Thermonuclear fusion: the need for a rapid research effort in science and technology

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Funding for nuclear fusion

Expensive Iteration

A huge international fusion-reactor project faces funding difficulties

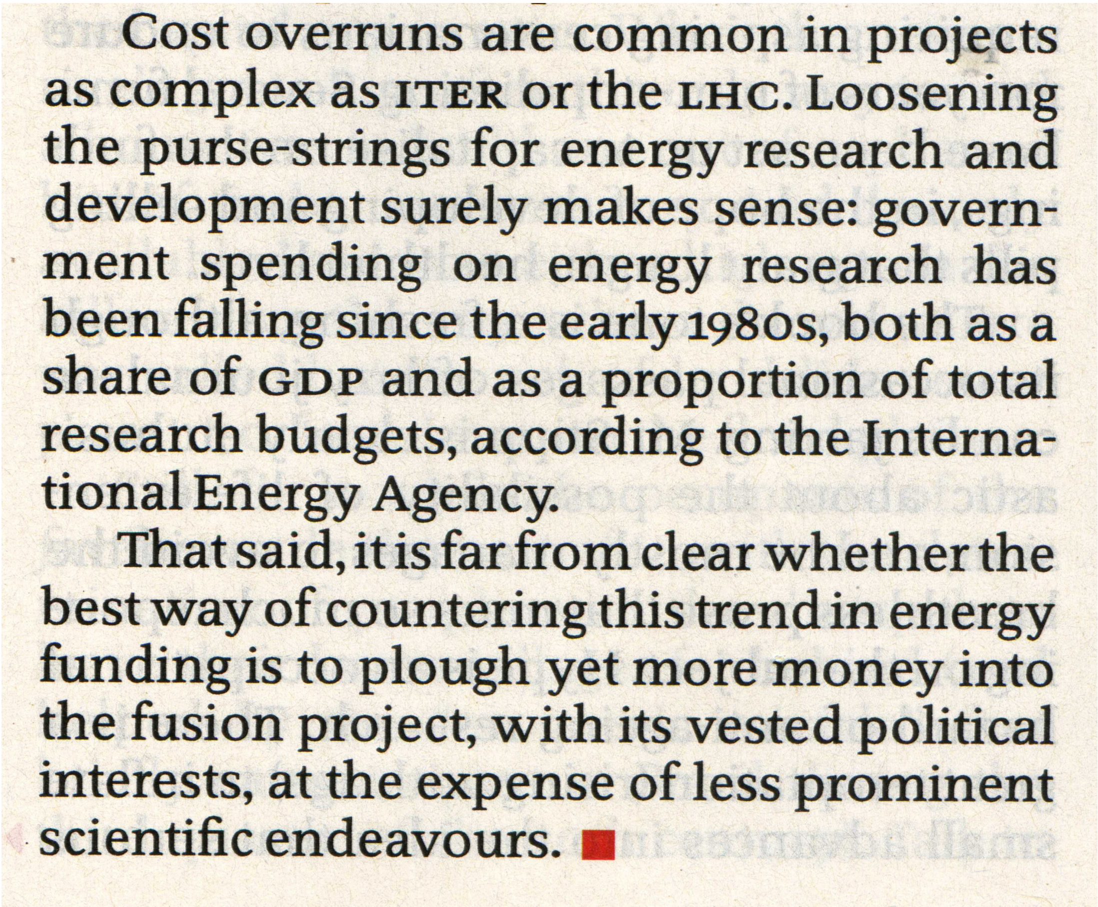
VIABLE nuclear fusion has been only 30 years away since the idea was first mooted in the 1950s. Its latest three-decade incarnation is ITER, a joint effort by the European Union (EU), America, China, India, Japan, Russia and South Korea to construct a prototype reactor on a site in Cadarache, France, by 2018. If all goes to plan, in about 30 years it will be reliably producing more energy than is put in.

Figure 1: From the *The Economist*, July 24^{th} 2010

For all its cosmic ambition, ITER has run into the earthiest of difficulties: spiralling costs. The project was never going to be cheap. Initial projections in 2006 put its price at €10 billion ($13 billion): €5 billion to build and another €5 billion to run and decommission the thing. Since then construction costs alone have tripled.

Figure 2: From the *The Economist*, July 24^{th} 2010

Jumping to the end of this short article, after a discussion over possible financial restrictions and cuts of the other EU research programmes, we read :



Cost overruns are common in projects as complex as ITER or the LHC. Loosening the purse-strings for energy research and development surely makes sense: government spending on energy research has been falling since the early 1980s, both as a share of GDP and as a proportion of total research budgets, according to the International Energy Agency.

That said, it is far from clear whether the best way of countering this trend in energy funding is to plough yet more money into the fusion project, with its vested political interests, at the expense of less prominent scientific endeavours. ■

Figure 3: From the *The Economist*, July 24th 2010

These excerpts from a recently appeared article identify three points I would like to have the opportunity to discuss here today:

- The nature and perspectives of thermonuclear fusion research and the perception that it is lagging behind,
- The expectations, cost and time-scale of the $ITER$ project,
- The need for a fast lane project to demonstrate the *scientific* viability of fusion.

On the first point I'll need to touch upon some physics and engineering issues.

Finally, in the Conclusions I'll mention some general observations about the price of fusion energy and stress a few points about safety.

Physics basis

The ultimate aim of the ongoing research effort into thermonuclear fusion is to bring processes similar to those that keep stars alight down to the scale of a power station.

At fixed "burned" mass, thermonuclear fusion produces approximately ten million times more energy than that produced by chemical reactions.

The energy that stars radiate originates from nuclear **fusion** reactions.
Contrary to **fission** reactions, in a fusion nuclear reaction two light element nuclei fuse and form the nucleus of a heavier element, releasing in the process a large amount of kinetic energy (and a lighter particle).

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons.* These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^{+}$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^{+}$, $N^{15}+H=C^{12}+He^{4}$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant

integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^{+}$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^4 *can be built up in ordinary stars.* This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

In order to fuse two light nuclei it is necessary to provide them with sufficient kinetic energy for them to overcome the Coulomb repulsion (the nuclei are positively charged and thus repel each other).

The physical conditions required for the nuclear fusion process to occur at a sufficiently fast rate in the laboratory require the fusing matter to be in the "state" of a high temperature $plasma$, i.e. of a fully ionized gas[1] with temperatures of the order of a few hundred million degrees.

In the Universe plasmas represent the most common state of visible matter, whereas the "anomalous" density and temperature conditions that are found on Earth make plasma phenomena appear only rarely.

[1] So "hot" that electrons are stripped from their atoms: the resulting gas of nuclei and electrons interact through electromagnetic forces.

Figure 4: Northern lights

Interest in the physics of plasmas started in the 1930s together with the development of radio communications and, soon afterwards, in connection with military developments and, most interestingly, in parallel with our growing understanding of the solar system (space physics and exploration[2]) and in general of astrophysical phenomena[3].

On the basis of the successful development of the thermonuclear bomb (the “H” bomb) after WW2, it was soon realized[4] that the fusion process could be harnessed in order to produce a peaceful energy source by reducing the scale and controlling the processes that feed the thermonuclear weapons.

[2]From the discovery of the Van Allen belts, of the solar wind, the understanding of the plasma processes that occur in solar flares to the highly "sophisticated" recent satellite missions in the solar system (and almost beyond).

[3]From pulsars magnetospheres and collapsed stellar objects to intergalactic plasma clouds.

[4]The II Geneva Conference, September 1958, is considered as the first world fusion conference. National research on fusion in many countries was declassified, following Academician Kurchatov's lecture at Harwell, UK in 1956.

