

PLASMA PHYSICS

IX. FUSION PLASMAS

Fusion reactions

Fusion reactions are the source of energy in stars.

You do. Look up this topic in a Modern Physics textbook, in particular the *proton-proton chain* and the *carbon cycle*.

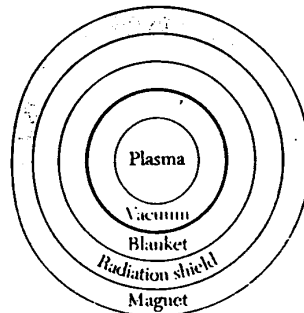
Controlled thermonuclear reactions are a potential source of energy on earth.

The first fusion reactors will exploit the reaction



D or ^2H is deuterium, T or ^3H is tritium and α or ^4He is an alpha particle. n is a neutron and p is a proton.

This reaction has the lowest ignition temperature (about 4 keV). *Ignition* - when all the energy in the α 's is sufficient to maintain the reaction.

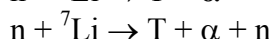
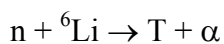


In a magnetically-confined plasma, the charged α 's remain trapped long enough to deliver most of their energy back into the plasma before escaping, the n's escape immediately.

Fuel is readily available.

D is a readily separable component of sea water. One hydrogen nucleus in 6700 is D.

T is regenerated when n's are absorbed in the lithium blanket surrounding the reactor vessel (*tritium breeding*).



Energy of n's and α 's is converted in the blanket into heat which is carried away by a suitable coolant to make steam for conventional electricity generation. One blanket design uses vanadium alloy as the structural material to withstand the high radiation environment and liquid lithium as both tritium breeder and coolant.

Another process is

$D + D \rightarrow T + p$ (4.0 MeV) or equally probably

$D + D \rightarrow {}^3\text{He} + n$ (3.3 MeV)

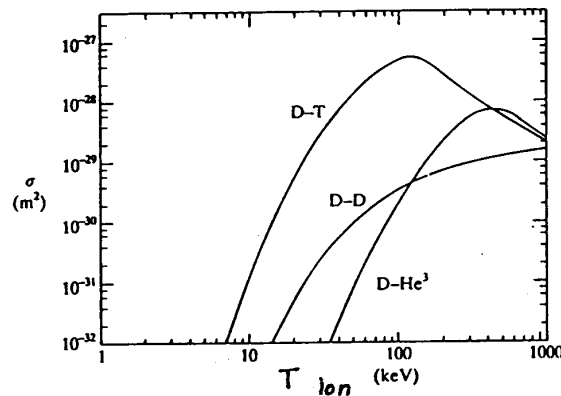
followed by

$D + {}^3\text{He} \rightarrow {}^4\text{He} + n$ (18.34 MeV)

In this process there is no need to manufacture T. However the ignition temperature is much higher (about 35 keV)

To get a fusion reaction, the two nuclei have to get sufficiently close to each other for the strong but short-range nuclear force of attraction to take over from the Coulomb force of repulsion. The plasma will have a Maxwellian distribution and it is the fast particles in the tail of the distribution which undergo fusion.

Cross-sections for D-T and other reactions. The D-T reaction has the highest cross-section.

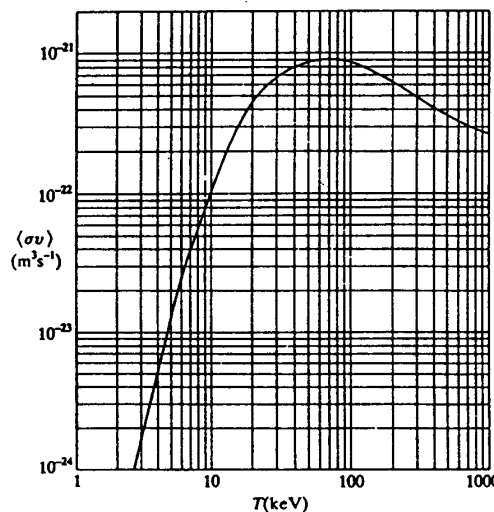


A reactor must produce more power from the reaction than is required for heating the plasma and operating the device.

Power produced per unit volume

$$p_{\text{reaction}} = \frac{n^2}{4} \langle \sigma v \rangle E$$

where $\langle \sigma v \rangle$ is an average over the distribution, E is the 17.6 MeV released in each reaction.



