Near-Term Experiments on Advanced Fusion.

B. COPPI

Massachusetts Institute of Technology - Cambridge, MA 02139
Politecnico di Torino - 10129 Torino, Italia

F. PEGORARO

Scuola Normale Superiore - 56100 Pisa, Italia
Università di Torino - 10125 Torino, Italia

1. – Introduction.

An important problem in the physics of high-energy plasmas is to learn how the presence of a considerable population of particles with multi-MeV energies produced in a thermal, fusing plasma mixture affects its stability and transport properties. The experiments that can be carried out with this aim can lead to the finding of the conditions where the energy released to the thermal plasma by the fusion-produced particles is sufficient to compensate for all the forms of energy loss. This condition is commonly called ignition and can be regarded as the proof of scientific feasibility of a fusion reactor.

A question that has been asked frequently since the first experimental program with this goal (Ignitor) was proposed [1] is whether experiments of this kind have any value for the economic aspects of fusion power. Our opinion is that it is difficult to attach an economic value to a scientific experiment, but, when it becomes known that fusion energy can be produced in a controlled way, this will certainly have an impact on the outlook for energy resources. By now it is commonly recognized that the experimental proof of ignition or near-ignition conditions is an important milestone and that the high-magnetic-field technologies adopted for experiments of the Ignitor type, like the physics involved in it, are directly relevant to the kind of power-producing plants that can be envisioned on the basis of present-day knowledge of plasma physics [2].

Referring to the deuterium-tritium reaction ($D + T \rightarrow {}^4He + n$) that is the easiest to exploit, we indicate the power deposition (heating), resulting from the α-particles (^{4}He) emitted at 3.5 MeV, as P_α and introduce the parameter

$$Q_\alpha = \frac{P_\alpha}{P_H},$$

where P_H is the total power supplied externally to the plasma in order to maintain it at given density and temperature conditions. At ignition $Q_\alpha \to \infty$ and the regime where α-particle heating becomes important can be considered to correspond to $Q_\alpha \approx 1$. In fact, as a gradual approach toward demonstrating ignition, a line of experiments aiming to reach $Q_\alpha \approx 1$ rather than $Q_\alpha \to \infty$ can be conceived. Experiments of this kind have, clearly, less advanced characteristics than ignition experiments. Some are presently receiving a significant degree of attention, but their worth, costs and time requirements are the subject of considerable controversy.

Our opinion is that fusion research needs to acquire a faster pace, made of rather basic experiments that address ambitious but well-identified issues of physics or technology. To illustrate this point we refer, for instance, to the necessity of preventing an intolerable build-up of ^{4}He «ash» in the plasma of a reactor following a period of intensive D-T burning. The problem of separating the ^{4}He nuclei from the fuel nuclei and of extracting them is not simple *a priori*. On the other hand, we have learned from existing experiments that there are plasma collective modes that can be excited in the center of the plasma column and that, according to theory [3], are capable of scattering α-particles with energies around 400 keV. Thus α-particles can be permitted to release most of their energy before being scattered toward the (nonburning) edge of the plasma column. It is clear that, in order to exploit this possibility, basic plasma experiments have to be carried out and, if this idea has any merit, it does not appear to require major facilities to exploit it.

On the other hand, the funding of fusion research has been progressively narrowed and based on the illusory expectation that a few large-scale enterprises, where a relatively large variety of physics problems are dealt with by a single machine, spaced at time intervals of about a (human) generation, will represent the optimal path toward the construction of a power-producing reactor. Our opinion is that this is an open-ended strategy with little likelihood of converging on a reasonable time scale toward the essential goals of fusion research.

2. – The Ignitor experiment.

The Ignitor experiment was suggested by the results [4] of the Alcator program developed at MIT which revealed the superior confinement properties of high-density plasmas, by reaching record peak densities up to $2 \cdot 10^{15}$ cm^{-3}, and their high degree of purity in compact, high-magnetic-field configurations. Some of the main physics issues that are connected with the Ignitor experiment are discussed in the next section. Here we shail briefly describe the machine.

