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THE IGNITOR PROJECT

The Ignitor concept was the first experiment (see Fig.1) proposed and designed in order to achieve, on the basis of existing technology, the conditions where a deuterium-tritium plasma can ignite$^{1)}$.

Ignition occurs when the energy deposited by the charged fusion reaction products in the plasma compensates all forms of energy losses. These include radiation emission and particles and energy transport, resulting mostly from the excitation of plasma resistive modes and only in part from the effect of interparticle collision. Thus a fusion burning plasma that contains a nearly monochromatic source of multi-Mev particles is inherently a system that departs drastically from thermal equilibrium. The limited validity of the theoretical description that have been formulated for this kind of systems makes it particularly important to have experiments readly available to gather key information on the nature of the collective modes (e.g. various forms of instability and plasma turbulence) that characterize an ignited plasma.

Since the Ignitor concept was introduced in 1975 and later developed, other advance experimental facilities (in particular TFTR in the US and JET in Europe) have been redesigned and allowed to extend their performances in order to come as close as possible to some design characteristics embodied in Ignitor. In the case of TFTR the magnetic field was raised and in the case of JET the maximum plasma current and the magnetic field associated with it were increased well above the reference values of their original design, while a phase of tritium operation was included in both programs.

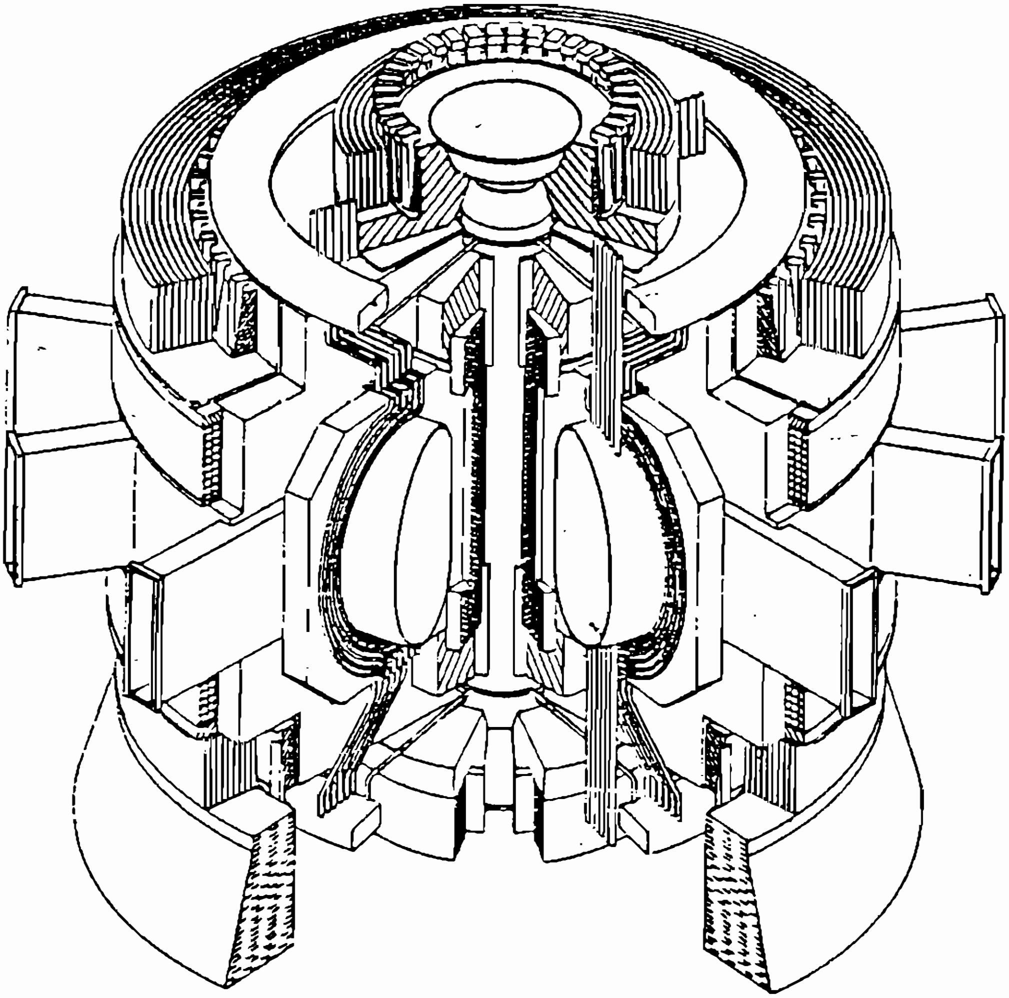

Figure 1: View of the Ignitor experiment

By now, one of the criteria that is commonly accepted as rating the potential performance of a toroidal machine as a confiner of the burning plasma is the value of the "strenght parameter":

$$F_S = I_p B_p$$

where I_p is the plasma current and B_p is the value of the magnetic field associated with it. On the basis of this, a comparison of Ignitor with existing advanced experimental devices is shown in Fig.2.