Power lost per unit volume by bremsstrahlung

$$p_{brems} = 1.6 \times 10^{-40} n_e n_i Z^2 T^{\frac{1}{2}}$$

This result follows from the expression for emissivity in Chapter VII.

Keep the effective Z as low as possible to minimize power lost by bremsstrahlung.

Power lost per unit volume by escaping D and T ions

$$\begin{aligned} p_{lost} &= \text{energy density} \div \text{energy confinement time} \\ &= 2 \times n \times \frac{3}{2} kT \div \tau_E = \frac{3nkT}{\tau_E}. \end{aligned}$$

The *energy confinement time* τ_E , how long it takes to cool down once the external heating is switched off, is a measure of how effective the confinement is.

Breakeven is when the power output is sufficient to maintain the reaction. Let us calculate a criterion for breakeven.

Assume that the external power input + power carried by the α 's produced in the DT reaction replaces the power lost.

$$p_{ext} + p_{DT,\alpha} = p_{brems} + p_{lost}.$$

This external power comes from retrieving some of the power lost by bremsstrahlung, escaping D and T ions and some of the power produced by the n's. The efficiency η is estimated to be about 0.3. So

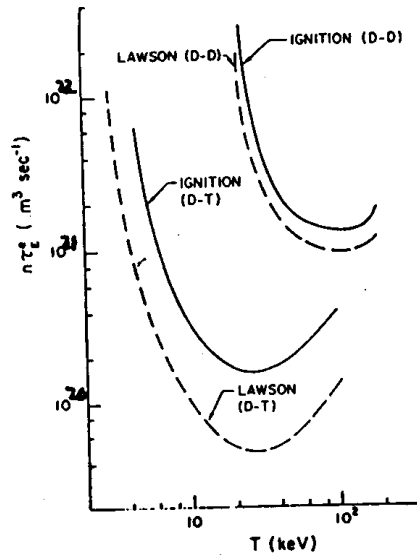
$$p_{ext} = \eta(p_{brems} + p_{lost} + p_{DT,n}).$$

Substitute using the earlier expressions and plot $n\tau_E$ vs T . There is a minimum at about 30 keV. This minimum leads to the so-called *Lawson criterion* that

$$\text{for D-T reactions, } n\tau_E > 10^{20} \text{ m}^{-3} \text{ s},$$

Similarly,

$$\text{for D-D reactions, } n\tau_E > 10^{22} \text{ m}^{-3} \text{ s}.$$



The temperature must be sufficiently high so an alternative criterion is that
for D-T reactions, $n\tau_E T > 5 \times 10^{21} \text{ m}^{-3} \text{ s keV}$.

Of course, economic viability will eventually be the most important consideration.

Ignition is when the power in the α 's is sufficient to balance the power lost by bremsstrahlung and escaping hot D and T ions. This is more difficult to achieve.

Major problems

Plasma confinement - keeping the hot plasma out of thermal contact with the vessel walls.

Plasma heating

Main candidates for controlled fusion

Magnetically-confined plasmas. Closed systems like tokamaks and stellarators.

Inertially-confined plasmas. Laser fusion.

Magnetic confinement fusion

Plasma confinement

The magnetic field guides the charged particles and restricts their diffusion to the walls. See Chapter II.

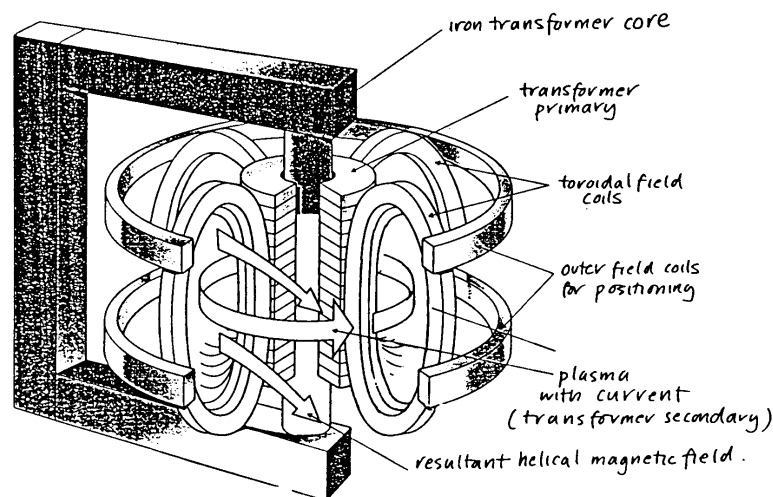
Use a closed system, a torus rather than mirror to avoid end losses.