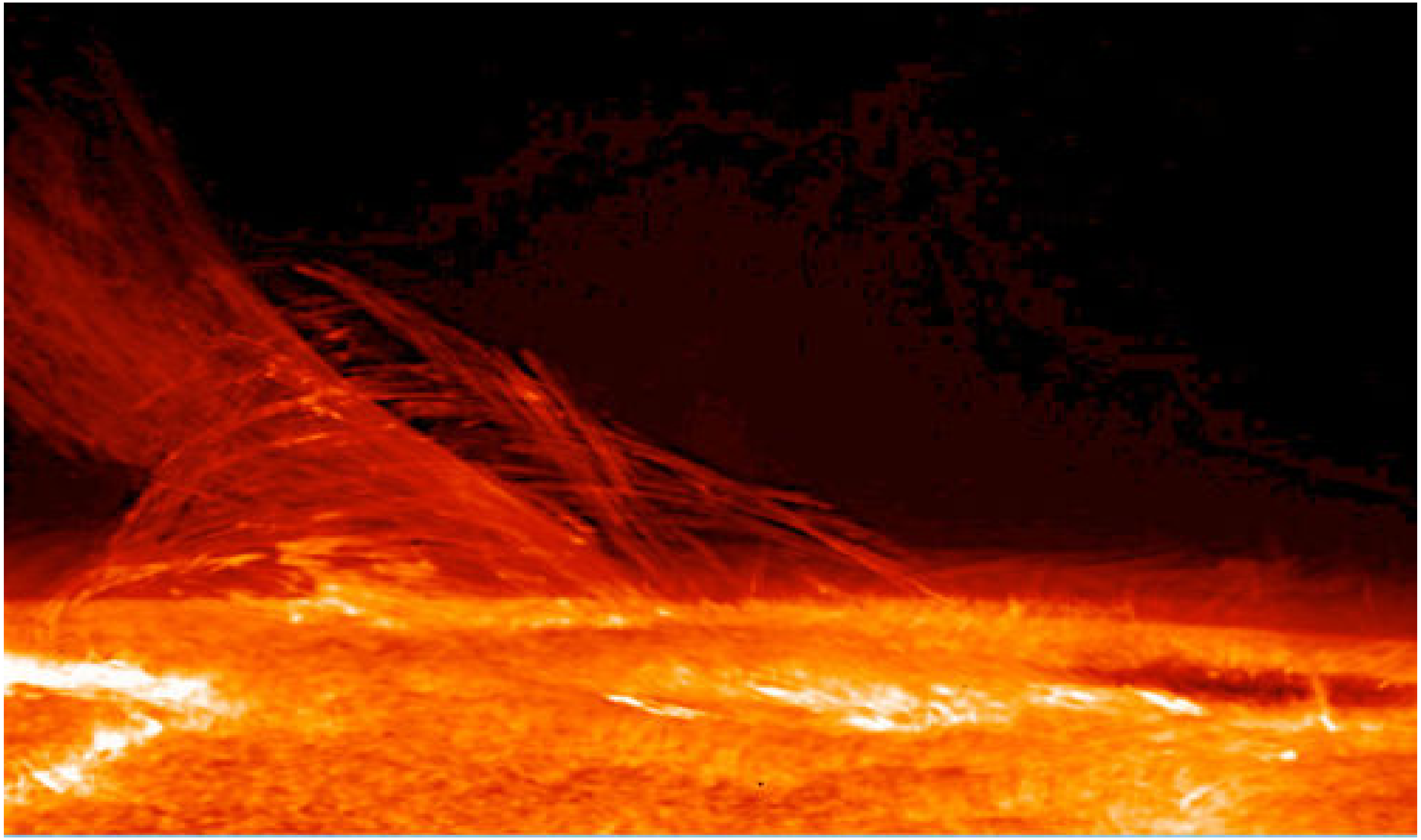


Figure 5: Image of the sun's chromosphere

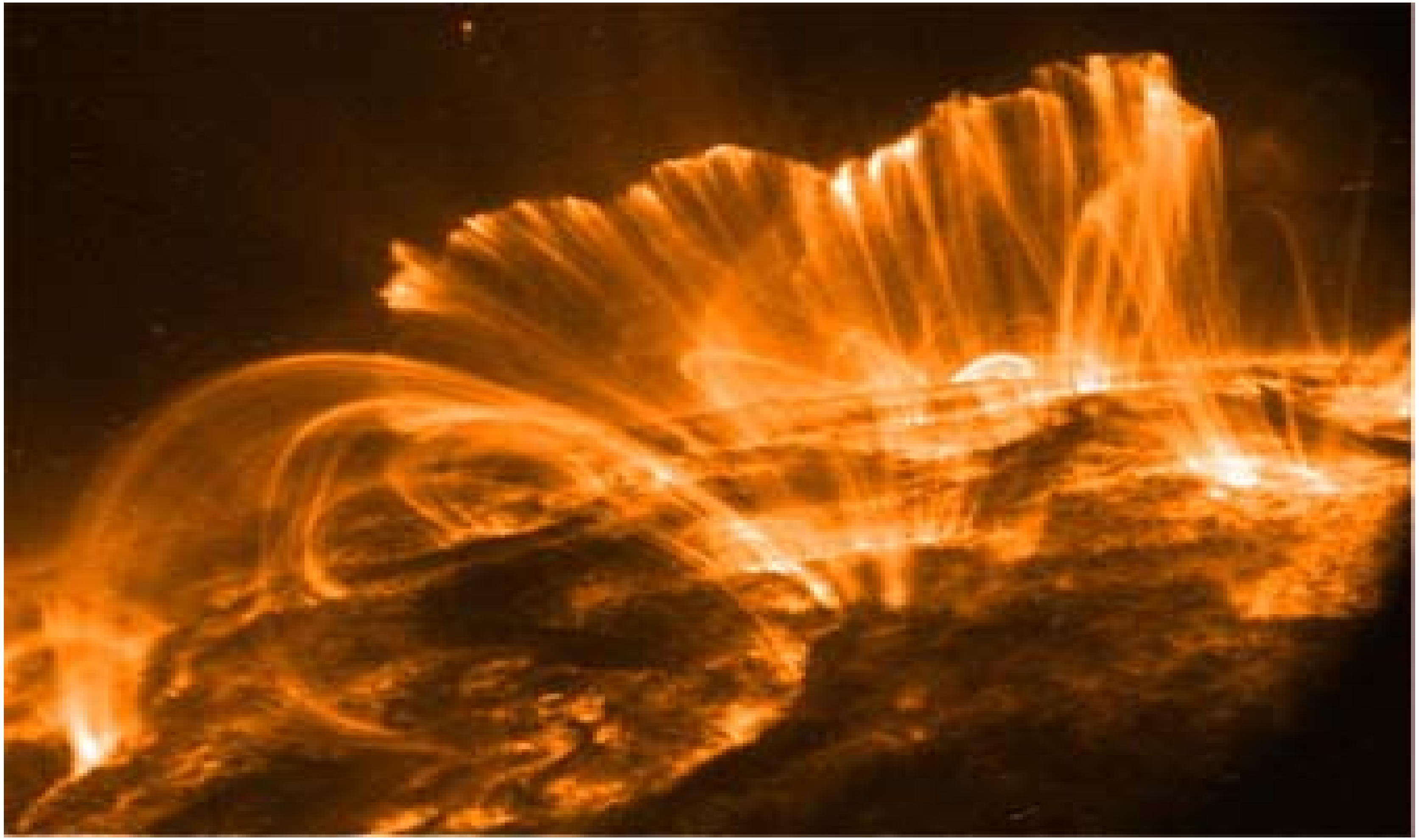


Figure 6: Solar Flares

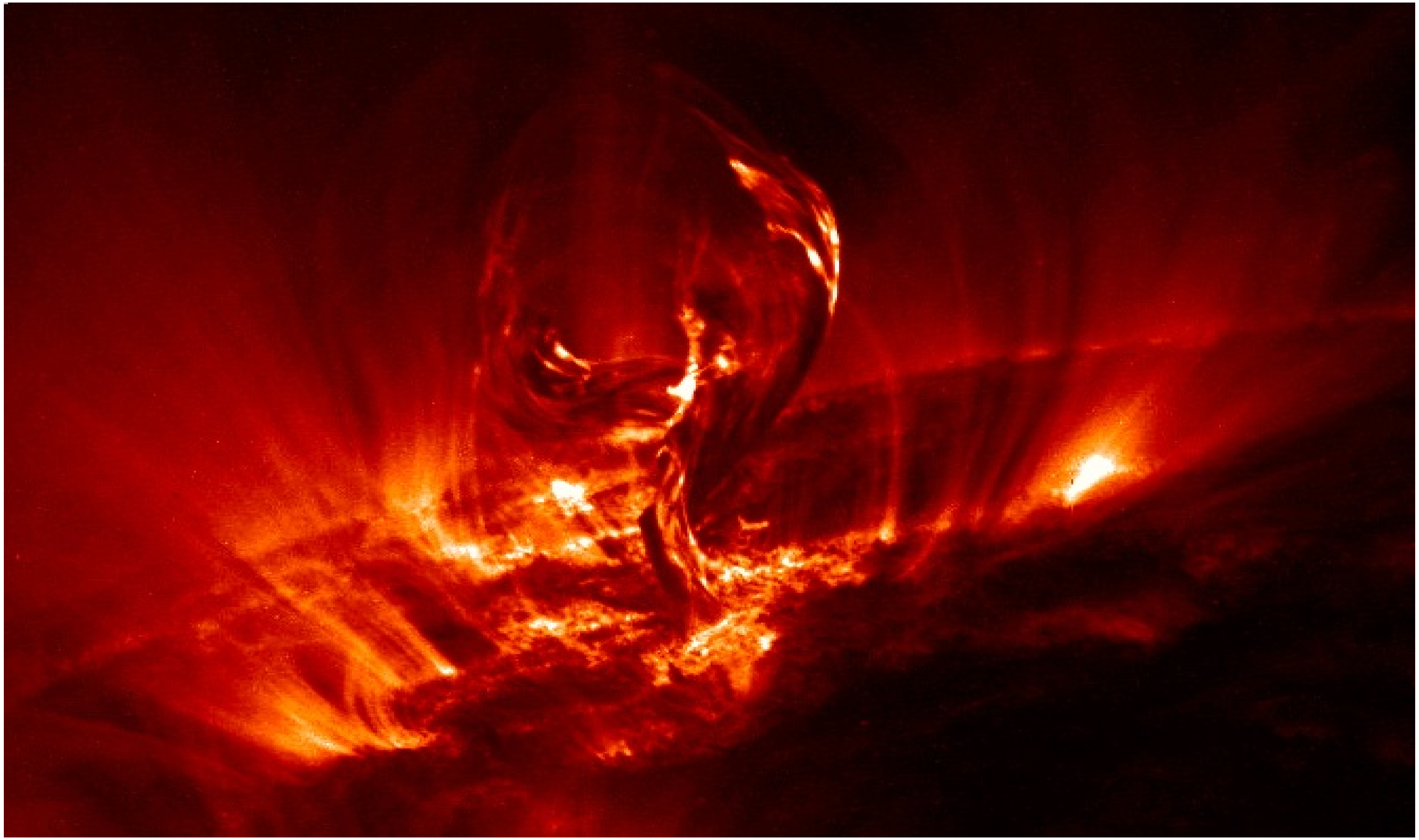


Figure 7: Solar filaments

Scale reduction

The physical mechanisms that are involved in the production of fusion energy in the laboratory are very different from those that light a star.

These essential differences arise from the reduction of physical scales from a gravitationally confined large object (a star that is opaque to its electromagnetic radiation) down to a small scale, electromagnetically confined, laboratory plasma that is transparent to its electromagnetic (e.m.) radiation:
• a star loses energy proportionally to its surface(essentially black body radiation) while it produces fusion power proportionally to its volume,
• a plasma in the laboratory loses energy proportionally to its volume and produces fusion power proportionally to its volume. *As a consequence "ignition" in the laboratory is more difficult than in a star and requires higher temperatures and*

higher yield fusion processes. *Per se* the observation that stars radiate and self sustain because they produce fusion energy is not a proof that net production of fusion energy can be obtained in the laboratory[5].

Figure 8: Castle Bravo (1954).

[5] On the scale of the Earth ignition has was reached in an explosive (uncontrolled) form in thermonuclear weapons in the fifties. Thermonuclear weapons are in a sense easier to realize because of their physical size larger than that uf controlled fusion experiments.

