IGNITOR

IN THE CONTEXT OF THE PROBLEM OF CONTROLLED THERMONUCLEAR FUSION

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1. GENERAL BACKGROUND – SCIENTIFIC FEASIBILITY OF A FUSION REACTOR

It is well-known that if nuclei of light elements are given sufficient energy they can "fuse" releasing large amounts of energy in the process. The fusion reactions which realistically can be considered involve hydrogen isotopes (deuterium and tritium) and helium3. Among these reactions, the easiest to be triggered at temperatures attainable in a fusion reactor is the deuterium-tritium reaction, which produces neutrons with an energy of about 14 MeV and α-particles with an energy of about 3.5 MeV.

The deuterium-tritium (DT) reaction is then the one to be used in the first generation of controlled thermonuclear fusion devices.

The DT plasma produced must have a high particle density n ($\geq 10^{13}$ cm^{-3}) and a temperature T sufficiently high (100-1000 millions degrees centigrade) in order to provide deuterium and tritium nuclei with enough energy to overcome electrostatic repulsion, and must be confined for a time τ sufficiently long to allow fusion reactions to occur. In a reactor, the neutrons produced in DT reactions, escaping from the plasma would be captured in a blanket put around the plasma, in which they would breed tritium by reaction with the lithium contained in the blanket. This breeding is necessary because tritium, being radioactive with a rather short half-life (~12 years), does not exist in nature in significant quantities. The heat produced by neutrons would be extracted and used to produce electricity with a conventional thermal cycle. α-particles electrically charged can instead be confined within the plasma then giving it their energy and further heating it. If this energy is high enough, i.e. if the reactions are sufficiently numerous, it is possible to offset plasma energy losses. The situation in which the produced fusion power equals that which is to be injected to heat and confine the plasma is said *breakeven*. Of course this condition must be overcome because what is important in practice is the net energy production. The situation to be reached is the one in which the power given to the plasma by α-particles (about 1/5 of the total reaction power) is sufficient to make up for all plasma losses. In these *ignition* conditions the plasma is self-sustaining. In this regard, the *Lawson criterion* exists which, with the required high temperature values and basing on an elementary energy balance, fixes for the product $n\tau$ (*confinement parameter*) a value not less then about 10^{14} cm^{-3}s.

To demonstrate the *scientific feasibility* of controlled thermonuclear fusion means to bring the plasma very near to ignition conditions in a laboratory experiment. It is important to specify the meaning of this terminology, valid for every new technological idea, as it is often used in an incorrect way. *Only after reaching this fundamental goal could one design a prototype reactor and subsequently a commercial one.*

Of course in all fusion devices existing around the world fusion reactions are produced. But fusion scientific feasibility, as also breakeven, is still to be demonstrated, in the sense that ignition has not been realized yet.

Plasma confinement, which takes place naturally in the stars due to the enormous gravitational forces, can be obtained in the laboratory by two different systems:

a) Inertial confinement – In this system a small DT pellet is compressed to high density (greater than about one thousand times the density of a liquid) by means of laser or charged particles beams. The compression time is very short, so that the fuel, constrained by its own inertia, burns before dispersing. Lawson criterion is satisfied with plasma densities greater than 10^{24} cm^{-3} and with confinement times less than 10^{-10}s.

b) Magnetic confinement – Here the plasma, being a mixture of charged particles, is slowed down in the diffusion towards the container walls by the action of suitable magnetic fields. In this case one can have, for instance, a confinement time of 0.5 s with a peak density of about 10^{15} cm^{-3}.

In the research with inertial confinement, the NIF (National Ignition Facility, [https://lasers.llnl.gov/]), using a system of high power lasers to attain ignition, is worth mentioning. This experiment, which already absorbed an investment of several billion dollars, is managed by the National Nuclear Security Administration (NNSA, [http://nnsa.energy.gov/aboutus/ourhistory/timeline]), an autonomous agency of the U.S. Department of Energy responsible for the security of armaments, for the non-proliferation of nuclear weapons, and for the naval use of nuclear reactors [NNSA 2011].

Among the various devices exploiting the plasma magnetic confinement the one which so far has been considered as the most promising and has then been prevalently studied is the *tokamak*.