Ignitor was conceived using the same high-field magnet technology as Alcator that involves cryogenically cooled normal conductors. The minimum starting temperature in Ignitor is 30 K and the coolant is helium gas while in Alcator liquid-nitrogen cooling was adopted with the minimum starting temperature about 77 K. The lower temperature and the lower current densities allowed by the design of Ignitor [5] (< 10 kA/cm^2 in the toroidal magnet of Ignitor *vs.* ~ 22 kA/cm^2, that was the maximum reference value considered for the Alcator C machine) make Ignitor suitable for considerably longer plasma current pulses that are to exceed about $10\tau_E$, τ_E being the expected plasma energy replacement time at ignition.

The Ignitor experiment, since it was proposed, has undergone a periodic process of optimization [6], reflecting the experimental and theorical advances that have been made in the physics of multi-keV plasmas. The Ignitor-Ult machine [7] is the latest embodiment of this process and its design parameters are indicated in table I. The machine key components are shown in fig. 1. The main structural components that take up the forces generated in the toroidal magnet

TABLE I. – *Reference parameters of the Ignitor-Ult machine.*

$R_0 = 130$ cm	major radius of the plasma column
$a \times b = 47 \times 87$ cm^2	minor radii of the plasma cross-section
$\delta_G \simeq 0.4$	triangularity of the plasma cross-section
$I_p \lesssim 12$ MA	plasma current in the toroidal direction
$I_\theta \lesssim 10$ MA	plasma current in the poloidal direction
$B_T \lesssim 13$ T	field produced by the toroidal magnet
$\Delta B_T \lesssim 1.5$ T	paramagnetic (additional) field produced by I_θ
$\langle J_\phi \rangle \lesssim 0.93$ kA/cm^2	average toroidal-current density
$\overline{B}_p \lesssim 3.75$ T	mean poloidal field
$I_p \overline{B}_p \lesssim 45$ MN/m	confinement strength parameter
$q_\psi \simeq 3.4$	plasma current safety factor
$V_0 \simeq 10.5$ m^3	plasma volume
$S_0 \simeq 45.6$ m^2	plasma surface
$W_J \simeq 15$ MW	injected heating power ($f \simeq 130$ MHz)