Ignition

In thermonuclear fusion we have a net energy production when the energy freed by the fusion reactions is greater than the energy that must be given to the plasma to bring it to, and maintain it in, the required temperature conditions (energy multiplier). We reach *ignition* when the fraction of the energy freed by the fusion reactions that is deposited into the plasma particles is greater than the energy that must be given to the plasma.

In the fusion reaction with the largest cross section a Deuterium nucleus and a Tritium nucleus[6] fuse forming a ^{4}Helium nucleus (α particle) and releasing a neutron[7].

[6] Hydrogen isotopes

[7] This process ($D + T \rightarrow^4 He + n$ releasing $17.6Mev$, of which $3.5Mev$ as kinetic energy of the α particle and $14.1Mev$ as kinetic energy of the neutron) is far more efficient that those that take place inside a star.

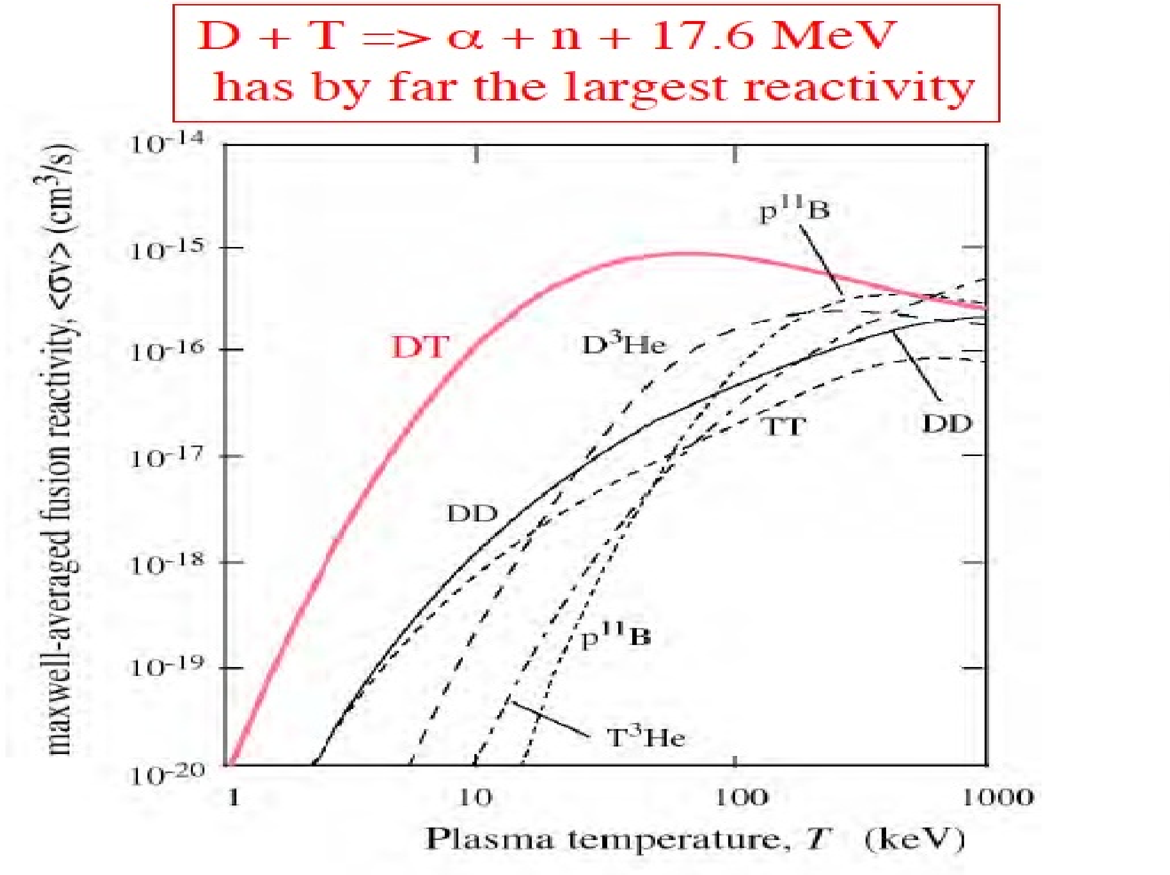


Figure 9: Fusion reactivity

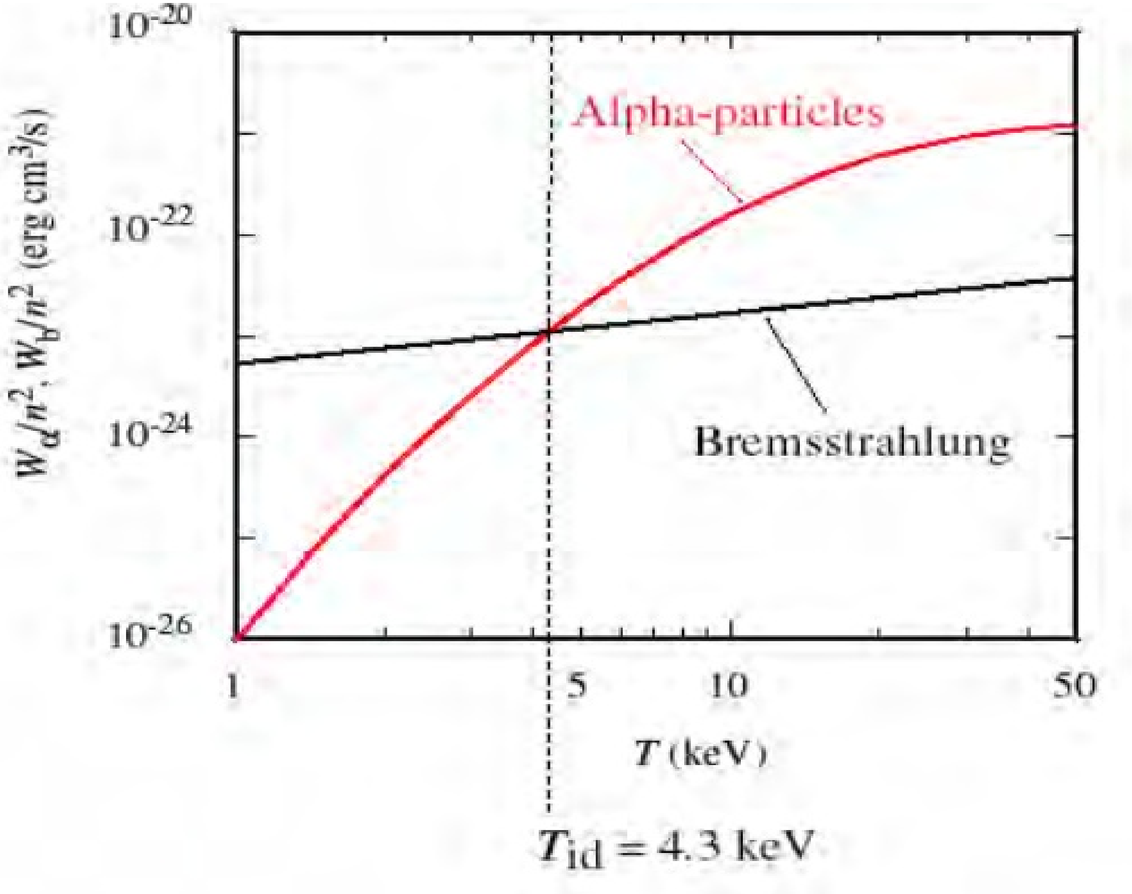


Figure 10: Ideal D-T ignition condition

Magnetic versus Inertial Fusion

There are two main lines of research development that compete in order to reach ignition: Magnetic Confinement Fusion and Inertial Fusion[8].
In magnetic fusion the plasma is confined inside a doughnut shaped "magnetic bottle" and is heated from outside in order to bring it to the required temperature conditions.
In inertial fusion a cryostatic pellet is compressed and heated through the use of an ultra-intense laser pulse shone on the pellet (direct ignition) or by the X-rays produced by a laser pulse shone on a (high Z material) capsule that contains the pellet (indirect drive).

In both schemes the energy produced will be extracted through a thermal cycle involving an external Lithium blanket.

[8] For a glossary of Fusion terms see e.g.: http://fusedweb.llnl.gov/Glossary/glossary.html

Deuterium can be easily extracted from water electrolytically (approximately one D nucleus for every 6500 Hydrogen nuclei). Tritium is a radioisotope and thus must be produced. Lithium is widely available in Nature and, when bombarded by the neutrons produced by the fusion reactions, it produces Tritium[9] which must be extracted and then reused[10].
It is also possible to reach ignition in the laboratory [11] in plasmas consisting either only of Deuterium or of Deuterium and ^{3}Helium. In these cases we obtain a strong reduction of the number of neutrons produced by the fusion reactions at the cost of higher plasma temperatures.