Another point to underline is that the containment of the charged fusion reactions products, on the basis of single particle orbit considerations, requires in pratice a minimum plasma current of about 3 megampere in the case of the 3.5 Mev α-particles and about 6 megampere in the case of the 14.7 MeV protons produced by the D-He^3 reactions. The miximum current considered in the present Ignitor design is about 11 megampere and is therefore sufficient to begin the study of the effect of D-He^3 reactions. However on the basis of present day knowledge, the other device characteristics are not adequate to reach conditions where substantial heating from D-He^3 reactions can be produced. To attain such conditions an extension of the Ignitor line has been envisaged, following the proof obtained at the begining of the 80's that, contrary the previous expectations, advanced fuel (D-D, D-He^3) reactors are feasible2) on the basis of our theoretical understanding. In this ontext we recall that the development of D-He^3 reactors is of great pratical relevance, as in a D-T reactor most of the enrgy is released in the form of energetic neutrons. The activation and the damage caused by the neutrons to the materials surrounding the plasma chamber are avoided in a D-He^3 reactor where the fuel is non radioactive and the reaction products consist almost exclusively of charged particles that can be guided by electromagnetic fields. However, similarly to Tritium that has a lifetime of approximately 12 years and decays into He^3, He^3 is extremely scarce on Earth and must be produced. Present reserves of He^3 are sufficinet for an experimental program, given in particular the large number of wartheads that have been stockpiled. For an application on a wider scale,the possibility has been studied of building deuterium-deuterium reactors in isolated locations, far from populated areas, and of devoting them to the production of He^3 reactor, but releases about 40% of its energy in the form of neutrons.

The guiding criterion in choosing the parameters of Ignitor is to advance the onset of effective α-particle heating to the lowest possible temperature. In particular the particle density of operation is maximized while taking into account all the constraints imposed by the temperature and the confinement time that havce to be achieved. In order to obtain the desirable density range,