In this device the plasma is contained in a vacuum chamber having a toroidal configuration with a circular cross section with major radius R_0 and minor radius a (Fig 1a). But, to improve some of its characteristics, in many cases an elongated section is adopted with minor radii a and b (Fig 1b)

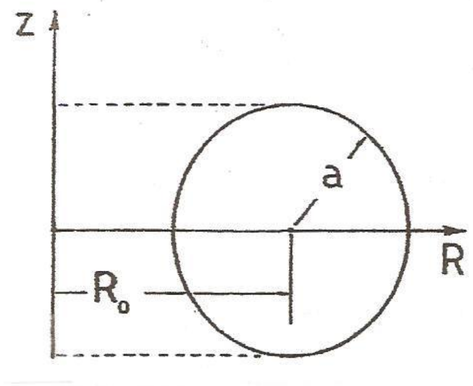

Fig.1a

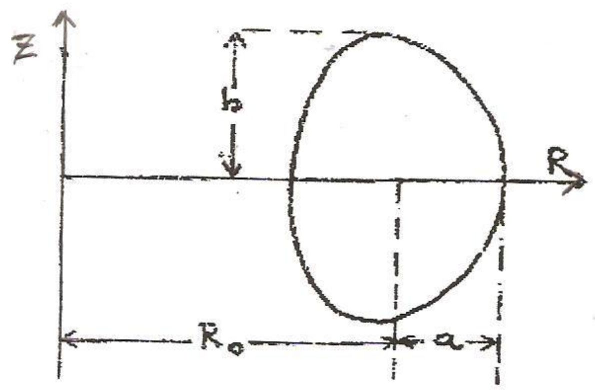

Fig1b

Two different ways are conceivable in order to attain ignition conditions, corresponding to two different ways for obtaining high values of the confinement parameter $n\tau$.

One can try to realize high confinement times with modest densities. This requires the use of large machines, i.e. machines having a major radius R_0 greater than about 2 meters. Of course this way leads to huge construction times and costs. Also, in this case scientific and technological problems are considerable.

The alternative line is that of realizing shorter confinement times with high plasma densities. The reduced dimensions of the device make then possible to apply high magnetic fields. Higher current densities can then be sustained, hence the possibility to obtain high plasma densities. It is then possible to produce "thermonuclear plasmas" in which heating is essentially due to α-particles. In larger low density machines external heating sources (neutral beams, radiofrequencies, etc.) are required.

It can also be seen that with high magnetic fields and high plasma densities, high plasma currents may be produced without running into instabilities.

It is also of paramount importance the fact, experimentally verified, that at high plasma densities the impurity degree, i.e. the percentage of heavy elements, is quite low. As to heavy elements radiation energy losses (Bremsstrahlung) are mainly due, a considerable impurity degree would make it impossible to attain ignition.

Progenitor in the line of compact high magnetic field devices was an evolution of the tokamak called ALCATOR. A first version, ALCATOR A, was conceived by professor Bruno Coppi who proposed it to Boston MIT in 1969. Its construction ended in 1972. It was a machine having a circular cross section and functioning with deuterium. A detailed description of this device can be found in [PEDRETTI 1988].

In Fig. 2 a schematic representation of ALCATOR is given.

