An introduction to fusion energy : magnetic confinement

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Fusion processes and the Sun

The purpose of research on **thermonuclear fusion** is to try to reduce to the scale of a power plant the process that keeps the stars lit.

This is far from straightforward for first principle reasons.

The Sun emits in the form of radiation, mainly electromagnetic, a power equal to

$$L_\odot \sim 4 \times 10^{26}\, W ,$$

and has a mass $M_\odot \sim 2 \times 10^{30}\, kg$ which corresponds, if it were made only of hydrogen, to a number of atoms N equal to

$$N \sim 10^{57} .$$

How old is the Sun ? We find[1]

$$T_\odot \sim 5 \times 10^{9}\, \text{years} \sim 10^{17}\, s .$$

[1] for example from dating obtained with measurements of radioactive elements on the Earth or in comets.

Orders of magnitude

Now imagine that the Sun's energy source is chemical, almost as if it were a gas power plant capable of producing a power of $\sim 10^{26}\,W$. Let us not ask ourselves questions about how this combustion process can actually take place, let us just ask ourselves how long the Sun could sustain it.

Chemical processes are characterized by a release of energy of the order of a few electronVolts per atom (molecule), think of the potential difference generated by an element of a battery (e.g. old fashioned zinc carbon battery, $\sim 1.5\,V$).
One electronVolt corresponds to $\sim 1.6 \times 10^{-19}\,J$.

The chemical energy reserve would therefore be of the order of $\sim 10^{38}\,J$ and would be consumed in approximately $10^{12}s \sim 10^5$ years.
One hundred thousand years (and it is an overestimate) are too few, it is approximately the age of Homo Sapiens.

Fusion processes and the Sun

But the Sun is held together by the force of gravity which is associated with potential energy. The sun is thought to have formed by the collapse of a cloud of gas that heated up as it contracted.

Suppose that this is the energy reserve, but in order to estimate it we need to know the value of the solar radius: $R_\odot \sim 7 \times 10^8\, m$.
Forgetting numerical factors of the order of unity, we can estimate the energy released in the contraction of the cloud to be

$$\sim GM_\odot^2/R_\odot \sim 10^{41}\, J.$$

This energy reserve is much greater but it is not enough, it only allows an age a little less than $\sim 10^8$ years.

The solution to the problem came with the discovery in the last century of nuclear processes whose characteristic energy is of the order of MeV, i.e. one million electron volts.
If the nuclear energy reserve is one million times the chemical reserve the allowed life of the Sun is one million times longer.

Fusion processes in the Sun and in the Laboratory

The energy that stars radiate originates from the reactions of nuclear fusion in which, unlike nuclear fission, the nuclei of two light elements come together to form a heavier nucleus by releasing energy in the form of kinetic energy of the particles produced.

To obtain the fusion of the two light nuclei it is necessary to provide them with enough energy to overcome the electrostatic repulsion that tends to hold them separated[2].
But this would not be sufficient since the fusion cross-section is much smaller than the scattering Coulomb cross-sections so that e.g. a beam target configuration would not lead to a positive energy balance where the energy produced by the fusion reactions more than compensates the required energy input.
In a sense the particles of the beam and of the (already ionized) target must meet several times to compensate for all forms of losses and lead to a positive energy balance.

[2] By tunnelling past the Coulomb barrier.

Fusion processes in the Laboratory

The physical conditions where fusion can be used as an energy source are those of a *confined plasma* with a high “temperature”[3], of the order of a hundred million degrees Celsius (several keV) because of the Coulomb repulsion.

A plasma is an ionized gas in which the atoms are split into electrons and ions that are free to move under the action of the electromagnetic fields that they themselves help to generate.

In the universe, plasma constitutes by far the most common state of aggregation of visible matter while, on Earth, our special conditions of density and temperature mean that matter only rarely appears as plasma.

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[3] Here temperature is used in a loose sense as the average kinetic energy of the particles.