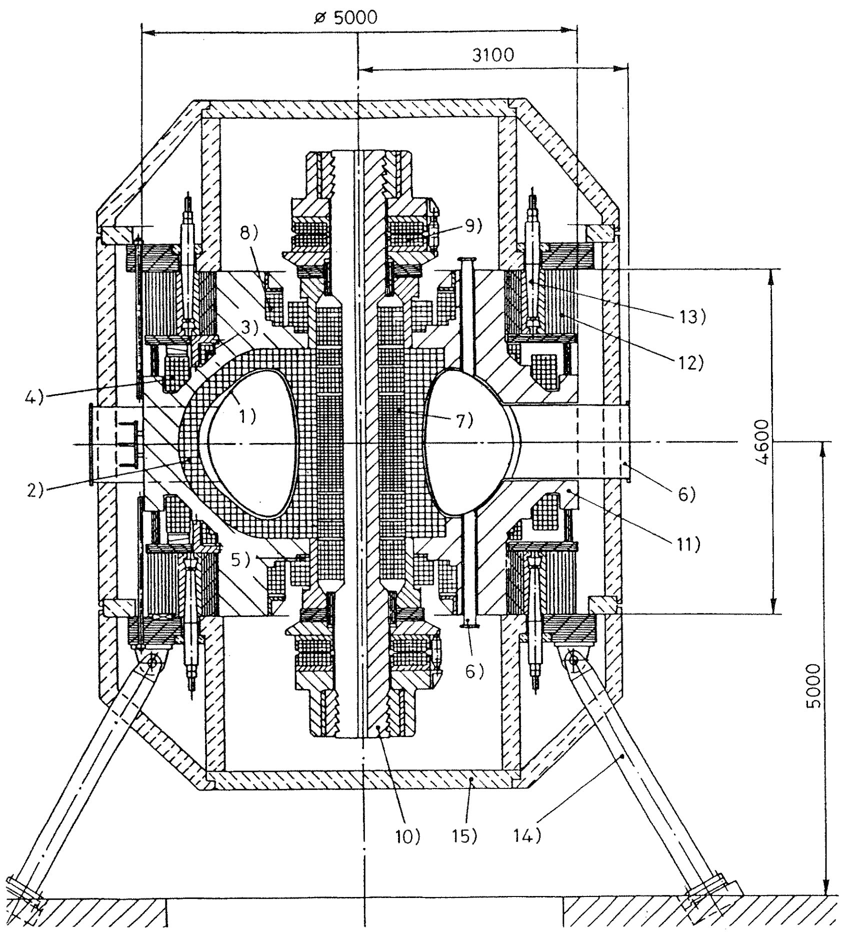

Fig. 1. – Main components of the Ignitor machine: 1) plasma chamber, 2) toroidal magnet, 3) shaping coil, 4) equilibrium coil, 5) outer transformer coil, 6) equatorial and vertical ports, 7) central solenoid, 8) shaping + transformer coil, 9) axial press, 10) central post, 11) C-clamp, 12) shrink ring, 13) tensioning wedges, 14) supporting legs, 15) cryostat, $R_0 = 1300$ mm, $a = 470$ mm, $b = 870$ mm.

are: a set of C-clamps surrounding the 240 (vertical) copper plates of which the magnet is made, two bracing (shrink) rings that are applied to the C-clamps, and an electromagnetic press that exerts a vertical force directly on the magnet plates. A highly optimized poloidal magnet system, of which the main component is the central solenoid, has the function of inducing the plasma current and of creating and maintaining the desired equilibrium configuration of the plasma column.

The 17 mm thick plasma chamber acts also as a support for the first-wall system that is made of graphite tiles covering the entire inner surface of the chamber. A set of tiles are attached to appropriate (double curvature) support plates that can be replaced by a remote-handling system.

An injector of deuterium pellets (~ 4 mm diameter) capable of a speed of 2 km/s or more is an important component of the Ignitor experiment. This can be used both as a fuelling system as well as for the purpose of creating and maintaining peaked spatial density profiles that make ignition conditions generally easier to attain and improve the energy confinement properties of the plasma column [8].

As shown in fig. 1, there are both vertical and equatorial access ports, to the plasma chamber, that are to be used for diagnostics, for the vacuum system, etc. In particular six out of the twelve equatorial ports are devoted to housing the r.f. antennae of the r.f. heating system. In fact, the Ignitor experiment is designed to reach ignition by exploiting the ohmic heating associated with the large currents induced in the plasma column as indicated in the next section. Therefore, the injected heating system, with each antenna capable of delivering between 2.5 and 4 MW, has the function of a back-up and of broadening the range of scenarios under which ignition can be attained.

3. – Physics considerations [9].

3·1. *Density and confinement time issues.* – The specific goal of Ignitor is to achieve ignition conditions at relatively low peak temperatures ($T_0 \lesssim 15$ keV). This, in practice, requires values of the confinement parameter $n_0 \tau_E \simeq \simeq 4 \cdot 10^{14}$ s/cm^3, where n_0 is the peak electron particle density and τ_E is the energy replacement time. The Ignitor design incorporates features that make attaining this regime possible with considerable safety margins. In particular, n_0 around 10^{15} cm^{-3} should be obtainable, on the basis of the series of experiments [4] started first by the Alcator machines at MIT and followed by the FT machine at Frascati and the TFTR at Princeton. Since the values of n_0 obtained experimentally correlate empirically to the ratio B/R, B being the magnetic field at the center of the plasma column, and R the torus major radius, the value of R in Ignitor has not been allowed to exceed twice that of the Alcator-C machine, where approximately twice the envisioned density, $n_0 \simeq 2 \cdot 10^{15}$ cm^{-3}, was achieved with comparable values of B, around 12.5 T. The maximum magnetic field in Ignitor is expected to approach this value with adequate reliability, considering also that the paramagnetic contribution of the plasma current is expected to add appreciably to the field produced by the toroidal magnet. In addition, we observe that the maximum value of $n_0 R/B$ obtained by the TFTR experiments is well above that obtained by the Alcator-C machine. Thus $n_0 \simeq 10^{15}$ cm^{-3} should be achieved in Ignitor with a considerable degree of confidence.