[9] It is necessary to have a breeding ratio slightly larger than one

[10] The relevant reactions are $n +^6 Li \rightarrow T +^4 He,\qquad n +^7 Li \rightarrow T +^4 He + n.$

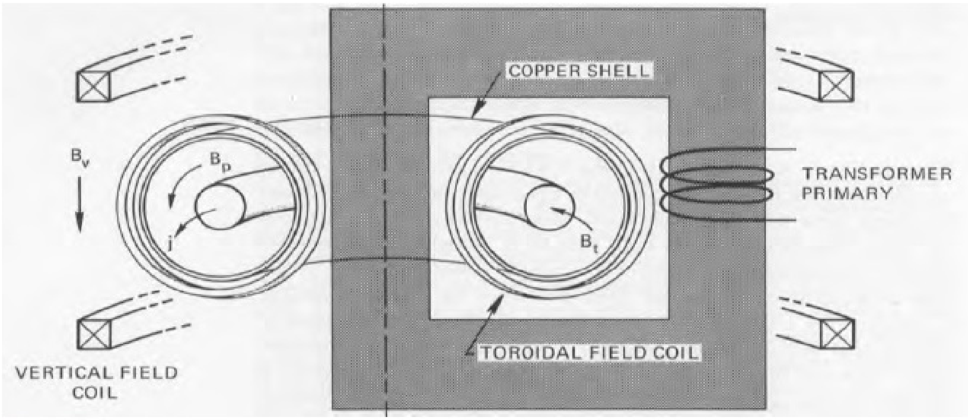
[11] According to the two reactions $D + D \rightarrow {}^3He + n$, $D + D \rightarrow T + p$ and $D +^3 He \rightarrow^4 He + p.$

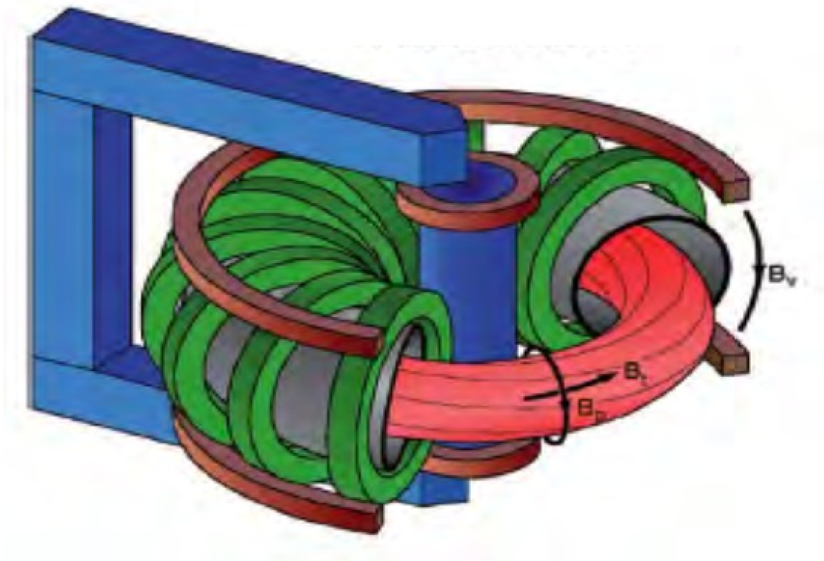
Main Physical Parameters

In magnetic confinement fusion the plasma pressure is counterbalanced by the pressure exerted by the magnetic field. Because of material properties related to the maximum mechanical and thermal stresses that the materials that make the external magnet can bear, it is not possible, on the required spatial dimensions, to generate static magnetic fields larger than, say, $\sim$ 20 Tesla. This constraint is related to the basic properties of materials and is thus difficult to overcome. As a consequence, at fixed temperature, the plasma density is limited.
In practice for a plasma with a temperature of the order of a few tens of KeV[12] the plasma density cannot exceed $10^{21}\ m^{-3}$, that corresponds to the density of a very rarefied gas.

[12]We use energy units for the temperature. An electron-volt (eV) corresponds to approximately $1.6\ 10^{-19} J$, i.e., to approximately ten thousand degrees Kelvin.

Tokamak

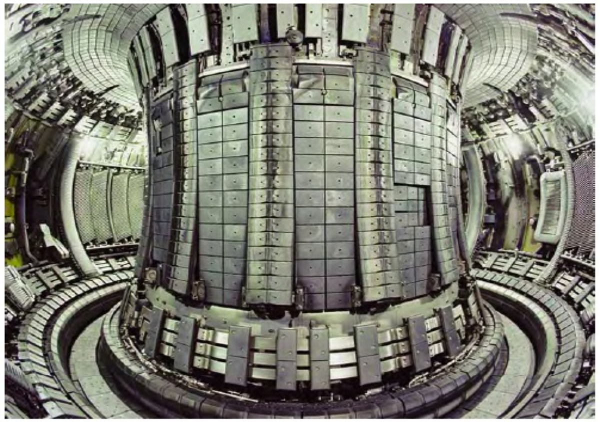

COPPER SHELL
TRANSFORMER PRIMARY
B_v
B_p
j
B_t
TOROIDAL FIELD COIL
VERTICAL FIELD COIL


B_v
B_t
B_p

Similarly the magnet, and thus the plasma, dimensions can be at most of the order of ten meters of so[13].

JET

raggio maggiore = 3 m, raggio minore = 1 m; B = 3.8 T, I = 7 MA,
riscaldamento ausiliario (rf + neutri) fino a 50 MW



(courtesy of EFTA-JET)

[13] The volume of the plasma chamber in JET is approximately $100\ m^3$

This makes the plasma transparent to its own electromagnetic radiation and at the same time leads to conditions where *the standard thermodynamic concepts do not apply*.

The physical behaviour of a multibody system far from thermodynamic equilibrium is much richer and much more complex than that of a thermal gas, being dominated by collective electromagnetic effects that overwhelm by orders of magnitude the effects of the "infrequent" (but conceptually much simpler) binary collisions.

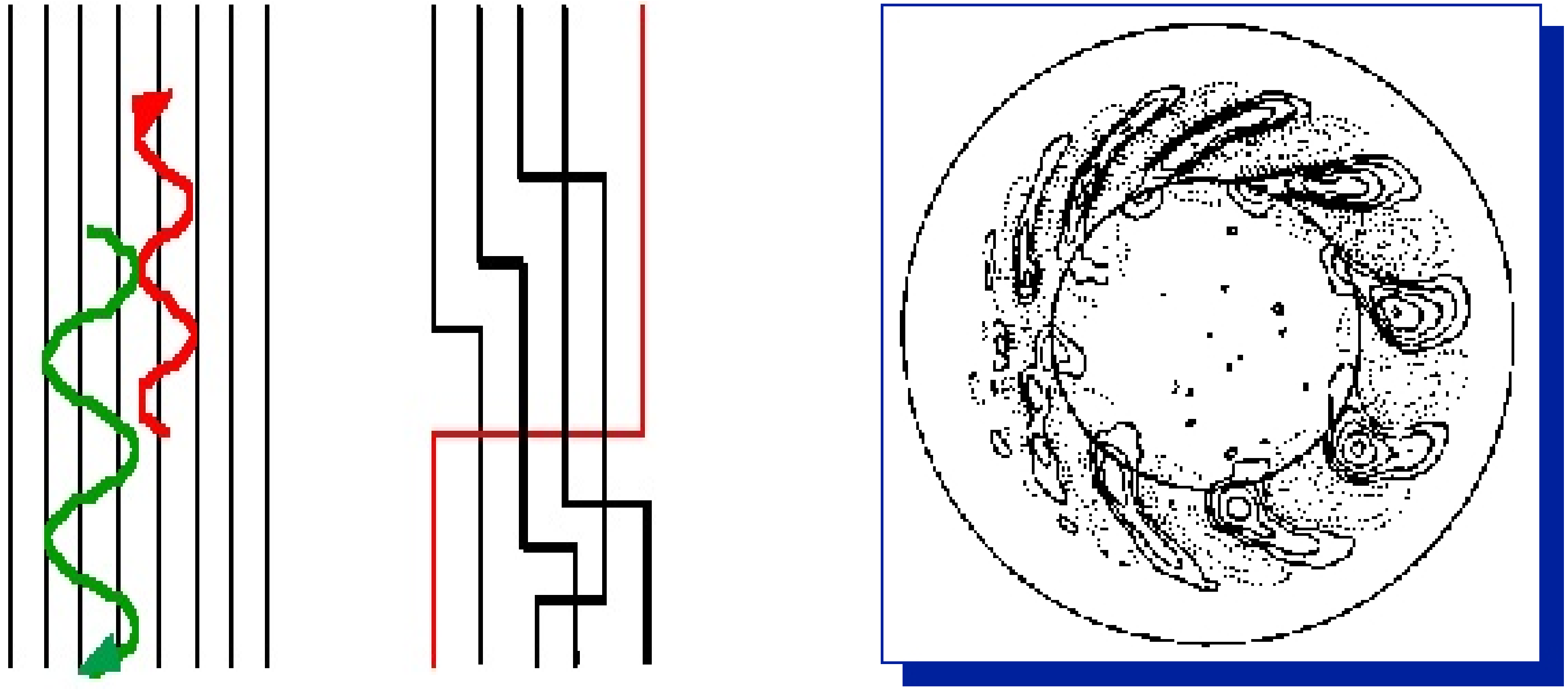


Figure 11: Transport mechanisms, classical left, anomalous right

In inertial fusion it is necessary to reach pellet compressions of the order of a thousand times the solid density for time intervals of the order of a few nanoseconds (10^{-9} sec) before the pellet re-expands. It is extremely important to obtain a highly symmetrical pellet implosion by limiting the effect of the onset of hydrodynamic instabilities of the type of the Rayleigh-Taylor instability.

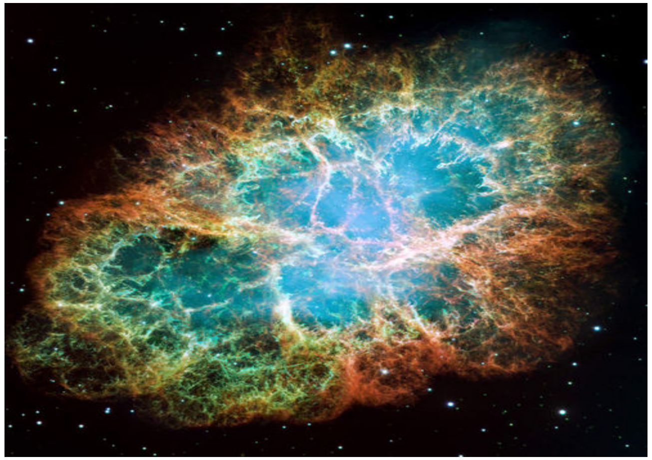
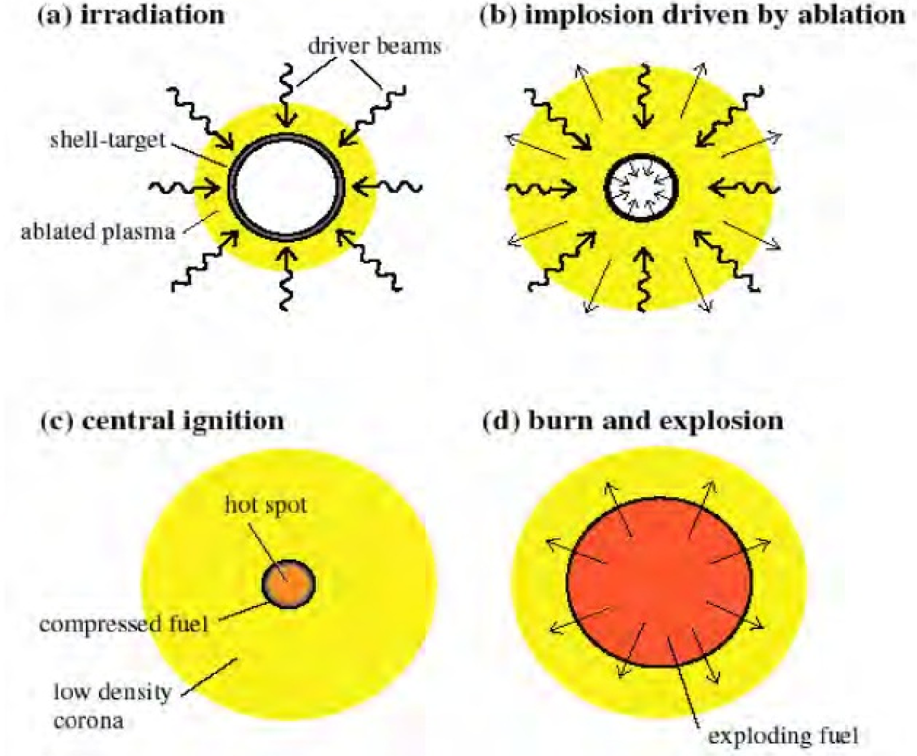