Twist magnetic field lines to avoid $E \times B$ drift.

tokamak: internal plasma current

stellarator: external helical conductors

Tokamak



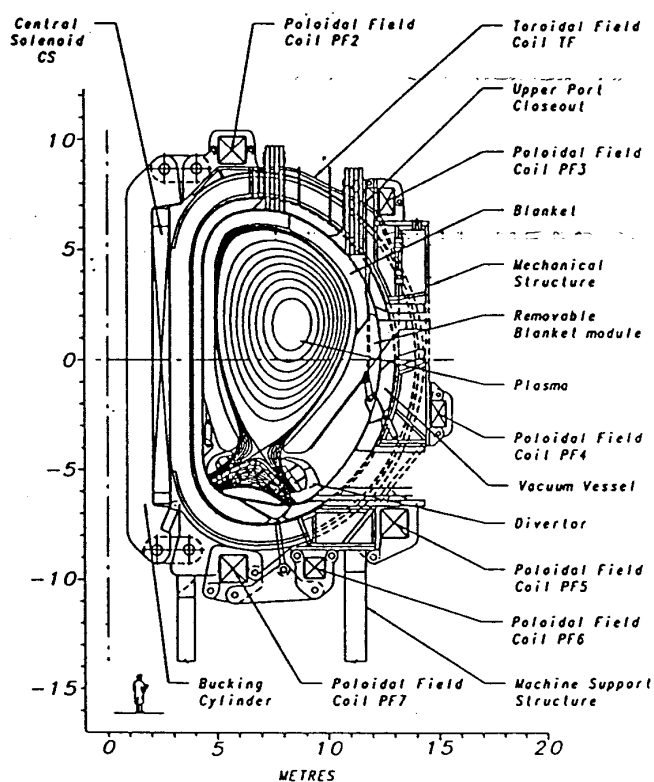
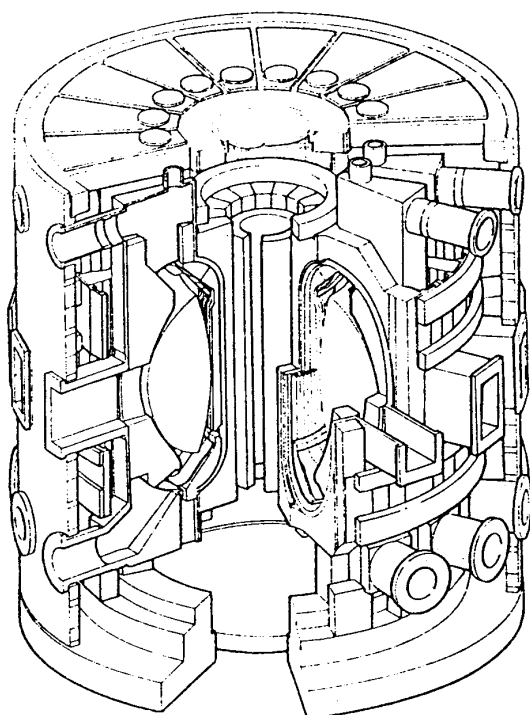
In a tokamak the plasma is like secondary winding of transformer.

The current heats the plasma (*Ohmic heating*) and helps confine it. Cannot analyse confinement and heating separately.

A steady current cannot be produced this way.