Two other important features of the Ignitor design are the high values of the poloidal magnetic field B_p and the toroidal plasma current I_p associated with it. The considered high values of B_p produce a strong rate of ohmic heating, while the corresponding high values of $I_p (\simeq 12$ MA) ensure that most of the α-particles produced by fusion reactions can be confined to deposit their energy in the central part of the plasma column. This is advantageous, as the diffusion coefficient for the plasma thermal energy is consistently found to be minimal in the central region. As indicated earlier, in addition to the toroidal current I_p, the Ignitor equilibrium plasma configuration, featuring an elongated plasma cross-section and a tight aspect ratio, ensures also the presence of a (paramagnetic) plasma current I_θ, flowing in the poloidal direction, that can be as high as 10 MA when the parameter $\beta_p = 8\pi \langle p \rangle / B_p^2$, where $\langle p \rangle$ is the mean plasma pressure, is small.

In fact, the high mean values of the poloidal field (up to 3.9 T) that are considered make it possible to attain ignition conditions with a relatively low value of β_p. This ensures a considerable margin for the stability against the onset of macroscopic internal (ideal MHD with dominant poloidal mode number $m^0 = 1$) modes [10], that can hamper the attainment of ignition [11].

Moreover, high values of I_p can limit the degradation of the energy confinement time, in the so-called L-regime, that is observed in present-day experiments when an injected form of heating is applied and prevails over ohmic heating. This is an important consideration, as the margin by which the desired value of τ_E can be obtained is generally more difficult to predict than the attainable peak density. Clearly, if the energy confinement time follows the trend indicated by experiments where only ohmic heating is present [12, 13], the margin to obtain $\tau_E \simeq 0.4$ s can be relatively large (2 to 4). The factor to be considered then is the rate at which degradation may take place when the α-particle heating prevails over ohmic heating. On the other hand, Ignitor has the unique favorable feature that it can reach ignition where P_α, the power associated with α-particle heating, compensates for all forms of energy loss but does not exceed $2P_{OH}$, P_{OH} being the power associated with ohmic heating. Then we notice that:

i) The degradation of plasma confinement in present-day experiments has been observed so far when ohmic heating becomes much smaller than other forms of heating, all of which are injected at discrete points around the torus. On the other hand, α-heating is internal to the plasma column and is axisymmetric, two features that it has in common with ohmic heating that has optimal confinement characteristics.

ii) In order to maintain a good margin for τ_E, the best strategy is to maintain a strong rate of ohmic heating up to relatively high temperatures where α-particle heating also begins to be strong. This is accomplished by programming the rise of the plasma current and the particle density while gradually increasing the cross-section of the plasma column [7]. By the end of this relatively long