Fusion processes in the Laboratory

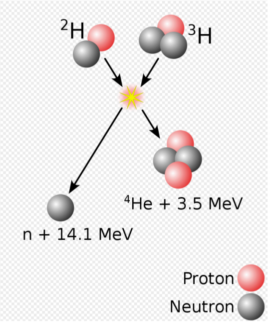
Even if in both cases fusion reactions are involved, the physical processes occurring in the production of energy in a laboratory plasma and in a star exhibit strong differences deriving from the *miniaturization* that is necessary in order to go from stellar dimensions to those of a laboratory and to ensure that energy is produced in a controlled manner.

This has the consequence that achieving “ignition” of a plasma is harder in the laboratory than in a star and requires more efficient fusion reactions and higher plasma temperatures[4].
In the process with the highest reactivity that will be first used for producing energy on Earth a Deuterium nucleus and a Tritium nucleus[5] fuse forming a nucleus of ^{4}Helium (i.e. an α particle) with the additional release of a neutron.

[4] On the terrestrial scale, but in an explosive regime, this ignition process has already been achieved in thermonuclear weapons since the 1950s .

[5] Generated in a closed process by neutron bombardment on a surrounding blanket of Lithium.

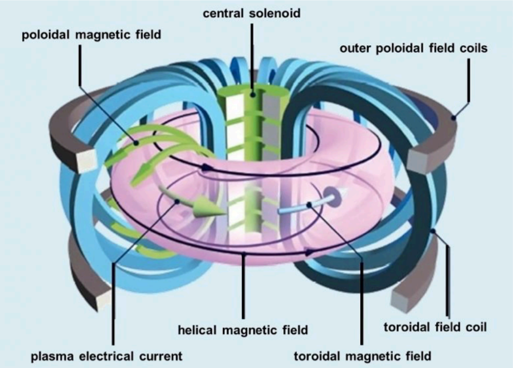
Fusion processes in the Laboratory



In a fusion plasma we have *ignition* when the power that the fusion reactions (the α particles) give to the plasma is sufficient to keep it in the required conditions (particularly temperature) even when energy is no longer supplied from outside in order to heat the plasma.

Fusion processes in the Laboratory

There are two main lines of research that compete to achieve ignition: magnetic confinement fusion and inertial confinement fusion.



In magnetic fusion the plasma is enclosed in doughnut shaped "magnetic bottles" and heated until it reaches the required conditions.

Fusion processes in the Laboratory

Why a toroidal (doughnut) geometry?
In a strong magnetic field charged particles follow essentially helical trajectories along field lines, i.e. magnetic confinement is only “perpendicular”. This is circumvented by adopting “closed” magnetic configurations (preferably azimuthally symmetric: *tori*).

Nearly 80% of the energy produced by the fusion reactions is carried by neutrons that cannot be confined by the magnetic field, while the energetic α particles must be confined so that they can deposit their energy in the plasma to maintain ignition. The energy of the neutrons is recovered by heat exchange in an external Lithium blanket.

Advanced fuels can also be considered in order to obtain *aneutronic fusion* and direct energy conversion but they require higher ignition temperatures. Of interest is the D-^{3}He reaction which produces an α particle and a proton (with a similar D-T energy balance because of isospin symmetry).

Some rough parameter values

The high temperatures of the confined plasma imply that material walls cannot be used because, if placed in direct contact with the plasma, they would quench it immediately[6].

In magnetic confinement the plasma pressure is counterbalanced by the pressure exerted by the magnetic field[7]. In practice, for reasons related to thermal and in particular mechanical stresses, it is not possible to generate stationary magnetic fields larger than about 10 Tesla (somewhat higher with high temperature superconductors).

It follows that the plasma pressure that the magnetic field can counterbalance is limited. $\beta = 8\pi p/B^2 << 1$

Therefore, at a fixed temperature, the (numerical) density of the plasma, is also limited. For a plasma with a temperature of the order of tens of keV the density n of the plasma cannot be larger than $\sim 10^{21}\, m^{-3}$, a density that corresponds to that of a very rarefied gas.