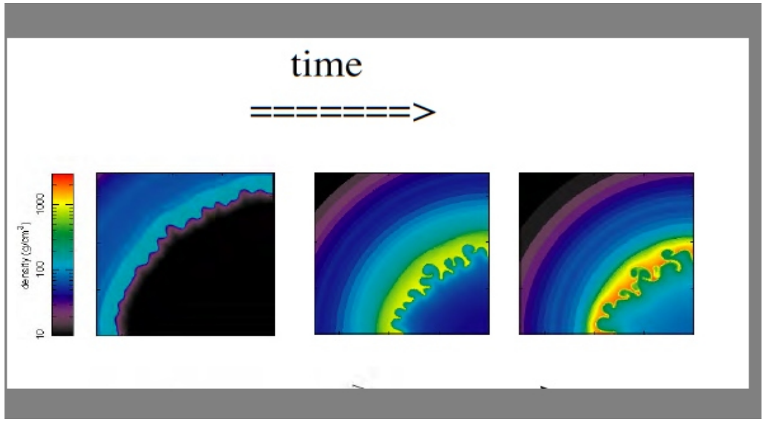
Figure 12: Rayleigh-Taylor instability in the expanding Crab Nebula

the standard approach: *central ignition*

imploding fuel kinetic energy converted into internal energy and concentrated in the centre of the fuel



(see, e.g., S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion, Oxford University Press, 2004.)



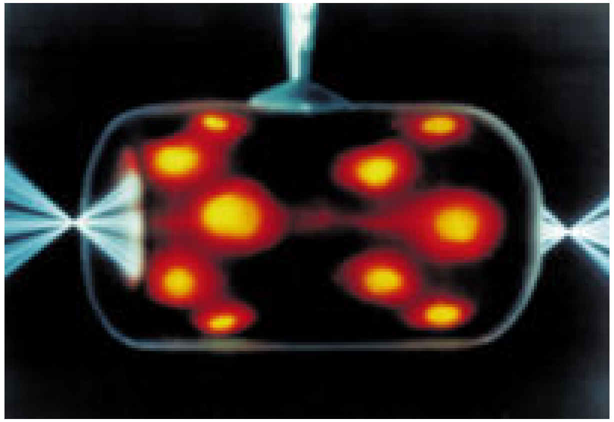


Figure 13: hohlraum for indirect drive

The so called Triple Product

In magnetic thermonuclear fusion literature the approach to the plasma ignition condition is often characterized in terms of a "figure of merit" (the so called Triple Product) involving the product of the plasma density, temperature[14] and energy "confinement time". The value of this product may be taken as a mark of the advancement towards ignition reached by a given magnetic fusion experiment[15]. For a D-T plasma the value beyond which, other required conditions being satisfied, ignition is reached is $\geq 10^{21}\ keV\,s/\mathrm{m}^3$.

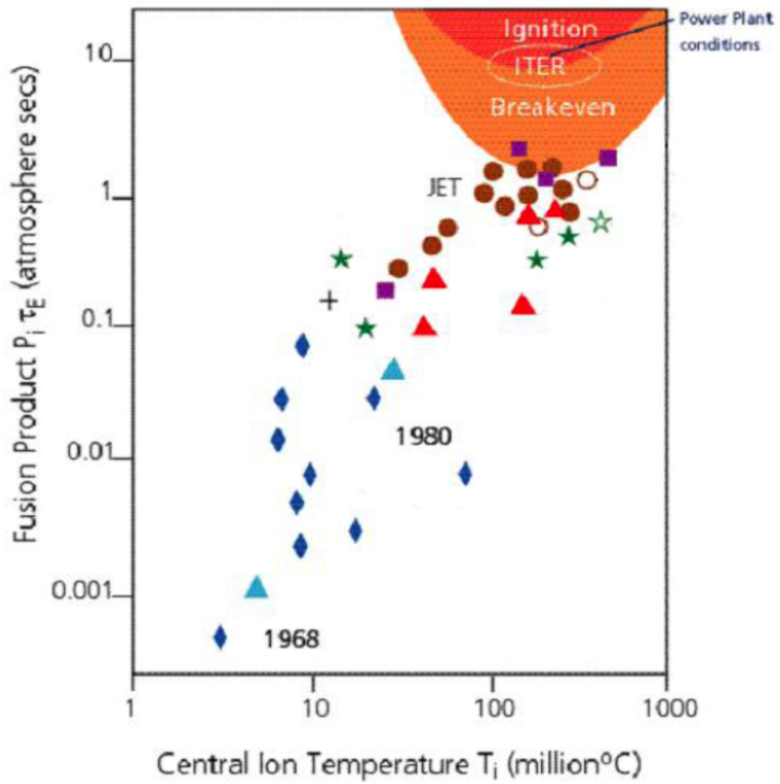
[14] Even if it is the nuclei that fuse, for reasons related to the plasma confinement, it is the electron temperature that should be used, not the ion temperature.

[15] Care must be taken in "interpreting" the record values given in the literature. In addition important parameters such a the plasma "purity" are not included in this figure of merit. If the plasma is not sufficiently pure, technically if its value of Z_{eff} is significantly larger than one, the plasma will not ignite whatever its temperature.

Fusion Progress Plot

Plot of the 'fusion product' (of the pressure (P) and the confinement time (τ_E) – which characterizes the time over which heat leaks out of a hot gas of fusion fuel) against temperature (T). The **Lawson Criterion** for the fusion of Deuterium-Tritium is satisfied in the orange region. The plot shows a small sample of results from different magnetic fusion confinement devices* (tokamaks). Results have moved steadily upwards in time, from the pioneering Russian result in 1968 at the bottom left.

* for the scientists: with the exception of some from JET and TFTR, the results are for deuterium



The region that ITER is expected to reach (on the basis of scaling up results from smaller devices) is indicated; ITER is being built by Europe, Japan, Russia, the USA, China, S Korea and India - a global response to the global problem of finding new, environmentally responsible, large scale sources of energy

Present situation and expectations

Both magnetic and inertial fusion are presently *close to reaching "burning" conditions*[16] *and, if well directed, full ignition conditions*.
In principle, burning conditions may be sufficient to realize an energy multiplier.

At this stage we are really talking about physics and technology *experiments* aimed at demonstrating the scientific feasibility of magnetic fusion, **not about fusion reactor prototypes**[17]**.**

[16] Defined as the regime where the energy deposited in the plasma by the charged fusion products dominates the plasma heating but is not yet sufficient to sustain the fusion reactions without an additional external energy source.
[17] Despite what you can find widely advertised e.g., on fusion web sites. See under the heading "Demo" http://en.wikipedia.org/wiki/DEMO.

Actually it is not even yet settled which of the two lines will eventually lead to a fusion reactor.
It is likely that this choice will be made will be in favour of the first line that reaches ignition, or at least energy multiplication conditions[18].

The physics[19], engineering and technology issues[20] that must be addressed in both approaches to fusion are complex. In addition, in part they do not overlap, which partly justifies their parallel and often competitive development.

[18] Once a FULL evaluation of the system efficiency is made. This must include the efficiency of the final thermal cycle, the efficiency of the high power lasers needed for inertial fusion, their repetition rate etc....

[19] Energy transport, stability (e.g. effects of fusion products on the onset of electromagnetic instabilities, wall loading etc...

[20] The behaviour of materials under extreme neutron fluxes, the efficiency of the Tritium breeding rate etc.

Open Physics problems: energy confinement time, plasma purity, relaxation instabilities

Some of the main physics issues of magnetic fusion are listed below.

Energy confinement time

The order of magnitude of the power that has to be given to the plasma to bring it to ignition conditions and that is finally sufficient to compensate for all energy losses is given by the ratio between the plasma energy content and the *plasma energy confinement time*. Depending on the plasma experiment characteristics it can range from several Megawatt to more than a Megawatt.

The energy confinement time in a fusion plasma is not determined by the effect of binary interactions between plasma particles (collisions), as would be the case in a gas at local thermodynamic equilibrium.
In fact due to the electromagnetic nature of the plasma particle interactions binary processes become irrelevant at high particle temperatures[21]

The energy confinement time in a fusion plasma is determined by the effect of the (micro)instabilities that inevitably occur in an inhomogeneous plasma. These lead to the onset of (micro)turbulence that determines the macroscopic anomalous transport properties of the system.

The study of the causal relationship between the measured anomalous (energy) transport and the physical mechanisms that can cause the onset of instabilities is still one of the major open problems in plasma physics, both in the laboratory and, in different forms, in space.

[21] The Coulomb cross section scales as T^{-2}.

The aim would be a *predictive* and quantitative understanding of transport.

In practice, it is not possible at the present moment to have a *detailed* prediction, based on a theoretical or even on a experimental basis, of how the new instabilities that we expect to occur in a burning plasma (driven by the fusion-produced α particles) will affect its macroscopic transport properties.