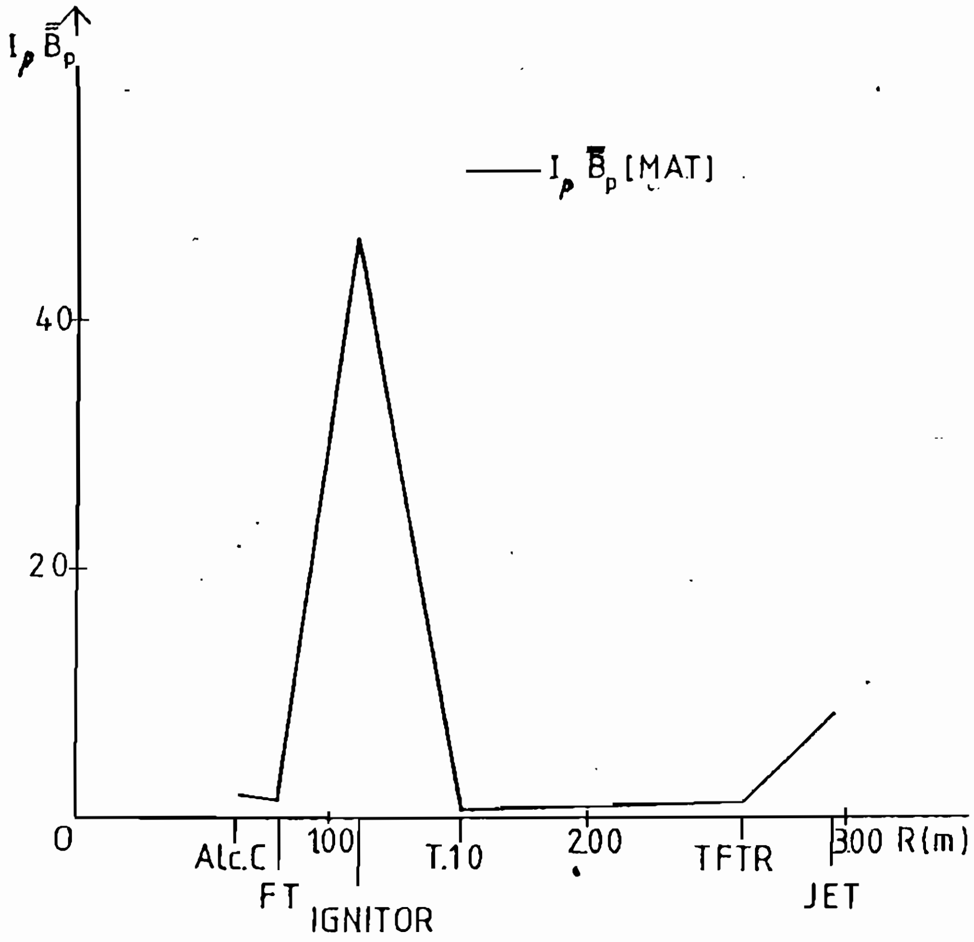

Figure 2: Rating of Ignitor versus exsisting advance confinement experiment in terms of the strength parameter $F_S = I_p \, B_p$.

corresponding to a peak density $n_0 = 10^{15}$ cm^{-3}, the prescription that is adopted is the same for Alcator, i.e. to produce the highest possible average current density $<j_{||}$ without exciting macroscopic instabilities. This guideline has been supported by an increasingly large body of experimental evidence. The average current density is:

$$<j_{||}> = (1.6\ B_T\ R_o\ q_E)$$

wher B_T is the toroidal field R_0 is the major radius and q_E is a "technical safety factor" that, for the toroidal configuration with low aspect ratio and non circular cross section considered, can be as low as 1.6 (see table 1). This explains why we consider experiments with high magnetic field and compact size.

We also notice that recent series of experiments performed on the TFTR machine3) have confirmed the existence of well confined plasma states with reduced plasma currents as found in 1974 in the Alcator experimental machine. Thus we can expect that it will be possible to decrease the plasma current in the regime where the α-particle heating is prevalent without spoiling confinement. We recall that in 1974 an important discovery was made on the Alcator A device where it was found that the energy confinement time τ_E increases linearly with the plasma density, thus indicating a favourable n^2 dependence of the Lawson parameter $n\tau_E$ (see Fig.3). Indeed this positive result obtained in a compact device was instrumental in making it thinkable, as early as eleven years ago, that an experiment could be built with the genuine expectation of being able to reach ignition. A group of Italian scientists working at MIT had a central role in this discovery4). This close collaboration continued and expled, including several Italian Universities, research laboratories and Firms, in the years during which the Ignitor project was developed and led to the strengthening of a network of intellectual and scientific interest and expertise, that can provide an important guarantee for the successful realization of the project.

In assessing the degree of advancement of existing confinement experiments, relative to the conditions needed for ignitor, it is necessary to weigh a variety of factor such as the degree of the plasma purity and the value of the electron temperature, and the conditions under which these are obtained. Instead, a common, often misleading, pratice is to assign each experiment a point in the familiar $(n\tau_E,T)$ plane using for instance the electron density, the ion temperature or the electron temperature without specifying whether Z_{eff}, the effective charge number, is close to unity. In fact, the relevant quantity to consider is the peak deuteron density, as this is representative of the plasma reactivity, that , when $Z_{eff} > 1$, can be considerably smaller than the peak electron density n_{eo}. Moreover, in an