[6] High temperature does non mean large heat, however (localized) wall damage is a serious risk.

[7] Both generated by the induced plasma current and, mostly for stability, by external magnets.

Some rough parameter values

For similar reasons of mechanical stress the dimensions that the magnet and therefore the plasma can have are at most on the order of several meters.

It is easy to verify that in these conditions the plasma is by far too diluted (and too small) to retain the fusion produced neutrons. Most importantly, under these conditions, the plasma is transparent to the electromagnetic radiation that it emits, for example Bremsstrahlung radiation (power density $\propto n^2 T^{1/2}$).

This causes the loss of power (by radiation) from the plasma to be proportional to its volume, contrary to what happens in a star.

In a physical system that is not transparent to its own radiation electromagnetic losses are proportional to its surface area, not to its volume. Since the power production due to thermonuclear reactions is proportional to the volume, in a celestial body the ignition condition can be satisfied as long as the celestial body is sufficiently large.

Ideal ingnition conditions

The "miniaturization" from stars to plasmas in the laboratory corresponds to the transition from a dense (electromagnetically opaque) system to a thin (transparent) system. This is the main reason why *it is harder to achieve ignition in the laboratory: it requires very "efficient" nuclear reactions, no high Z impurities*

that increase the Bremsstrahlung losses and reduce the density of the reacting nuclei at constant electron pressure

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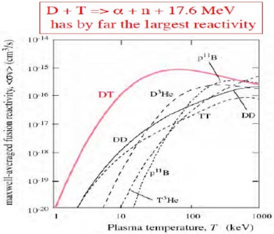

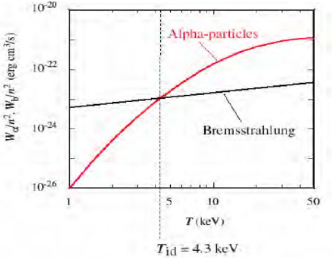

Lawson criterion: The power deposited by the fusion α particles must compensate for all losses. If losses were restricted to Bremsstrahlung radiation, since both fusion reactions and Bremsstrahlung depend on the square of the density, this criterion would define an ideal ignition temperature: $\sim 4keV$ for a D-T plasma.

Anomalous losses

Bremsstrahlung and synchrotron radiation are not the only form of losses of a fusing plasma: its density and temperature are inherently inhomogeneous and thus conduction and convection enter into play.

A major point to stress is that the required temperature and density conditions lead to the non-applicability of quasi- thermal-equilibrium methods to estimate the rate of energy and particle losses[8].

Binary processes becomes increasingly marginal as the plasma temperature grows[9] and the plasma density and energy transport turns out to be *anomalous*, i.e. governed by the onset of collective fluctuations of the plasma density and temperature and of the electromagnetic fields with amplitudes far above those expected in the near thermal equilibrium limit.

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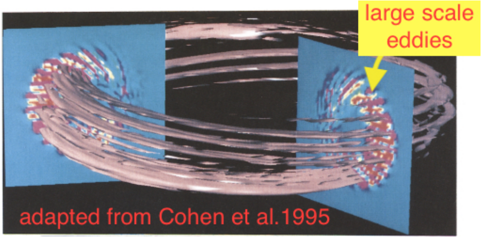
[8] The Coulomb cross section decreases as the square of the particle energies: the hotter the plasma the less binary collision effects count.

[9] at least until the e.m. field can be treated as a classical field.

Anomalous losses

These collective excitations are in general non-local (i.e. they depend on the global magnetic structure of the plasma configuration) and may not be easy to diagnose and control.
They may develop as turbulence or generate coherent large scale structures, see eddies below, that mix different plasma regions.



One of the main aims of the magnetic fusion experiments has been to clarify the physics of these processes in plasmas approaching ignition conditions and to search for plasma configurations and operational regimes that reduce the impact of anomalous transport processes.

The tokamak approach. The Joint European Torus

The Tokamak (Russian for “Toroidal Chamber inside Magnetic Coils") has been the main experimental line in magnetic fusion research. Its relative structural simplicity (the secondary of a transformer) has contributed to achieving the best experimental results so far. This may not imply that it will the most suitable configuration for fusion.