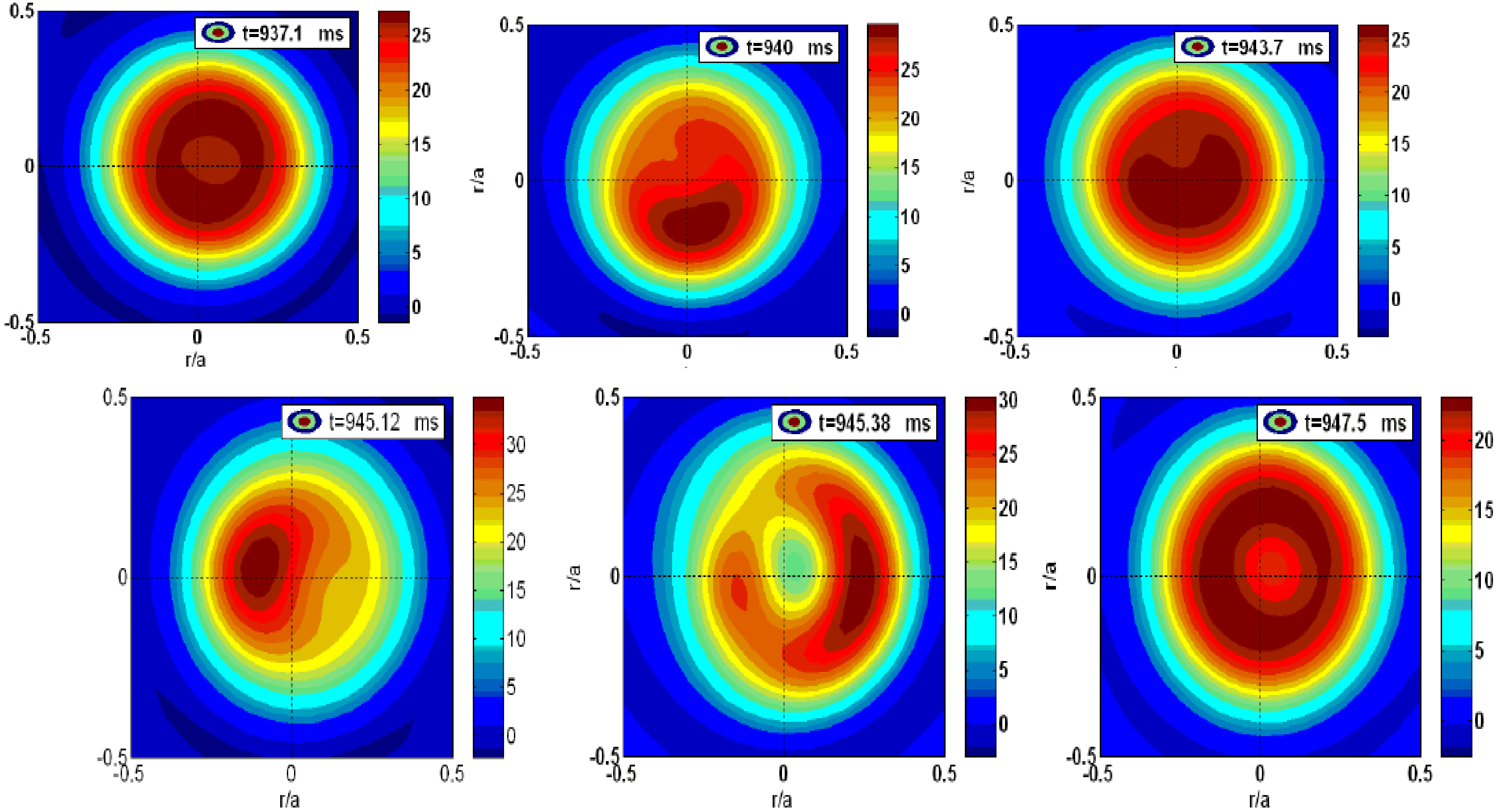
Phenomenological approaches do exist, but by necessity these models have been tested on a relatively narrow range of parameters and cannot be safely extrapolated to a burning plasma experiment where a factor two uncertainty on the value of the energy confinement time can discriminate between a successful and an unsuccessful experiment.

Relaxation instabilities

Besides the microinstabilities that are responsible for the anomalous transport processes, in a magnetically confined plasma macroinstabilities may occur and develop on large spatial scale of the order of the size of the experiment. Since these instabilities affect the whole plasma configuration, they can either destroy it or at least significantly rearrange it. It is clear that one must design the experiments in such a way that the most dangerous of these instabilities cannot occur. In present experiments and in the experiments that have been proposed in order to study burning or ignited plasmas, the main macroscopic instabilities are still likely to be the relaxation instabilities of the plasma current.

The peculiar temperature dependence of the electrical resistivity in a plasma (the resistivity decreases as $T_e^{-3/2}$) causes the plasma current to filament and concentrate in the hottest part of the discharge making it still hotter. This process is interrupted by a macroscopic instability that redistributes the current and expels the hotter part of the plasma.
The central temperature in the plasma is thus subject to sawteeth oscillations which correspond to a repetitive cooling of the portion of the plasma where most fusion reaction should occur.
In addition this relaxation process could scatter the fusion-produced α particles before they can deposit their kinetic energy into the plasma.

Tomographic reconstructions



Plasma density and purity

Besides energy, it is also necessary to replenish the plasma with particles in order to keep its density steady or, e.g., to increase it during the plasma start phase.

Most importantly it is imperative that the plasma should not be *contaminated by impurities* (heavier nuclei) originating from the (metallic) wall of the experiment under the action of particle bombardment and/or localized excessive energy deposition.

•• It is thus necessary to investigate experimentally the behaviour of a burning, actually of an ignited, plasma before being able to design a reactor prototype based on magnetic fusion.

Considerations along these lines hold for inertial fusion too.

Material science problems.

At fixed power the neutron flux in a DT fusion reactor will be approximately one hundred times larger than in a fission reactor.
Even if, clearly, the energy of the fusion-produced neutrons is correspondingly smaller than that of fission-produced neutrons, this large neutron flux will give rise to a range of difficult technological problems.

In addition the neutron flux could cause activation of the external structures confining the plasma.

All these issues must be addressed before we proceed to the stage of designing a fusion reactor.

Material structural damage and activation

The large neutron flux raises the following issues.

1) the use of superconducting magnets i.e. whether superconductivity is quenched by the intense neutron flux,

2) the radiation fatigue of the confining structures, as the neutron flux can destroy their crystalline structure, in particular in conjunction with the large mechanical (and thermal) stresses these structure will be subject to,

3) the activation problem can be alleviated by using vanadium alloys instead of steel or by substituting some steel components such as molybdenum and nickel with manganese and tungsten. In this way we can ensure that no radioactive isotope is created with long decay times (tens instead of thousands of years), without degrading the mechanical properties of the external structures.

Material developments are also imperative in the case of inertial fusion where, after the ignition of a single pellet has been experimentally demonstrated, one must improve the repetition rate of the laser system [22] by a huge factor.

• • Even if it is extremely important to stress that *no "show stopping" problem has yet been encountered either in magnetic or in inertial fusion*, even this very restricted list of scientific, engineering and technological issues that must be addressed indicates that it is very difficult to set a believable date for the first fusion rector to come into operation. Certainly not in the next two decades.

This excludes the possibility that fusion might be able to contribute to any short term fixing of the energy problem, such as complying with the so called "20-20-20 objectives"[23] set by the EU.

[22] The repetition rate is limited by the time required to cool the large nonlinear crystals that are required for the pulse amplification from a few shots per day to, say, ten shots per second.

[23] 20% reduction in emissions, 20% renewable energies and 20% improvement in energy efficiency by 2020.

•• This apparently ever growing shift towards the future, as it is generally perceived by the public, of the realization date of fusion energy is due, in my opinion, to two main reasons that play synergically:

one is inherent to the fundamental scientific difficulty of realizing fusion in the laboratory in a controlled fashion,

while the second is due to a slow down in the development of research for something like fifteen years around the end of the last century

These years were characterized by a lack of well aimed political decisions and by an actual, even if not explicitly manifest, lack of interest in a large scale new energy source in the presence of cheap fossil energy.

Present plans in magnetic fusion

At the moment there are a few projects (for both magnetic and inertial fusion) that have been proposed, or that are under some stage of design or construction and that aim to explore the physics of a burning, or better of an ignited plasma, and to test solutions to the related engineering and technological problems.
These are mainly international projects, in particular in the case of magnetic fusion.
As already stressed, none of these projects can be considered a prototype for a fusion reactor.

In the following I will restrict myself to magnetic fusion and discuss briefly some characteristics of the ITER and of the Ignitor projects.

First, however, I would like to mention some documents that summarize the results of a scientific-political debate that took place in the very last two years in Italy.

XVI Legislatura

Senato della Repubblica

Commissioni permanenti 7a e 10a

INDAGINE CONOSCITIVA

SULLE RICERCHE ITALIANE RELATIVE ALLA FUSIONE NUCLEARE

Roma, giugno 2009

and in Europe

R&D Needs and Required Facilities for the Development of Fusion as an Energy Source

Report of the Fusion Facilities Review Panel
October 2008

Foreword

In December 2007 the European Commission established an independent Panel for a review of the R&D visions and the required facilities[i] of the European fusion programme. This review which is stipulated by the EURATOM FP7 Specific Programme on Fusion Research[ii] has the "motivations to support the rapid and efficient development of fusion as an energy source and to maintain in the programme the facilities needed to fulfil its medium and long term objectives". A vision of the R&D required to make fusion energy production ready for commercial exploitation shall be developed and all significant facilities, existing or under construction including proposed or considered upgrades, shall be reviewed. The required facilities should be incorporated in a road map; and prioritised according to the corresponding benefits, costs and risks. Non priority facilities should be identified. The full terms of reference to the panel are given in Annex I.