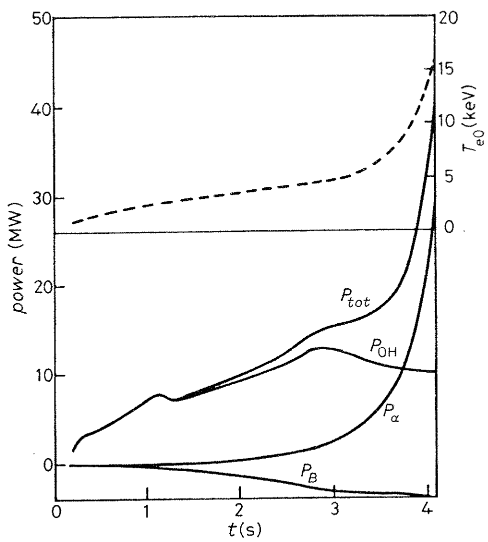

Fig. 2. – Expected time evolution (powers and temperature) of a typical Ignitor plasma column where the current was ramped to 12 MA in 3 s. Here P_{tot} indicates the total power produced by the plasma ohmic heating (P_{OH}) and the α-particles (P_α) emitted by fusion reactions, and P_B indicates the power loss by bremsstrahlung radiation emission. In this example of numerical simulation [7] ignition is achieved at about $t \simeq 4$ s.

(3 to 4 s) transient phase the applied electric field is strongly inhomogeneous, being low at the center of the plasma column, where the temperature can achieve relatively high values, and finite at the edge of the plasma column (corresponding to values of the loop voltage $V_\phi \simeq 1.8$ V). The ohmic power input can then remain considerable up to ignition, as shown in fig. 2.

iii) Provision has been made in the machine design to allow for the appearance of the so-called H-regime, where the confinement time is not degraded relative to that expected for regimes where only ohmic heating is present, when other forms of heating are prevalent. These consist of

a) a choice of machine parameters that enables the plasma column to maintain its reference dimensions and characteristics while having its outer edge detached from the first wall by a distance more than sufficient for the onset of the observed H-regime, a procedure suggested and confirmed by a significant set of experiments;

b) an optimized set of poloidal-field coils placed in proximity to the plasma column that can generate plasma equilibrium configurations of the same type as those produced by experiments with divertors. In order to implement this provision it is necessary, of course, to avoid the presence of narrow regions where the thermal loading on the first wall is too high. This is, in fact, a serious problem with divertor configurations.

We observe that the improvement of the confinement time τ_E in the H-regime over the values found in the so-called L-regime is due largely to the increase of thermal-energy density in the outer region of the plasma column, whose contribution to the rate of fusion reactions is not major. Therefore, most of the ignition scenarios for which Ignitor has been designed are based on the pessimistic assumption that the confinement time will have values predicted on the basis of scalings of τ_E found for the L-regime.

3·2. *Plasma purity and divertor issues.* – Another important requirement in order to achieve ignition conditions is that the plasma have a relatively high degree of purity. In practice, the parameter Z_{eff} that is a measure of the average charge number of the plasma nuclei should not be higher than about 1.75 ($Z_{eff} = \sum_j n_j Z_j^2 / n_e$, n_e = electron density, j indicates the nuclei species). This rough purity criterion was, in fact, first pointed out by us. The most reliable and proven way to keep Z_{eff} below the indicated value, according to the experiments that have been performed so far, is to produce plasmas with very high densities, in the range for which Ignitor has been designed. The reason is that a long series of experiments have confirmed the observation made first by the Alcator machine [4] in late 1974 that Z_{eff} is a monotonically decreasing function of the density.

We note that the use of a divertor to improve the thermal-energy confinement was proposed first in ref. [14] that included one of us. Therefore, the presence of a divertor in the Ignitor design was carefully considered since the beginning of this program. The factors that have led to its exclusion are

i) regimes with a high degree of purity have been obtained in high-density plasmas, where the effectiveness of divertors to obtain low values of Z_{eff} has not been demonstrated yet;

ii) the design of the plasma chamber and of the toroidal magnet would become considerably more complex;

iii) the major radius would have to undergo a large increase and the attainable values of B/R would be considerably degraded; this would undermine the margin by which peak densities $n_0 \simeq 10^{15}$ cm^{-3} can be predicted to be produced and well confined;

iv) the increased dimensions and lower magnetic fields would, assuming that the maximum plasma current can be held at 12 MA, lead to lower values of the poloidal field B_p and to a decrease of the maximum temperature achievable by ohmic heating alone, as well as of the maximum plasma pressure that can be confined without driving macroscopic (ideal MHD) internal modes unstable;