JET parameters

Major radius $\sim 3\,m$

Plasma volume $100\,m^3$

Plasma current 3.2 - $4.8\,MA$

Toroidal magnetic field $\lessapprox 4\,T$

Poloidal magnetic field $\lessapprox 0.4\,T$

In Dec. 2021 JET produced $59\,MJ$ for $5\,s \to 11\,MW$ with an energy gain smaller than 1

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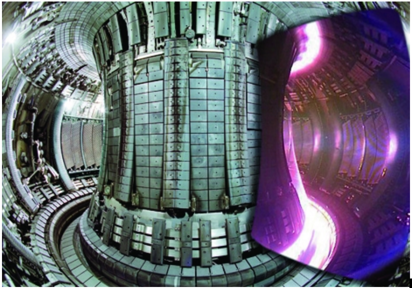
The plasma current confines the plasma and the α particles. The large toroidal magnetic is required for global stability.

JET - EAST Cooler border plasma emits visible light



Composite picture

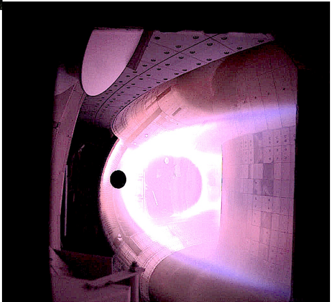
Joint European Torus

Culham UK

Experimental Advanced

Superconducting Torus

Heifei China



Expected power outcome

To be seen as a general indication as it depends on several assumptions that may turn out to be too restrictive.

We have seen that in a magnetically confined plasma its size, its temperature and density are essentially fixed by physical and engineering constraints.

In a D-T plasma with a volume of $\sim 600\,m^3$ (~ 6 times greater than JET), a temperature of ~ 20 KeV and an average density of $10^{20}\,m^{-3}$, the total energy of the plasma is of the order of a few hundred Megajoules.

Estimating from the measured plasma losses that the energy confinement time[10] must be of the order of seconds in order to reach ignition, we find that the power deposited in the plasma must be at least a few hundred Megawatts.

Recalling that 80% of the fusion power is not deposited in the plasma because it is transported by neutrons, we find a characteristic fusion power of the order of Gigawatts[11].

[10] The time it would take the plasma to cool down in the absence of energy sources.

[11] This is the fusion power, not the power in the grid which is reduced by the efficiency of heat extraction from the Lithium blanket.

Plasma Heating

The power that must be supplied to the plasma in order to bring it to ignition conditions is given by the ratio between the energy content that the plasma must reach and its energy confinement time.

Depending on the characteristics of the experiment it varies from several Megawatts up to over one hundred Megawatts.

The simplest and most direct method for heating a magnetically confined plasma is to exploit the ohmic power produced by the very current that confines it.

Since the resistivity of the plasma decreases[12] as its temperature increases $\eta \propto T^{-3/2}$ at fixed current the ohmic power $E \cdot J \propto \eta J^2$, becomes less and less effective the closer the plasma is to ignition conditions.

[12] As follows from the Coulomb cross section

Plasma Heating

Auxiliary heating:

two main types.

a) radio frequency heating
in which electromagnetic waves of great power and appropriate frequency (electron cyclotron, ion cyclotron, ...) are generated outside the plasma chamber and propagated in the plasma where they are resonantly absorbed,

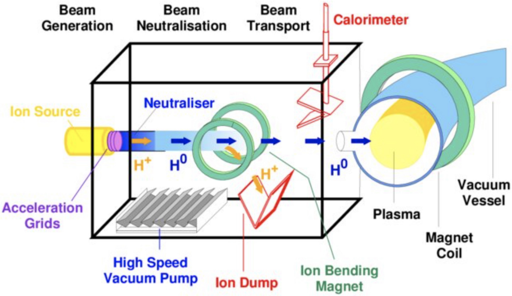
b) heating by neutral beam injection
in which a beam of atoms e.g. of high energy hydrogen (~ 100 keV neutralized, pre-accelerated protons) is injected into the plasma. Inside the plasma the atoms are ionized and, once ionized, they are trapped[13] and deposit their energy in the plasma.