ITER (International Tokamak Experimental Reactor)

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Major Radius	8.0m
Minor Radius	3.0m
Elongation	1.6
Plasma Current	24MA
Toroidal Field	5.7T
Fusion Power	1.5GW
Burn Time	1000s

Existing large tokamaks

MACHINE	COUNTRY	MINOR RADIUS a(m)	ELONGATION κ	MAJOR RADIUS R(m)	PLASMA CURRENT I(MA)	TOROIDAL FIELD B(T)	INPUT POWER P(MW)	START DATE
JET	EC	1.00	1.8	2.96	7.0	3.5	42	1983
JT-60U	JAPAN	0.85	1.6	3.2	4.5	4.4	40	1991
TFTR	USA	0.85	1.0	2.50	2.7	5.6	40	1982
TORE								
SUPRA	FRANCE	0.80	1.0	2.4	2.0	4.2	22	1988
T-15	CIS	0.70	1.0	2.4	2.0	4.0	-	1989
DIII-D	USA	0.67	2.5	1.67	3.0	2.1	22	1986
ASDEX-U	GERMANY	0.5	1.7	1.67	1.4	3.5	16	1991
FT-U	ITALY	0.31	1.0	0.92	1.2	7.5	-	1988

Stellarator can operate steady state.

Existing and projected large stellarators.

MACHINE	COUNTRY	MINOR RADIUS A(m)	MAJOR RADIUS R(m)	PLASMA CURRENT I(MA)	TOROIDAL FIELD B(T)	START DATE
CHS	JAPAN	0.2	1		2	
HELIOTRON E	JAPAN	0.2	2.2		2	
WENDELSTEIN 7-AS	GERMANY	0.2	2		3.5	
H-1	AUSTRALIA	0.2	1		1	
LHD	JAPAN	0.5-0.6	3.9		3	1998
WENDELSTEIN 7-X	GERMANY	0.5	5.5		3	constr. begun

Plasma heating

Ohmic heating

$P = I^2 R$. However this is far from sufficient to reach fusion temperatures. Auxiliary heating is required. The main methods used at present and envisaged for the future are:

Electron cyclotron resonance heating

heat electrons, collisions transfer energy to ions.

The system proposed for ITER uses a bank of millimetre-wave gyrotrons each delivering a power of 1 MW cw at the fundamental frequency, 170 GHz, a total power > 60 MW.

Neutral particle injection

neutralize accelerated D and T ions in a gas cell.

neutral particles can pass through the magnetic field into the plasma.

in plasma, energy is transferred in charge-exchange collisions with cold ions.

TFTR used 4 neutral-beam injectors with accelerating voltages of 110 kV delivering 40 MW of power.

Ion cyclotron range-of-frequencies heating

DIID-D uses 4 MW of radio-frequency power in the 30-120 MHz range for heating and current drive.

Current drive

The plasma in the tokamak is like the secondary winding of a transformer and the current drops to zero at the end of the pulse.

The millimetre-wave power from the gyrotrons will also be employed to “push” the electrons so they move in the same direction thereby maintaining the plasma current.

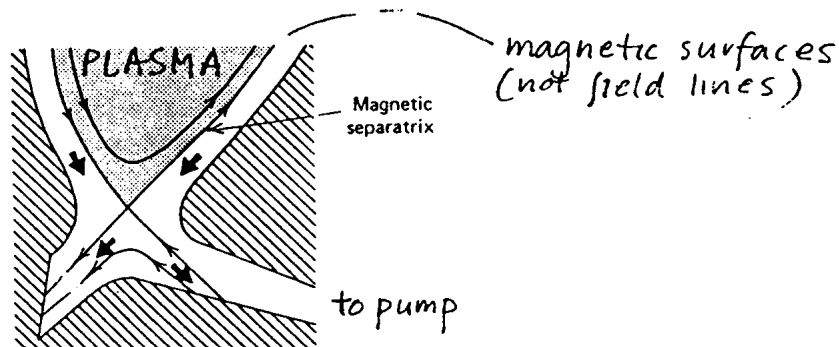
Impurities

Want to restrict impurities sputtered off the vessel wall to reduce bremsstrahlung radiation losses.

Choose suitable wall materials (e.g., carbon has a low Z).

Use *limiter* to define the outer boundary of the plasma and keep it away from the walls.

Use a magnetic *diverter* to divert particles into a separate chamber from which they are pumped out.



Stability

The operation of present tokamaks is limited not by confinement but by *disruptions* - if a certain maximum density is exceeded a MHD instability suddenly destroys confinement.

Other approaches

spherical tokamak, reversed-field pinch, spheromak
fission-fusion hybrid.