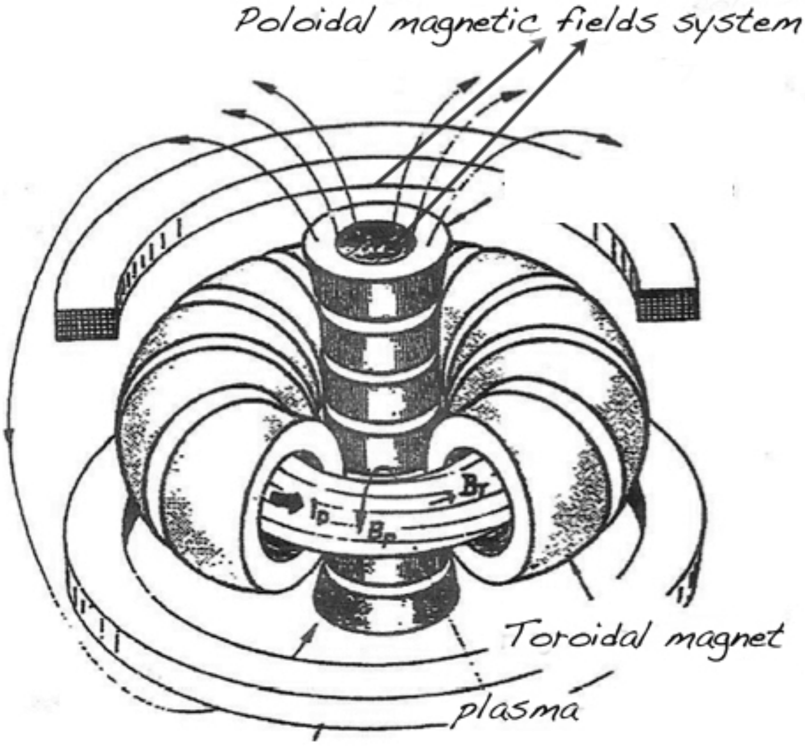

Fig.2

The system for poloidal magnetic fields including the central solenoid induces the current I_p which heats the plasma and produces the poloidal magnetic field B_p which of course is different from zero only for the limited time during which the current in the transformer primary varies. The toroidal magnet produces the toroidal magnetic field B_T. The toroidal and poloidal magnetic fields combine to produce a helical field pattern required for equilibrium and stability. In Fig.2 the coils are also shown which are part of the poloidal field system and which produce a control magnetic field used to center the toroidal plasma in the discharge chamber.

The main parameters of ALCATOR were:

R_0= 0.54 m a= 0.10 m B_T= 10 T I_p= 0.4 MA

The second device in the line of compact machines was the FT (Frascati Torus), also conceived by Coppi and which may be considered as the natural evolution of ALCATOR. This, too, had a circular section and operated with a deuterium plasma. Its construction started in 1971 and ended in 1978. From 1981 to 1983 it held the record for the highest confinement parameter, of about $4x10^{13}$ $cm^{-3}s$ with an ion temperature slightly greater than 1keV.

The main parameters of FT were:

R_0= 0.83 m a= 0.2 m B_T= 8 T I_p= 0.6 MA

Let us now end this introductory paragraph by spending a few words on the problem of the most convenient fuel to be used. As has been said, the DT reaction appears as the easiest to achieve. As such, it will have to be used in attempts to reach ignition and to experimentally study the behavior of any ignited plasma. However, some inconveniences are connected with the use of the DT fuel, especially if fusion reactors are concerned. First, the tritium is radioactive. Also, 14 MeV neutrons escaping from the plasma, reach the machine structures producing material activation and radiation damage. As a consequence, a DT reactor would give rise to safety and environmental problems.

For this reason, after having attained ignition in a DT plasma, the next logical step is to look for an alternative better than DT fuel.

Among the various possible fuels, the one which, after DT, is the most probable is deuterium-helium3 (D^3He), which produces α-particles with an energy of 3.6 MeV and protons with an energy of 14.7 MeV. This reaction does not involve tritium and neutrons (apart from the few and less energetic ones produced in secondary and side reactions). In this case, there will not be serious safety problems. In addition to that, α-particles and protons, being electrically charged, could be collected in a suitable device where they would be utilized to produce energy (direct conversion), without resorting to a conventional thermal cycle with the resulting yield reduction. Also, thermal load on the walls would be reduced.

This kind of reactor would request the presence of DD reactors in order to produce the necessary amount of ^3He.

One problem connected with the use of the D^3He cycle is the scarcity of terrestrial ^3He, and –as is the case for tritium– it must be produced starting from other elements. One possibility is to obtain ^3He from the decay of the tritium contained in nuclear warheads; and this would be sufficient for an experimental program.

For a long-term program, aiming at producing energy by fusion reactors, one possibility is given by the extraction of ^3He from the lunar soil. This possibility has been investigated since 1986 in U.S. by NASA. More recently, there has been a declaration of interest on this matter by the Chinese and Indian groups responsible for exploration of the lunar soil.