[13] Injection of charged particles would be inefficient, essentially because of Liouville theorem

Auxiliary Heating

RF heating
on Alcator C Mod
Lower hybrid antennas
tunnelling the vacuum gap

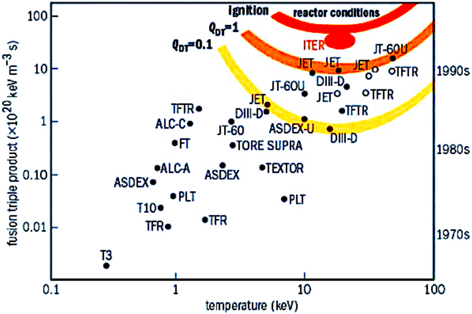
Schematic representation
Neutral Beam Heating
Note relative proportions



Figures of merit: Triple product

Triple product

Besides the Lawson criterion, the approach to the ignition conditions is often quantified by a similar figure of merit, the so-called triple product, defined as the product of the density times the temperature and the energy confinement time. This product can be taken as a (partial) indication of the progress of an experiment towards ignition. For a D-T plasma at ignition its value is $\sim 10^{21} keV\, s/m^3$.



Figures of merit: Q factor

Fusion energy gain factor

The fusion energy gain factor Q is the ratio of fusion power produced and the power required to maintain the plasma in steady state.

$Q = 1$ when power released by the fusion reactions is equal to the required heating power, it is referred to as power breakeven.

$Q = 5$ when power released by the α particles is equal to the required heating power, the minimum condition to maintain fusion burning.

$Q = \infty$ full ignition.

$Q > 5$ is needed in order to enter the so called “burning plasma regime” where plasma heating by α particles plays a major role.

Large vales of Q below the ignition value can lead to a reactor acting as an energy multiplier. The lower the values of Q, the higher will be the cost of the produced fusion power.

As of today's lecture

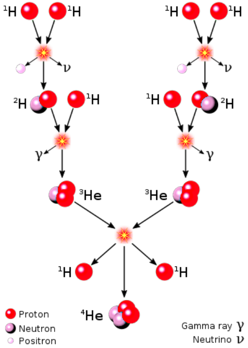
In this presentation I just mentioned a few basic facts about magnetic confinement fusion.
I spoke mainly about physics problems, but engineering and, in general, technological developments are also extremely important.

I did not mention the structure and the organization of the different research centers on magnetic fusion and how it changed over time. Nor did I detail the present state of advancement of fusion research, mention possible missed opportunities, list the different present projects, their research costs, or ask what will the political and social issues involving fusion energy be (will it also be widely available for less developed countries?).
I also avoided any prediction on when fusion power will be available to feed the world electric grid, and I did not try to evaluate what can be expected to be its cost for the consumer.

Some of these points will be addressed in the following lectures, starting from the next one on the principles of inertial fusion.

Numbers - p-p cycle

Coulomb cross section : $1.6 \times 10^{-20} / (W_{kev}^2)\, cm^2$
D-T fusion cross section at $10\,KeV$: $\sim 10^{-26}\, cm^2$



Sparc, Smallest/Soonest Possible ARC Cambridge MASS

High field parameters
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SPARC is a high-field ($B = 12.2T$), medium-size ($R = 1.85m$), deuterium-tritium (DT) capable machine under construction by Commonwealth Fusion Systems in Devens, Massachusetts (USA), with construction to be completed by 2025 and first plasma in 2026. The accelerated timeline of SPARC is enabled thanks to novel high-temperature superconductor technology, which allows the operation at high magnetic field at a moderate size.

The high magnetic field results in the capability to operate at high plasma current ($I_p \leq 8.7MA$) and high absolute density ($n_e \sim 3 \times 10^{20} m^{-3}$).