v) with the demise of ohmic heating a large and reliable injected heating system becomes necessary, rather than having the role of a backup as in the case of the Ignitor design; the issue of degraded confinement then becomes important well before α-particle heating begins to be a key component of the overall energy balance;

vi) relatively narrow regions (the divertor plates) where the thermal wall heating reaches very high values are introduced with operation in the divertor mode;

vii) the combination of circumstances mentioned above renders the objective of ignition practically impossible to attain. In addition, the compact nature of the experiment, with the limit on costs, time scales, etc., that this characteristic involves, is lost.

The design history of the CIT (Compact Ignition Tokamak) machine, proposed originally by one of us for the Princeton Plasma Physics Laboratory, is a good illustration of the arguments we have just given. In fact CIT, that is no longer compact and does not maintain the objective of ignition [15], has been renamed BPX (burning plasma experiment).

4. – «Neutronless» fusion burn experiments.

There are several motivations that make it interesting to investigate the conditions under which a deuterium-helium-3 plasma mixture can be brought to fusion burn conditions [16]. Specifically, we consider the reaction [17]

$$D + {}^3He \rightarrow p(14.7\ MeV) + {}^4He(3.6\ MeV)$$

and notice that its products are charged particles both of which are available to heat the plasma. Neutrons are produced by the DDD reaction sequence

$$\begin{aligned} & \qquad D \rightarrow {}^4He(3.52\ MeV) + n(14.06\ MeV) \\ & \qquad + \\ & D + D \rightarrow T(1.01\ MeV) + p(3.03\ MeV) \\ & D + D \rightarrow {}^3He(0.82\ MeV) + n(2.45\ MeV) \\ & \qquad + \\ & \qquad D \rightarrow {}^4He(3.67\ MeV) + p(14.67\ MeV)\,, \end{aligned}$$

that is sometimes referred to as the «catalyzed DD reaction», but the fraction of power released in the form of neutrons can be minimized. Therefore D-^{3}He reactors are frequently called neutronless.

It is evident that the characteristics of a fusion reactor based on the D-^{3}He reaction or the DDD reaction sequence are quite different from those of DT reactors. We note, in particular, that the DDD reaction sequence is characteristic of the age of nucleosynthesis, according to our current views of the evolution of the early Universe. The requirements for fusion burn conditions of a 50-50% plasma mixture of deuterium and helium-3 are not much different from those for the DDD reaction sequence in a pure deuterium plasma. Therefore, besides the practical aspects of proving the feasibility of an advanced type of fusion reactor, there is an additional incentive, to simulate an aspect of one of the phases of evolution of the early Universe, for pursuing this line of research. We observe that the DDD reaction sequence produces about 42% of its energy in the form of neutrons, while the corresponding fraction for the D-T reaction is 80%.

Since the Coulomb barrier for the D-^{3}He reaction is higher than that for the D-T reaction, it is evident that the ignition temperature in the former case will have to be higher. On the other hand, in the case of the D-^{3}He reaction both of the reaction products are available to deposit their energy within the plasma column. We note that the ideal ignition temperature T_I is defined as that at which a homogeneous plasma with equal temperature of the electrons and the fusing nuclei produces the same power in the form of charged particles emitted by fusion reactions as that of bremsstrahlung radiation emission. Thus for a 50-50% D-^{3}He mixture $T_I \simeq 30$ keV, while for a 50-50% D-T mixture $T_I \simeq 4.3$ keV. Moreover, when we consider the total energy balance for a magnetically confined D-^{3}He plasma under ignition conditions, we find that radiation losses (bremsstrahlung and cyclotron emission) are the major component of this balance, unlike the case of a D-T plasma where bremsstrahlung and cyclotron emission are rather minor forms of energy loss.

5. – The Candor experiment.