2. IGNITOR

In 1976 Bruno Coppi conceived the idea of going further in his line of high magnetic field devices by designing another tokamak –the Ignitor– whose goal is that of producing plasma ignition conditions.

For a historical reconstruction it may be useful to read some pages from chapter 7 ("The entrepreneurs") of the book "The man-made sun" by T.A. Heppenheimer. In these pages, Heppenheimer describes, in his brilliant style, when and how Coppi conceived the idea of Ignitor. In particular it is interesting to quote the following passage [HEPPENHEIMER 1984]:

Coppi was a man who could easily bubble over with ideas, and right then he was particularly ebullient. He wanted to follow up his Alcator success by building a new tokamak, which he called the Ignitor.

The importance of reaching ignition has been effectively confirmed in 1995 White House Report of the President's Committee of Advisors on Science and Technology (PCAST), from which it is appropriate to quote the following statement:

Producing an ignited plasma will be a truly notable achievement for mankind and will capture the public's imagination. Resembling a burning star, the ignited plasma will demonstrate a capability with immense potential to improve human well-being. Ignition is analogous to the first airplane flight or the first vacuum-tube computer. As in those cases, the initial model need not resemble the one that is later commercialized; much of what would be learned in a tokamak ignition experiment would be applicable both to more advanced tokamak approaches and to other confinement concepts.

These are in fact the criteria on which the Ignitor programme is based [COPPI ET AL., 2010]. Its design characteristics and the physical principles inspiring it, based on the already tested technology of high magnetic fields with relatively small dimensions, make it the most advanced experiment for producing burning by fusion reactions and, up to now, the only one having the capability to reach ignition.

The ITER programme, sprang from a meeting between Reagan and Gorbachev in 1985, consists in the design of a machine much larger than Ignitor, with a lower magnetic field. However, this design is affected by a series of physical, technological and financial problems. In addition to that, very long construction times as well as organizational difficulties make its realization quite uncertain.

The previously quoted PCAST report, for instance, considers ITER objectives non realistic and suggests, instead, the construction of a machine having the same technology and the same philosophy of Ignitor, to be realized at reasonable costs.

Ignitor is conceived to produce high density plasmas. That of high density plasma machines is one of the main research lines in the U.S., and the major in Italy. Recently this line has been experimentally rediscovered in Japan and is intensely pursued for the study of power reactors functioning in this regime.

It is convenient to recall that in high density plasmas the percentage of heavy elements is quite low; as has been said, a high plasma purity is a necessary condition for achieving ignition, so demonstrating the scientific feasibility of the controlled thermonuclear fusion.

Ignitor is often criticized from large machines researchers because –so they say—its burning time is too short to make it useful for designing a reactor. However, this criticism completely ignores the fact that Ignitor is not a reactor but an experiment, intended for producing and studying an ignited plasma, whose burning time exceeds all the intrinsic time scales.

Of course, an experiment of this kind must necessarily precede the design of a reactor.

A hypothetical future reactor need not necessarily resemble Ignitor and need not necessarily by a tokamak. It could for instance be a stellarator, a device which has come up again for some years now. Examples are the German W7-X [SCHWARZSCHILD 1980] and the Japanese LHD [NIFS 2008-2009].

In addition to representing a fundamental step in the way towards the attainment of nuclear fusion energy, Ignitor has also a variety of important applications.

Quoting Bruno Rossi, one of the fathers of high energy astrophysics ("*Whenever you do experiments in an unknown regime, you will find something new*"), Coppi maintains that the scientific potential of Ignitor is such to allow new discoveries in the field of fundamental physics with a strong impact on astrophysics [MIT NEWS 2010]. In fact, from ignition experiments, of which Ignitor is the prototype, one may expect important contributions to the comprehension of many phenomena in this field.

For instance, most of the visible mass in the largest identifiable objects, so-called Galaxy Clusters, is in the form of plasmas ("brilliant matter" revealed by X-ray astronomy) whose electron temperatures are in the range 6-10 keV which is that of the plasmas currently studied for fusion research.