Inertial confinement fusion

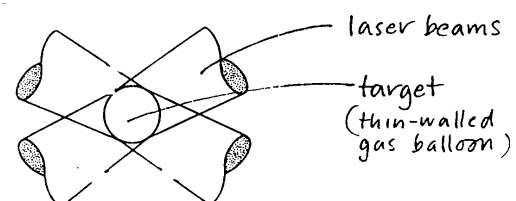
In laser fusion, the power from a bank of high-power pulsed lasers is focussed onto a D-T target.

Application of the Lawson criterion shows that the energy required to initiate a reaction is too high, we need to compress the fuel beyond solid densities. Need a central hotspot $100\text{-}200\times$ solid density at about 5 keV and the surrounding main fuel region $1000\text{-}5000\times$ solid density at a lower temperature.

Two kinds of targets are being studied:

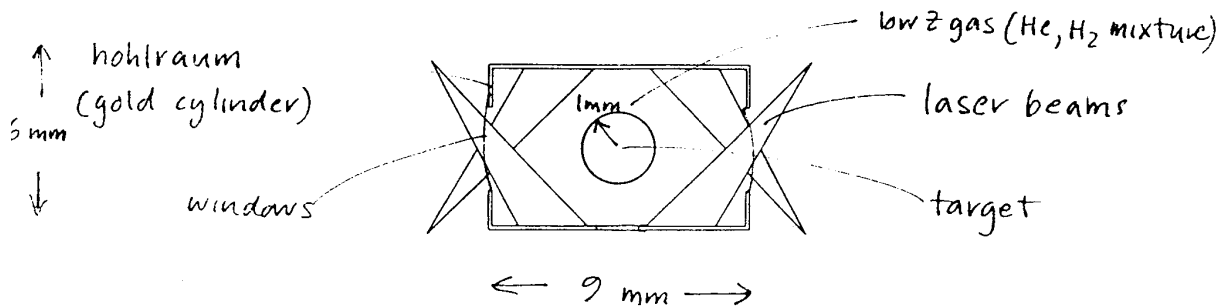
Direct drive

A spherical target. The fuel is surrounded by a spherical shell. The outer part is ablated and the rest of the shell implodes towards the centre compressing the fuel. This approach requires uniform irradiation to avoid instabilities.



Indirect drive

The target is in a hohlraum (a radiation cavity) made of a high-Z material. The laser beams strike the walls and are converted to x-rays. This gives a more uniform implosion.



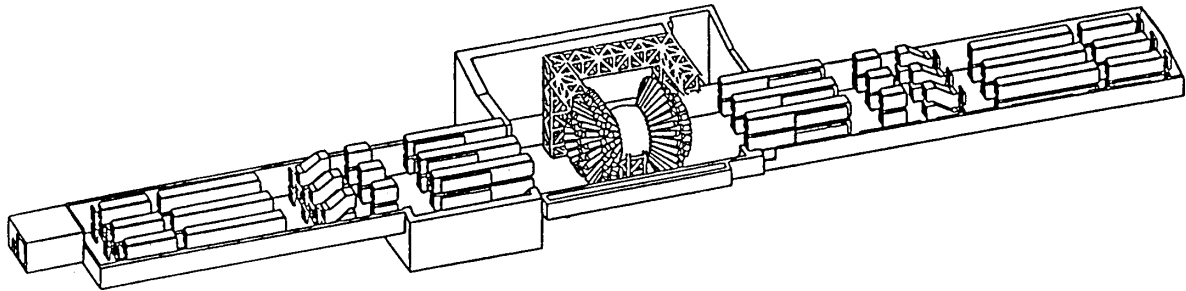
The lasers used in the present high-power experiments are Nd-glass lasers operating in the infrared at $1.06 \mu\text{m}$. The radiation is frequency-tripled to 351 nm .

Current installations

MACHINE	COUNTRY	ENERGY (kJ)	NO. OF BEAMS
NOVA	USA	40	10
GEKKO	JAPAN	100	12
OMEGA	USA	30	60

Experiments can achieve $1000\times$ solid density, can produce neutrons.

The illustration shows the Nova upgrade.



NIF Proposed National Ignition Facility

1.8 MJ, 500 TW peak power, 20 ns pulse glass laser. 192 beams grouped into 12 lines. Targets have been designed on the computer that should ignite under a 1.35 MJ pulse.

Other approaches

Inertial confinement fusion by light ions and heavy ions is also being studied.