Towards burning plasmas: the ITER project

The international magnetic fusion experiment was first proposed at Reagan-Gorbachev times (1985).
ITER (International Thermonuclear Experimental Reactor) was officially approved in November 2006 when the ministers of the seven parties participating in ITER (EU, Russia, Usa, Japan, India Korea and China) signed the agreement that established the so called ITER Organization, as an "international collaboration to establish fusion as a new source of energy".

Construction has (slowly) started at the Cadarache site in southern France. As far as EU participation in concerned an EU administrative office, "Fusion for Energy", is based in Barcelona, Spain.
Its task will be to organise the contributions of EU Member States to the construction of the fusion reactor in Cadarache.

No "executive plan" had been completed at the time of ITER's approval in 2006

ITER had a long and costly "gestation" with alternating up and down phases [24]. The discussion on where to build the experiment (the last two competitors were Hokkaido in Japan and Cadarache) was apparently very fierce[25]. It has to be mentioned that in this project there is a very complex cost and contracts sharing scheme among the 7 partners where the host country (France) contributes in a prominent way to costs while receiving a large share on the contracts.

ITER construction should have been completed by 2016, when the first plasma was expected to be produced.

[24]USA left the project in 1999 but rejoined it in 2003, Canada after joining the project left it in 2003

[25]The stepping down of Japan was "compensated" by several financial advantages that Japan will enjoy, such as a higher contracts/contributions ratio, and by becoming host to the large parallel activities related to the main project development.
In a sense Japan an excellent game of poker with Europe which did not call a likely bluff and lost.

However it was soon realized, when an executive plan was finally worked out, that the envisaged schedule was completely non realistic and the experiment piled up delays before even starting.
Costs followed a similar path to the point that the trimming down of the project hardware was recently hotly discussed.

It is not easy to give a safe date for the start of the experimental activity on ITER (at least some 3 years after the initially scheduled date), in particular in a time of economic crisis and wide cuts of scientific research budgets, see e.g. the articles on ITER published in the last two years by “Nature”.

The experimental activity will last for two decades with “significant” results not expected before, say, 2030

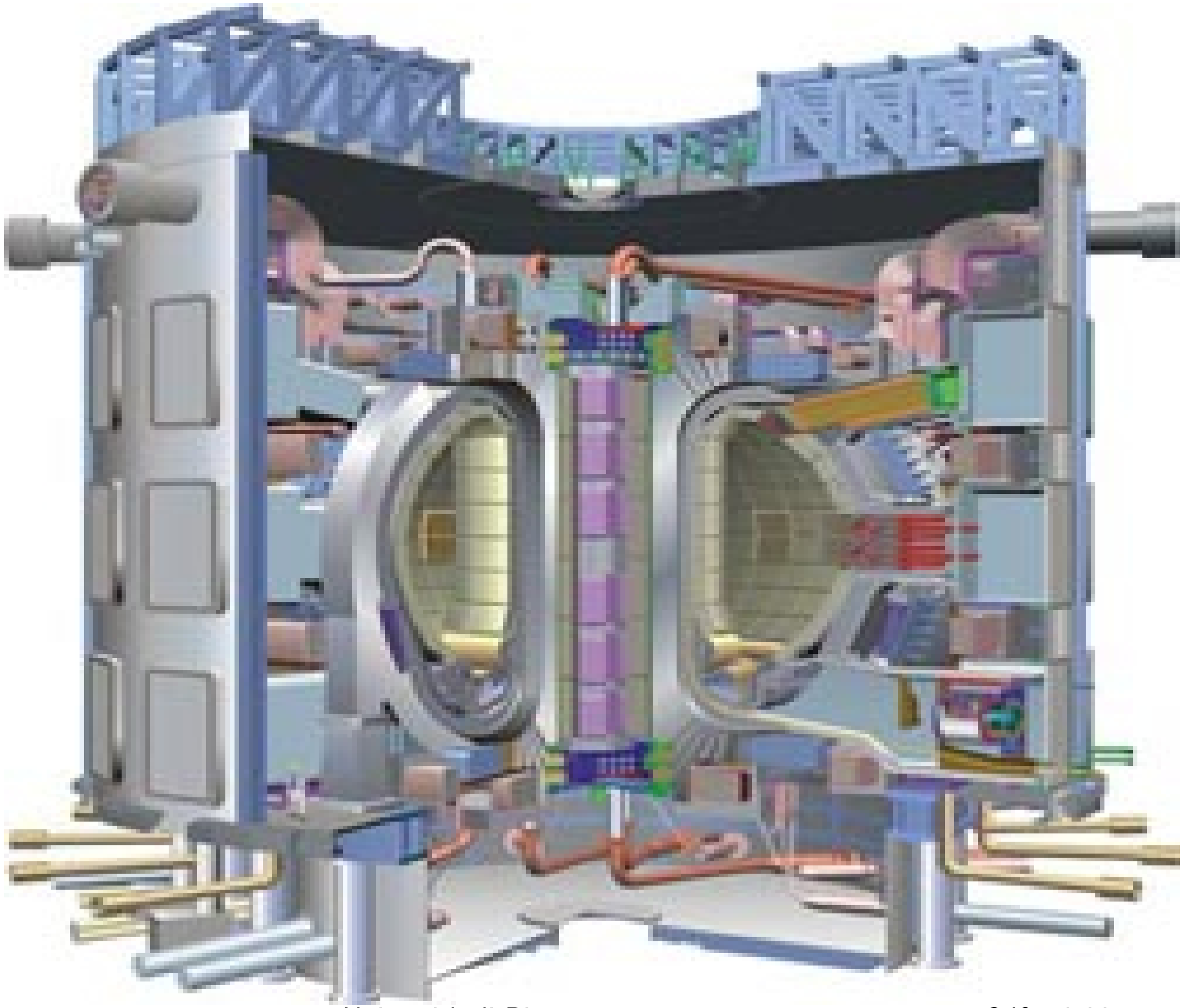
The ITER project follows in the line of the large size experiments (such as the JET experiment in Culham) and aimed initially at studying the physics and technology issues of an ignited plasma.

The project has long since been downgraded, because of rising costs, and reaching ignition is no longer an aim of the ITER project.[26]

Of interest for Italy is the fact that it is envisioned[27] that a negative ion source of energetic neutrals will be used to heat the plasma. Consorzio RFX in Padua e and INFN in Legnaro (Padua) are in charge of the delivery of this rather complex and expensive injector.

[26]Quoting the official ITER web site: "ITER has to be able to produce $Q = 10$, or Q larger then 5 when pulses are stretched towards a steady state. This is done so that, in the "burning plasma", most of the plasma heating comes from the fusion reactions themselves." $(Q = P_{fus}/P_{heat} \leftrightarrow Q = 5 \rightarrow P_\alpha = P_{heat}.)$

[27]There has been some recent debate on the wisdom of using such a system in view of a likely economic squeeze.

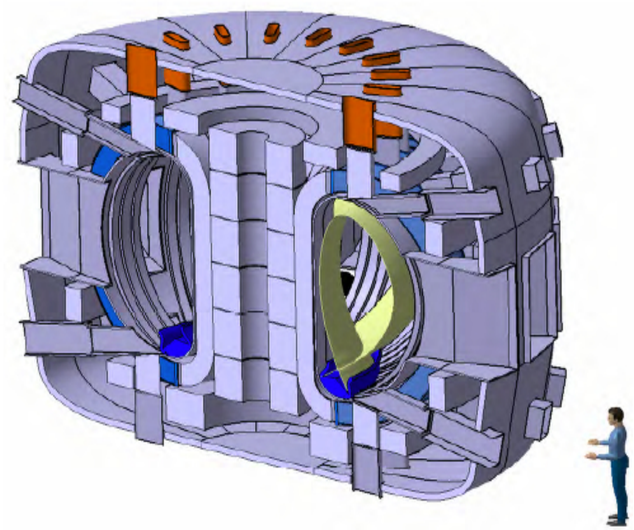


Comparison of JET and ITER parameters

	JET	ITER
Plasma volume	$100\ m^3$	$840\ m^3$
Magnetic field on axis	$4\ T$	$5.3\ T$
Plasma current (D-shaped plasma)	$7\ MA$	$15\ MA$
Neutral injection	$22\ MW$	$33-50\ MW$
Coupled ICRH		
Coupled LHCD		
Coupled ECRH		
Current drive		
Central density	$2\text{x}10^{20}\ m^{-3}$	$10^{20}\ m^{-3}$
Electron temperature	$20\ keV$	$21\ keV$
Ion temperature	$48\ keV$	$18\ keV$
Q value in D-T plasma	0.6	10
Fusion power	$16\ MW$	$500\ MW$

Both in the scientific world and in the political/decision-making world there is no unified view of the scientific merits and strategic role of ITER.
Construction and high technology industries are clearly interested.
In the USA the scientific environment is far from unanimous in supporting ITER, because of both scientific misgivings and because it is felt that such a costly experiment, so extended in time with possible results being obtained so far from now, will starve all other activities in magnetic fusion research, will produce a loss of personnel with technical and scientific know-how and might even, if unsuccessful, put a final end to fusion research.
EURATOM on the contrary has always backed ITER, being convinced (wrongly in my opinion) that achieving thermonuclear fusion power is only an engineering and technology problem, all physics problems being essentially already solved. A corollary of this is that all surviving national projects where Euratom is involved must be (or must appear) *ITER-relevant*.

FAST



Plasma Current	**6.5 MA**
B_T	**7.5 T**
Major Radius	**1.82 m**
Minor Radius	**0.64 m**
Elongation k_{95}	**1.7**
Triangularity δ_{95}	**0.4**
Safety Factor q_{95}	**3**
$\langle n \rangle$	2×10^{20} m^{-3}
$t_{\text{pulse-Flat-top}}$	**13 s**
H&CD power	**40 MW**
ICRH: 30 MW	
ECRH: 4 MW	
LH: 6 MW	

courtesy of G. Mazzitelli, ENEA

Within the international physics community however, it is NOT clearly perceived by the scientists who do not work on magnetic fusion, that ITER will be an experiment, not a reactor prototype[28]. This is partly due to some of the fanfare with which ITER is officially presented.

Often a negative perception of ITER (and sometimes on all fusion research activities) can be found in opinion making journals, see e.g. "A White Hot Elephant", *The Economist*, November 25th 2006 or "ITER's $12 Billion Gamble", *Science*, **314**, 238 , 13 October (2006).