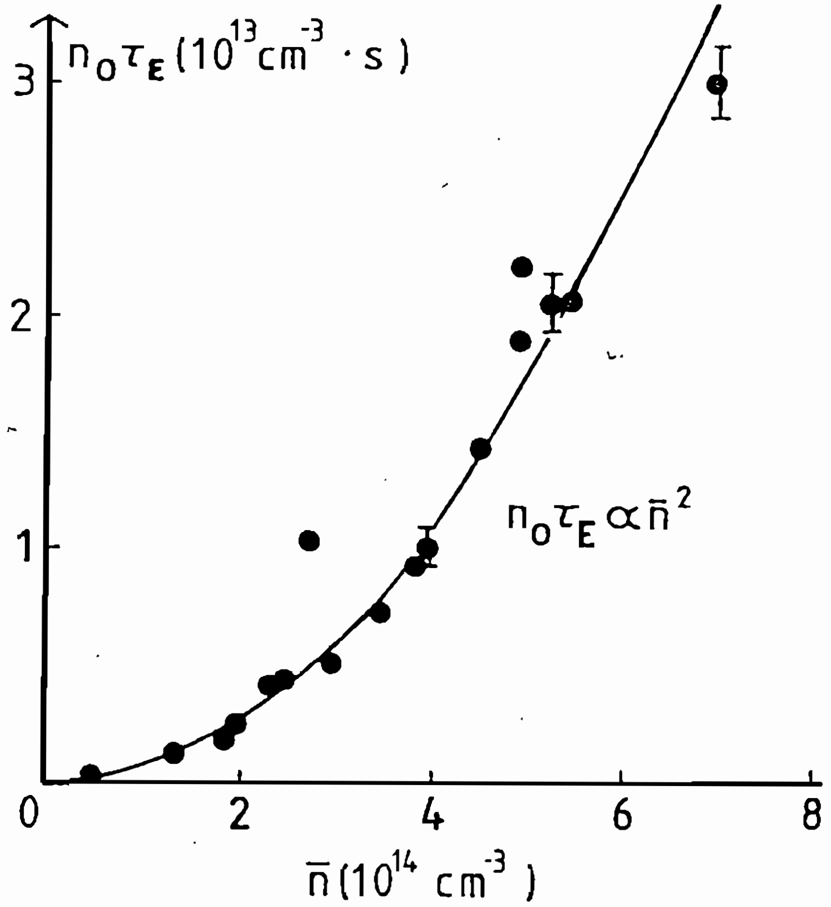

Figure 3: The discovery of the so called 'Alcator Scaling' for the confinement parameter $n\tau_E$.

igniting plasma the peak electron temperature T_{eo} exceeds T_{io}, the peak ion temperature, as most of the α-particle energy is deposited on the electron population and then transferred to the reacting nuclei. In addition, it is important that Z_{eff} be quite close to unity, as this affects the ignition conditions seriously. On the other hand, both T_{eo} and the energy replacement time τ_E have been observed to increase with Z_{eff} in most experiments. Therefore, we argue that n_{Do}, T_{eo} (Z_{eff}= 1) and τ_E (Z_{eff} 1) should be used in the appropriate ($n\tau_E$,T) diagram instead of n_{eo}, T_{io} and τ_E (Z_{eff} >1). Alternatively, the experimentally obtained values of $n_{Do}\tau_E$ (Z_{eff}>1) and T_{eo} (Z_{eff} >1) should be related to the ignition curve ($n\tau_E$, T) that would be obtained for the same values of Z_{eff}.

In addition to this, in order to assess the degree of advancement of a given experiment fairly, it is important to take into account the fact that when its linear dimensions are reduced, all the intrinsic time scales become shorter.

In praticular, we observe that the type of plasma collective modes influencing the effective energy transport have their frequencies and growth rates related to the average electron transit frequency:

$$\omega_{te} = v_{the} \frac{2\pi}{L}$$

where L is the periodicity lenght of the magnetic field lines (L = 2π q R for an axisymmetric toroidal configuration). This frequency expresses the obvious fact that all relevant physical processes are faster in smaller experiments. Consequently, on the basis of the previous considerations we propose, as an intrinsic parameter of merit, the effective pressure:

$$P_{eff} = n_{Do}\, T_{eo}\, \tau_E\, \omega_{te} \ ,$$

and we refer, in addition to the $n_{Do}\tau_E$ versus T_{eo} plane, to the plane P_{eff} versus the lenght of the plasma column. If we follow these criteria the compact line of experiments that is represented by the Alcator manchines of MIT and includes the FT device of the Frascati Laboratories still occupies the top position. This becomes even more striking if, instead of P_{eff}, we take a parameter of merit that includes instead of τ_E, the associated diffusion coefficient:

$$\bar{D}_E \equiv \frac{4\bar{a}^2}{\tau_E\,(Z_{eff} = 1)}$$

and we introduce the intrinsic parameter of advancement:

$$A = \frac{n_{oD} \; T_{eo} \; (Z_{eff} = 1)}{D_E}$$

The Ignitor design, as indicated earlier, tends to maximized the role of ohmic heating, up to the point where this is not overwhelmed by α-particle heating. We can expect the confinement time τ_E to follow the scaling laws that we have learned from present day experiments. In this case we find that the extrapolated confinement parameter $n_o\tau_E$ considerably exceeds the value needed to achieve ignition.