The first proposal that a D-^{3}He burn experiment be undertaken on the basis of present-day technologies and knowledge of the physics of magnetically confined plasmas was made [18] in 1980. Since then, the considerations [19] on which the experiment was proposed have not lost their validity, while the interest in reactors that would burn D-^{3}He mixtures has increased sharply [20]. We may point out that research on the physics of D-^{3}He fusing plasmas was not allowed officially by the funding agencies in Europe until 1988 [21]. Therefore, the evolution of the concepts of D-^{3}He burn experiments was hampered both by lack of adequate research effort and by the absence of an experiment to explore the burn conditions of deuterium-tritium-burning plasmas. In fact, events have shown, starting from the 1974 experiments on high-density, well-confined plasmas by the Alcator machine, that the scientific demonstration of a fusion reactor can best be approached by a series of experiments addressing the most important identifiable scientific issues as we advocated earlier.

The design of the Candor machine evolves from that of the Ignitor experiment. The major differences between the two designs come from the larger sizes considered for Candor, resulting from the need to insure larger confinement times both by increasing the geometrical dimensions and the total plasma current [22, 23]. With the larger size and the higher currents it becomes important to minimize the stored electromagnetic energy and, given the low temperatures ($\simeq 30$ K) to which the machine magnets are brought, the skin effect on the current in the conducting plates of which the toroidal magnet is made.

One possible solution is to split the toroidal-magnet coils (see fig. 1) in two nested parts, an internal and an external one operating in parallel. The central solenoid that is the most critical component of the poloidal field system is inserted between the two parts of the toroidal magnet. This ensures that the toroidal-magnet field at the inner edge of the toroidal-magnet cavity be kept minimum, relative to a design solution where the central solenoid is within the toroidal-magnet cavity, while the vertical field within the central solenoid attains rather moderate values. We notice that the classical solution adopted for Ignitor has the central solenoid outside the toroidal magnet. The disadvantage of the classical solution is that the vertical field within a limited region inside the central solenoid reaches values well in excess of 20 T.

We have considered in particular two similar configurations for the Candor experiment. One capable of producing a plasma current up to 20 MA and a smaller one corresponding to a maximum current of 18 MA. The relevant reference parameters are given in table II and table III, respectively.

The value of the confinement strength parameter

$$S_c = I_p \bar{B}_p$$

is extraordinarily high ($\simeq 77.5$ MN/m), and we compare it, as a reference, to the value obtained in experiments carried out by the Alcator-C machine. In this

TABLE II. — *Reference parameters of the* Candor-200 *machine.*

$R_0 = 200$ cm	major radius of the plasma column
$a \times b = 73 \times 146$ cm^2	minor radii of the plasma cross-section
$R/a \simeq 2.74$	aspect ratio ($b/a \simeq 2$, elongation)
$B_T \simeq 13.5$ T	field produced by the toroidal magnet
$I_p \simeq 20$ MA	plasma current in the toroidal direction
$\bar{B}_p \simeq 3.8$ T	mean poloidal magnetic field
$I_p \bar{B}_p \simeq 77.5$ MN/m	confinement strength parameter
$\langle J_\phi \rangle \simeq 0.6$ kA/cm^2	average current density
$V_0 \simeq 42$ m^3	plasma volume
$S_0 \simeq 115$ m^2	plasma surface
$q_\psi \simeq 3.5$	plasma current safety factor
$W_J \simeq 50$ MW	injected heating power

TABLE III. – *Reference parameters of the* Candor-180 *machine.*

$R_0 = 180$ cm	major radius of the plasma column
$a \times b = 67.5 \times 135$ cm^2	minor radii of the plasma cross-section
$R/a \simeq 2.66$	aspect ratio ($b/a \simeq 2$, elongation)
$B_T \simeq 13.5$ T	field produced by the toroidal magnet
$I_p \simeq 18$ MA	plasma current in the toroidal direction
$\bar{B}_p \simeq 37.7$ T 3,77	mean poloidal magnetic field
$I_p \bar{B}_p \simeq 68$ MN/m	confinement strength parameter
$\langle J_\phi \rangle \simeq 0.63$ kA/cm^2	average current density
$V_0 \simeq 32.3$ m^3	plasma volume
$S_0 \simeq 96$ m^2	plasma surface
$q_\psi \simeq 3.7$	plasma current safety factor
$W_J \simeq 40$ MW	injected heating power