As far as the feasibility of a fusion reactor is concerned, it is evident that the "Reactor Physics" (using a well known terminology in the field of fission reactors) which will come out from Ignitor experiments, will be directly applicable to a power reactor. The same can be said for the technological solutions adopted in Ignitor (for instance the external heating system). Also, think to the system for poloidal magnetic fields (the *air-core transformer*) invented and realized for ALCATOR and now adopted in all machines for advanced experiments on plasma magnetic confinement.

Finally, a possible use of a fusion reactor achievable in the short-term, could be the production of neutrons to create fissionable material.

The approach involving the combination of compact geometry and high magnetic fields characterizing the Ignitor design also allows a possible development path to tritium-poor reduced-neutron-production fusion, which could yield interesting kinds of fusion reactors.

It is also particularly attractive the idea of using a D^3He plasma, with the advantages already described in the paragraph 1. The technological feasibility of an experiment, called Candor, designed to study the ignition conditions of a D^3He plasma has been investigated by Coppi with encouraging results.

In 1976 Coppi proposed the realization of Ignitor in Italy and for its design he put together a group of many individuals affiliated to a variety of government agencies, universities, research centers and industries. Of this group Coppi was the principal investigator. ENEA provided part of the financial support as well as the management of the project.

The main parameters of Ignitor are:

R_0= 1.32 m a= 0.47 m b= 0.86 m B_T= 13 T I_p= 11 MA

In Fig.3 a general view of Ignitor is given.

As for the site where Ignitor will operate, it is of considerable interest the fact that a Memorandum of Understanding was signed in April 2010 between the Government of Italy and the Russian Federation for a research program for fusion centered on the construction and operation of Ignitor at the Triniti site (Troitsk, near Moscow). The site will be accessible to scientists from all countries.

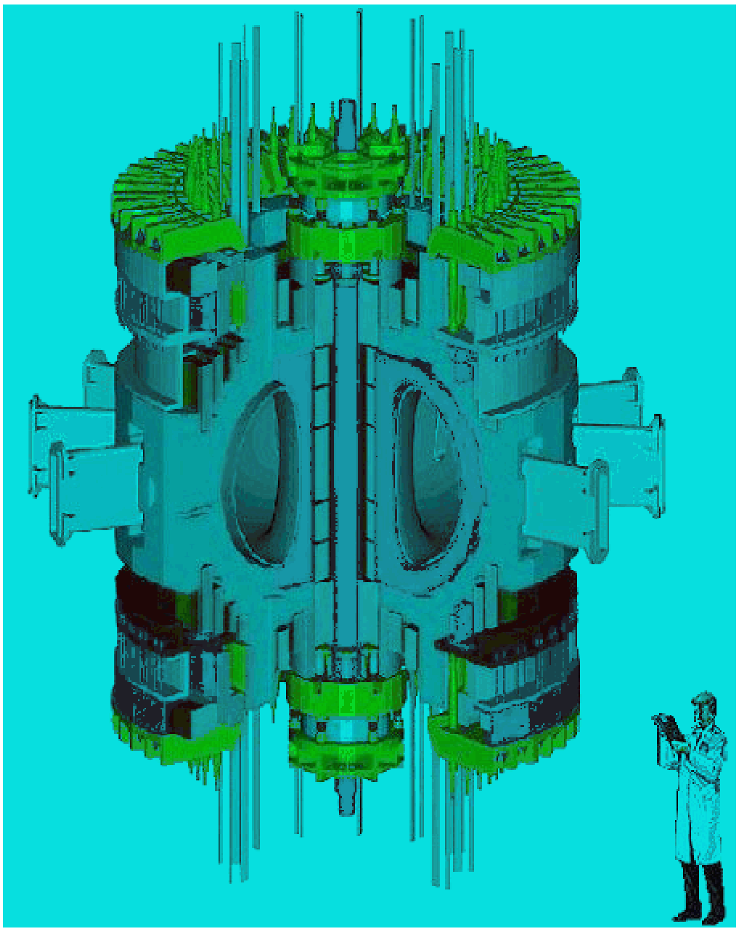

Fig. 3

3. IGNITOR vs. ITER

Comparing Ignitor with ITER is tantamount to comparing the two lines of nuclear fusion research exploiting the magnetic confinement, i.e. the line of large machines with the one of compact high magnetic field devices.