We refer, in particular, to the recently reported results of the experiments5) that were carried out on the Asdex machine where the plasma cross section is about 40 x 40 cm^2. The energy replacement time, corresponding to a line average density <n> of about 10^{14} cm^{-3}, is about 160 msec. Consequently, if we assume for simplicity that τ_E scale as <n> $<a^2>$, where $a = \sqrt{ab}$, and that the appropriate density of operation of Ignitor corresponds to about $n \cong 5 \times 10^{14}$ cm^{-3}, the value of τ_E would be approximately 1.5 sec. This is higher by about a factor 4 than what is needed for ignition and represents therefore a considerable safety margin for Ignitor.

A significant safety margin can be argued to exist also in obtaining plasmas with Z_{eff} close to unity as this parameter has been observed to approach unity in all experiments when the density is increased toward the values we have just mentioned.

We may also consider a series os design parameters of merit6) in order to rate the ability of a given experimental device to navigate toward igniting regimes through all the foreseable instabilities and factors that degrade confinement. One of these parameters that can be assumed to measure the maximum attainable value of $n_o\tau_E$, on the basis of present day knowledge, is the confining strength $F_S = I_p B_p$ that we have mentioned already. Here we notice that

$$F_s = I_p^2 / a^2$$

as $B_p \infty I_p/a$, a being the mean radius of the plasma column. By now the high field-technologies have been developed for compact magnets that can confine and produce tha highest plasma currents. Since the relevant values of a are relatively small, this would indicate that the compact line of experiments have the best possible intrinsic characteristics in order to achieve ignition conditions.

An important point to be added in this connection is that ignition is not achieved through a sequence of steady states, but through transients that can be exploited to reach the desider conditions. Indeed the present theoretical knowledge of the behaviour of magnetically confined plasmas does not allow us to predict how the plasma will reach ignition. Two of the most crucial processes determining how ignition can be achieved are the possible onset of oscillations of the central part of the plasma column induced either by the peaked distribution of the α-particle heating or directly by the mode resonant interaction with these particles. Compact ignition experiments can be designed to attain ignition with relatively low values of β_p, which expresses the ratio between the plasma pressure and the energy density of the poloidal magneti field, so that the threshold for the hard onset of these modes can be avoided to the extent that they are driven by the plasma pressure gradient. In addition , since the design of these experiments include high values of the plasma current I_p, another possibility is to decrease the plasma current to the point where the region that is affected by the instability $(q < 1)$ is so reduced that it is irrelevant.

As a final point, it is worth noting that the Ignitor project will bring about a number of beneficial developments, both scientific and technological. In this context it is important to recall that the development of a free electron laser in the wavelength range around half a millimeter, which is of general interest for the physics community at the present time, would provide a convenient tool for heating electrons in a high density, high field configuration. This would allow us to reach ignition conditions at lower temperatures and higher densities or, in a D-He^3 reactor, to avoid the use of tritium at the begining of the discharge to increase the reactivity of the plasma.

Table 1. Main design parameters of the Ignitor Ω experiment.

Major radius R_o = 110.5 cm

Plasma cross section a x b = 40 x 72.5 cm^2

Aspect ratio R_o/a = 2.75

Plasma current I_p = 11.25 megampere

Poloidal field B_p = 40 kG

Stregth parameter $I_p B_p$ = 45 megampere-tesla

Average plasma current density $<J_{||}>$ = 1234 A/cm^2

Toroidal field at the magnetic axis B_o = 134.6 kG

Technical safety factor q_E = 1.57

Table 2. Charcteristics parameters of an experimental D-He^3 reactor of the Candor type. The name has been chosen to stress that such a reactor is almost completely neutron free.

Major ratio R_o = 165 cm

Plasma cross section a x b = 55x100 cm^2

Aspect ratio R_o/a = 3

Plasma current I_p = 13.5 megampere

Poloidal field B_p = 35 kG

Stremgth parameter $I_p B_p$ + 47 megampere-tesla

Average plasma current density $<J_{||}>$ = 781 A/cm^2

Toroidal field at the magnetic axis B_o = 130 kG

Technical safety factor q_E = 1.6.

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