Most important are the scientific objections that have been raised on the ITER project.

[28] As far as the technology related to material behaviour is concerned, a parallel investigation is planned at the International Fusion Materials Irradiation Facility (IFMIF)
http://insdell.tokai-sc.jaea.go.jp/IFMIFHOME/ifmif_home_e.html
located in Japan as agreed within the so called "Broader Approach" agreement.

Essentially these objections stress the fact that, notwithstanding its exceedingly high costs and extended construction times, ITER does not aim for ignition.

It is feared that in the case of a less than optimal performance, the ITER experiment will not even be able to provide relevant information on the physics and technology problems of a burning plasma, as already mentioned this would be likely to be fatal to fusion research.

A faster lane to ignition

I will briefly describe the Ignitor project, making it clear from the start that, in my opinion, the fact that Ignitor has not yet been built represents a major strategic error of the international fusion research programme.

The Ignitor project follows the line of the compact, high field tokamak experiments initiated by Bruno Coppi in the 70s at MIT and later brought to Frascati.

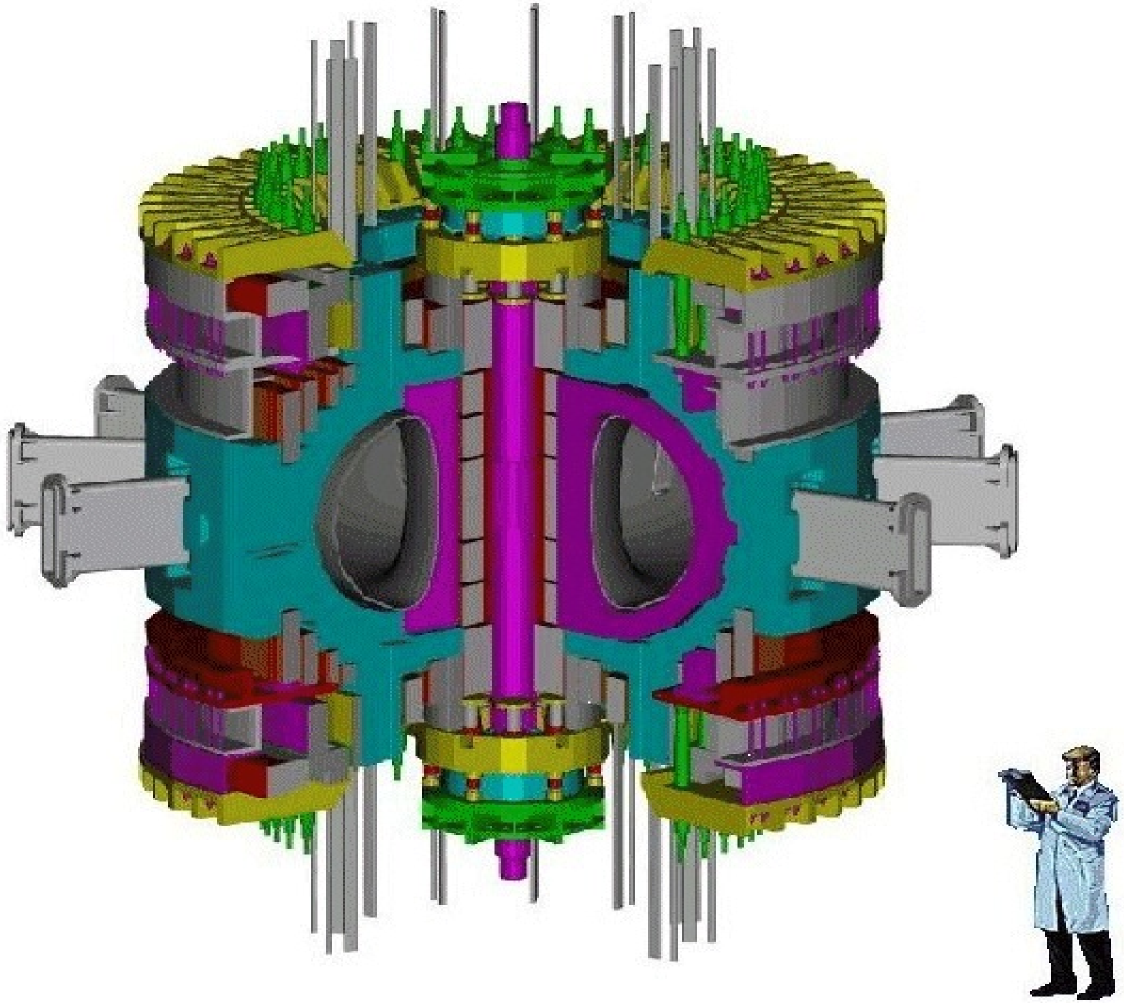
The rationale underlying this approach is based on the fact that, by applying a larger external magnetic field, it is possible to increase the plasma current and density and reach ignition at a lower temperature. All these factors have been seen to have a positive effect on plasma transport and plasma purity. This project envisions innovative engineering solutions in order to make it possible to account for the magnetic and thermal stresses in the external magnet.

An objection that is often raised is that such high field configurations are not easily extrapolated from an experiment to a fully fledged fusion reactor.

Recently an agreement was signed between the Russian and the Italian governments to collaborate in the realization of the Ignitor experiment.

The implementation of this agreement has not yet, as far as I understand, fully been worked out.

IGNITOR MACHINE



Ignitor parameters

Major radius $1.32\ m$,
Plasma current $11\ MA$,
Toroidal magnetic field $13\ T$,
Central electron temperature $11.5\ keV$,
Central ion temperature $10.5\ keV$,
Central plasma density $10^{15}\ cm^{-3}$,
Plasma energy $11.9\ MJ$,
Ohmic power $11.2\ MW$,
Energy confinement time $0.6\ s$.
Additional RF plasma heating is envisioned.

A strategic element of strength of the Ignitor project is that it can be realized on a time schedule much faster than that required by ITER and at much lower costs.

In addition it will make it possible to study the physics of an **ignited** plasma not too far away in the future.

The Italian scientific community has contributed significantly over the last two decades in addressing the physics and engineering issues of the Ignitor design.

My main point is that it is imperative in the present situation to adopt a fast lane to proving the scientific feasibility of magnetic fusion.

If we wait too long, inertial fusion, or a totally different approach, will present itself as the only viable long term solution to the world's energy needs.

Conclusions

Some additional considerations on safety and on the financial viability of fusion-produced electricity.

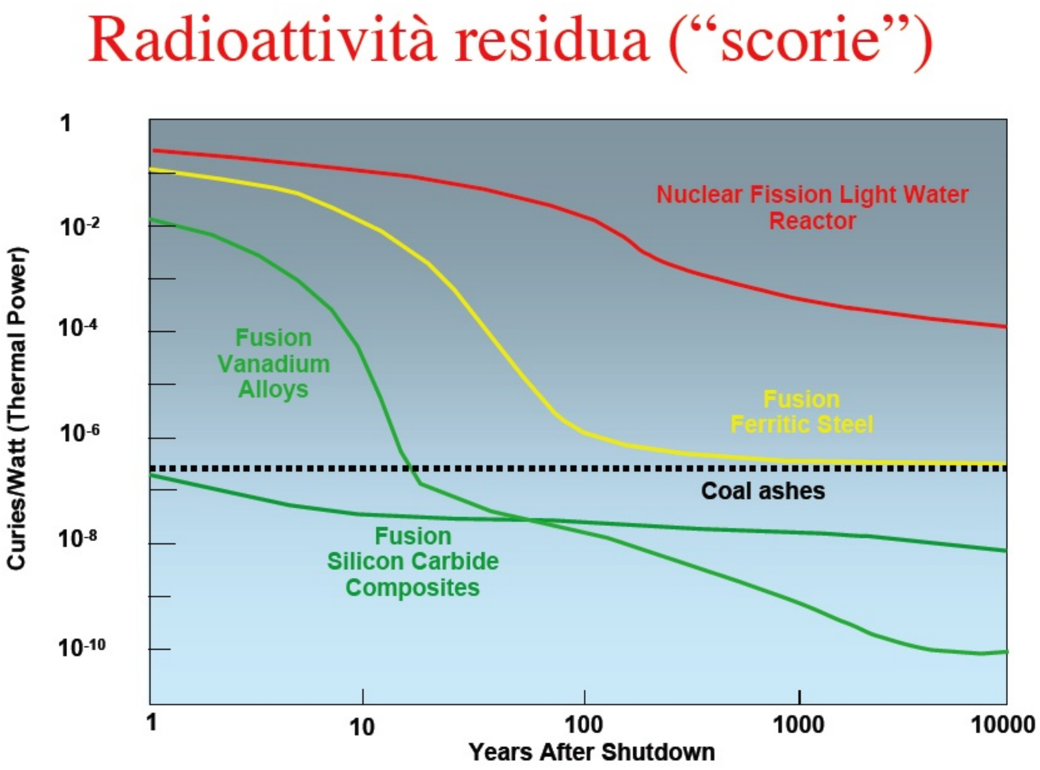
Safety

Both in the case of magnetic and inertial fusion, an intrinsic safety factor is the smallness of the amount of "reacting" material that will be present at each moment inside the reactor.

If something malfunctions the fusion reactions will simply stop (there is no chain reaction process). Lithium does however have corrosive properties.

Even in the case of a chemical mishap radioactive losses should be limited since the total Tritium inventory is relatively small.

A partly analogous point can be made, as already mentioned, for radioactive waste, see table below.



Financial viability of fusion-produced electricity

In the present economic environment, putting enviromental issues aside, no alternative energy source can compete with the low cost of fossil fuel energy.

At the present stage of development of fusion energy it is not possible to forecast in any reliable way what the cost of fusion-produced electricity will be (in particular compared to nuclear or solar energy).

Clearly the cost of the fuel is minor in the case of fusion[29].
The cost of fusion electricity will be determined by the cost of the large initial financial investment that the building of a fusion reactor is expected to require.

[29] In addition fusion fuel i.e. Deuterium and Lithium are rather wide spread.