On this matter something has already been said in the previous two paragraphs. However, for a comprehensive comparison between Ignitor and ITER, more information must be given on the research with large machines which has been carried out all over the world.

Let us then describe, in short, the history of this activity, considering in particular the one carried out by the European Community (Euratom); a research which has eventually led to the ITER programme.

The story starts in 1993 with the realization in the Euratom laboratory at Culham (Great Britain) of the large tokamak JET (Joint European Torus) still functioning at present. It has a major radius R_0 of about 3 meters, a magnetic field of 4 tesla, and can operate with a DT fuel.

The origin of JET and the choice of its characteristic parameters is well described in a paper by A. Sestero [SESTERO 2005].

According to the initial Euratom program, JET should have been followed by the realization of the tokamak NET (Next European Torus) whose study began in 1978. However, it was set apart to pass to the design of INTOR (INternational TORus) abandoned in its turn to start designing ITER. This program which, as has been said was decided in a meeting between Reagan and Gorbachev, envisaged the construction of a gigantic machine (major radius about 6 meters) at the declared cost of 10 billion dollars, and was advertised by the proponents as capable of attaining plasma ignition. However, it was subsequently demonstrated [GLANZ 1996, LAWLER 1998] that this goal would have been prevented by instabilities. A new reduced version of the machine, called ITER-FEAT, was then decided which, plainly, was not conceived for attaining ignition [FUSION POWER ASSOCIATES 1998].

Coming to more recent times, on June 29, 2005 the French newspaper *Le Monde* announced the decision to base the project in France at the nuclear research center of Cadarache. According to the proponents this ITER, having a major radius $R_0 = 6.2$ m, a plasma current $I_p = 15$ MA and a toroidal magnetic field $B_p = 5.3$ T and with an auxiliary heating of 50 MW, should produce a power of about 500 MW. If so, the power gain Q would be equal to 10 (Q=∞ at ignition).

Most French pro-government newspapers greeted the announcement as good news for France, and president Chirac himself called the decision "an enormous success". Much less enthusiastic, instead, was the reaction in scientific circles even in France [ALLÈGRE 2005, GODOY 2005, LE HIR 2005, SORTIR DU NUCLÉAIRE 2005, DAUTRY 2005]. For instance, former minister for science and technology C. Allègre described ITER as “just another prestige project” with very few chances of success”.

In 2006, when European Union, USA, Russia, South Corea, India and Japan came to an agreement to finance the project, the cost for the construction was estimated to be 5 billion euros; at present, however, this cost has considerably increased [BRUMFIEL 2010A, BRUMFIEL 2010B, BRUMFIEL 2011] and is officially estimated at about 15-16 billion euros. The European Union, main contributor to the project, has seen its share particularly increased.

Due to the present financial crisis, however, ITER funding has been brought up for discussion again. The European Commission suggests that this project, along with future long-scale science programs, be supported through new inter-governmental organizations. In any case, the future of ITER is likely to go through tortured negotiations between the Commission, the Council of Ministers and the European Parliament until the 2014 budget settlement [BUTLER 2011].

To conclude this paragraph it may be useful to summarize all has been said concerning the research carried out up to now in the following schematic comparison:

RESEARCH WITH LARGE TOKAMAKS

- Huge dimensions. Very high costs and long construction times
- Preclusion of ignition, with consequent impossibility of realizing a reactor
- Use of DT as the only possible fuel. As a consequence: 1) a lithium containing blanket surrounding the plasma is necessary to breed tritium; 2) high-energy neutrons are produced, with consequent activation of structure materials
- Uncertainties concerning the physical behavior of the plasma

RESEARCH WITH COMPACT HIGH MAGNETIC FIELD DEVICES

- Limited dimensions. Reasonable costs and realization times
- Production of high-density plasmas
- Attainment of ignition (Ignitor)
- Possibility of using advanced fuels (typically deuterium-helium3) with consequent strong reduction of high-energy neutrons

It is then evident that the preference too often given to large machines must have political motivations, completely disregarding all scientific criteria as well as the well-being of humanity. As if there were a definite will to hamper and delay the attainment of nuclear fusion energy.

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