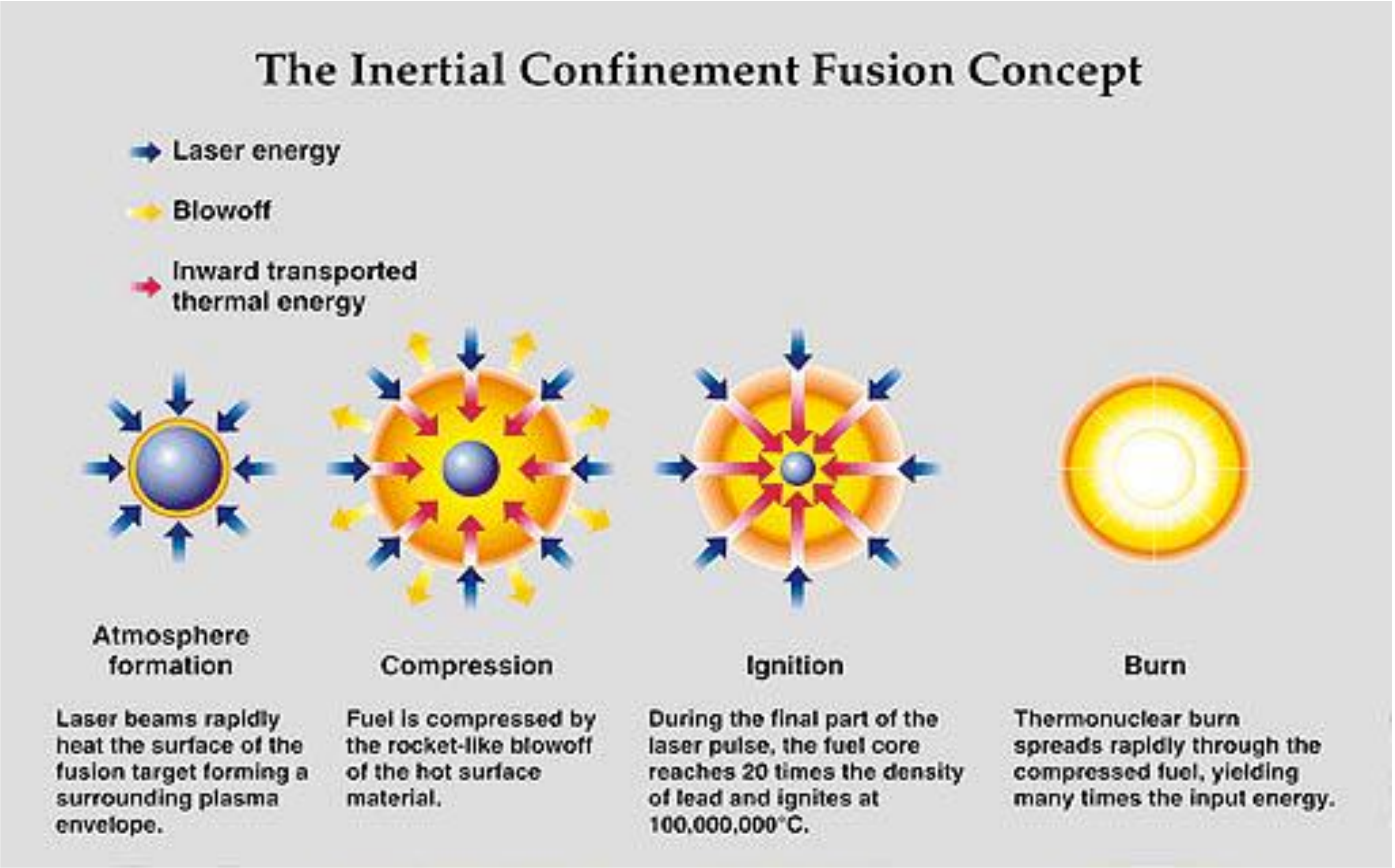


Achieving High Temperatures

- If the implosion velocity exceeds 10^5 m s^{-1} then the collision of the walls at the centre leads to temperatures sufficient to start fusion reactions and the alpha particles heat the rest of the plasma



Controlling Fusion using Inertia

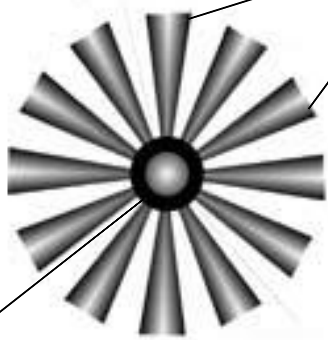


Inertial Confinement Fusion

Direct Drive:

- **Laser Beams are focused onto the surface of the target (pellet of fuel)**

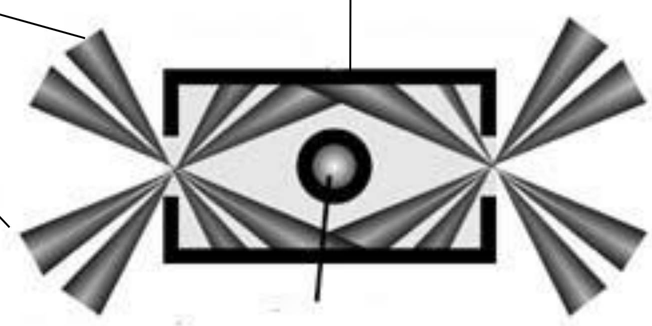
HiPER



Indirect Drive

Laser Beams are focused at the inner site of the cylinder

NATIONAL IGNITION FACILITY



In this approach, multiple laser beams with a 20 ns duration precisely shaped pulse are arranged in cones about the axis of a high-Z cylindrical hohlraum. A hohlraum is a hollow, cylinder-shaped device that is used to focus and control radiation.