case the maximum achieved confinement parameter was $n_0 \tau_E \simeq 0.8 \cdot 10^{14}$ s/cm^3, where τ_E is the total energy replacement time, with $I_p \simeq 0.78$ MA and $\bar{B}_p \simeq I_p/5a \simeq 0.95$ T, as $a \simeq 16.5$ cm, that corresponds to $S_c \simeq 0.73$ MN/m. Thus Candor-20 would have a value of S_c about 100 times larger than Alcator. On the other hand, we note that a typical value for the peak electron density is about $2 \cdot 10^{15}$ cm^{-3}, under D-^{3}He burn conditions, that is the maximum achieved by the Alcator-C experiments.

We observe also that the temperature T_0 in the center of the plasma column should reach a typical value around 65 keV. This corresponds to a total pressure $p_0 = (n_3^0 + n_D^0 + n_e^0) T_0 \simeq 34.6$ MPa since $2n_3^0 + n_D^0 = n_0$, for $n_D \simeq n_3$. Here n_D, n_3 and n_e indicate the density of D, ^{3}He and of the electrons, respectively. The magnetic-field pressure corresponding to 13.44 T is about 72.5 MPa. Therefore, the parameter

$$\beta = \frac{8\pi \langle p \rangle}{B_T^2},$$

where $\langle p \rangle$ is the volume average pressure, is about 10% if we assume $p_0/\langle p \rangle \simeq 5$. The thermal-energy content of the plasma is then

$$W_T \simeq 0.1 \frac{B_T^2}{8\pi} V_0 \simeq 460 \text{ MJ},$$

where V_0 is the plasma volume. Thus if the overall energy confinement time is about 4/3 s, the power loss is about 345 MW. It is easy to estimate that bremsstrahlung emission makes up the largest fraction of this power [19, 23, 24] as indicated earlier.

The procedure that has been envisioned in order to bring the plasma column to D-^{3}He burn consists of an initial phase where D-T ignition is achieved with peak electron density around $1 \cdot 10^{15}$ cm^{-3}. In fact D-T ignition can be achieved by ohmic heating alone. In the following, intermediate phase an auxiliary heating system is applied while the electron and the deuterium densities are increased, and the appropriate concentration of helium-3 is introduced. At this time, the most appropriate type of heating system to adopt is the injection of r.f. power at the ion cyclotron frequency.

It may be appropriate to point out that, when we proposed the first D-^{3}He burn experiments in 1980, a common opinion was that plasmas with high value of β such as 10% could not be produced. One of the main reasons brought forward was because of the possible excitation of macroscopic instabilities so-called «ballooning modes» found originally [25] by COPPI and ROSENBLUTH in 1965. On the other hand, we had just proven that the original theory was not complete and shown the existence of a new stable regime that we called «second stability region» of the relevant parameter space [26]. This allowed us to show that plasmas with the desired values of β could be stable. After the usual initial skepticism our theory was accepted, but, of course, the experiments needed to prove that β around 10% or slightly higher could be produced. By now these experiments have been performed. In addition, the design of high-field experiments has progressed to the point where values of $\bar{B}_p$ around 4 T can be seriously considered. Therefore, the values of β_p for which D-^{3}He ignition can be attained become only slightly larger than unity (*e.g.*, $\beta_p \simeq 1.2$) and this makes maintaining the plasma in a stable region easier [27] than we originally thought.

Another adverse type of argument that we had found to be not well founded is that synchrotron emission would make D-^{3}He ignition impossible in a high-field confinement configuration. In reality our early estimates that pointed to the contrary have been confirmed by sophisticated numerical analyses, for which ref. [28] serves as a standard.

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