ENGINEERING CHARACTERISTICS OF THE IGNITOR ULT EXPERIMENT

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ABSTRACT

The latest embodiment[1] (Ignitor Ult) of an advanced machine with the purpose of investigating D–T burn ignition conditions is presented. The main engineering characteristics and the design of the machine's principal components are driven by the plasma parameters that have to be achieved while ensuring the stability of the chosen equilibrium configuration of the plasma column.

I. INTRODUCTION

The Ignitor experiment[2] has been conceived on the basis of the well known properties of high density plasmas[3], in terms of good confinement and high degree of purity, and of the developments of existing technologies in order to achieve fusion ignition conditions.

The reference plasma dimensions and parameters of Ignitor Ult are reported in Table I and a vertical cross-section is shown in Fig. 1.

TABLE I
Reference Design Parameters of the Ignitor Ult Configuration

$R_o \simeq 1.30$ m	Major radius of the plasma column
$a \simeq 0.47$ m	Minor radius of the plasma cross section
$\delta_G \simeq 0.4$	Triangularity of the plasma cross section
$\kappa \simeq 1.85$	Elongation of the plasma cross section
$I_p \lesssim 12$ MA	Plasma current in the toroidal direction
$B_T \lesssim 13$ T	Vacuum toroidal field at R_o
$V_o \simeq 9.5$ m^3	Plasma volume
$S_o \simeq 36$ m^2	Plasma surface area
$t_r \simeq 3$ to 4 s	Ramp up time for I_p
$t_{ft} \simeq 4$ s	Flat top time at maximum I_p and B_T
$P_J \lesssim 15$ MW	Injected heating power at $f \simeq 130$ MHz

The physics basis of the experiment and the expected machine performance have been discussed elsewhere in this conference[4] and will be assumed for the present paper.

The main problems that have been addressed in designing the machine are connected with the need to:

- create and control different plasma configurations;
- induce the toroidal plasma current and maintain the plasma discharge for a time $\gtrsim 10\ \tau_E$ at ignition, where τ_E is the energy replacement time;
- operate with an acceptable thermal loading on the first wall;
- withstand the static, dynamic, electromagnetic, thermal and disruptive loads on allthe affect machine components;
- provide access for diagnostics, pellet injector, r.f. antennae, vacuum system, remote maintainance, etc.

The design of the main machine components is summarized in the following.

II. POLOIDAL FIELD SYSTEM

A highly optimized set of 14 up-down symmetric poloidal field coils, placed in proximity to the plasma column (see Fig. 1), has the functions of inducing the plasma current, creating the desired equilibrium configurations and maintaining them against unstable radial and vertical motions.

Copper OHFC has been selected as the material for the central solenoid in order to maximize its electrical conductivity, while a material with enhanced mechanical properties (GLIDCOP) is used for the other poloidal field coils that are self-supporting structures. This is possible since these coils are located in a region of the machine where more space is available and, furthermore, they carry high current only during a limited time interval of the discharge.

The central solenoid consists of a double array of copper coils wrapped around the central steel pole of the machine. Each conductor coil is provided with a cooling channel at its center. The cooling medium is He gas. The initial temperature before a plasma discharge is about 30 K.

A. Volt–second Requirement

An analytical assessment[5] of the magnetic flux variation linked with the plasma column has been carried out and the results have been checked with numerical analysis performed using the Tokamak Simulation Code[6] (TSC). The volt–second requirement at ignition is lower than 32 V s, under a range of assumptions on the values of the ion and electron thermal conductivity, effective charge, etc., for plasmas reaching ignition during the flat top phase of the discharge, with the maximum value of the plasma current. The volt–second consumption during the flat top, at a rate of about 1.5 V s per second, is due to resistive losses as well as an inductive component corresponding to an increase in the internal inductance. We note that in discharges aided by injected heating, where the plasma can reach ignition during the current ramp, the volt–second requirement may be as low as $\simeq 25$ V s due to the lower value of plasma current that is nedeed to provide the necessary plasma heating and the higher plasma temperature that reduces the resistive loss. The poloidal field system is designed to produce a flux variation of about 32 V s.

B. Plasma Equilibria

Several kinds of plasma equilibria have been analyzed[7]:

- limiter configurations that fill the entire cavity of the plasma chamber are useful to keep the thermal wall loading as uniformly distributed as possible;
- transient double x-point configurations that can be used to reproduce the characteristics of the so-called H–regime where τ_E is only slightly degraded, relative to that expected for regimes where only ohmic heating is present, when other forms of heating prevail. In order to implement this provision it is necessary, however, to keep I_p well below its maximum design value, and

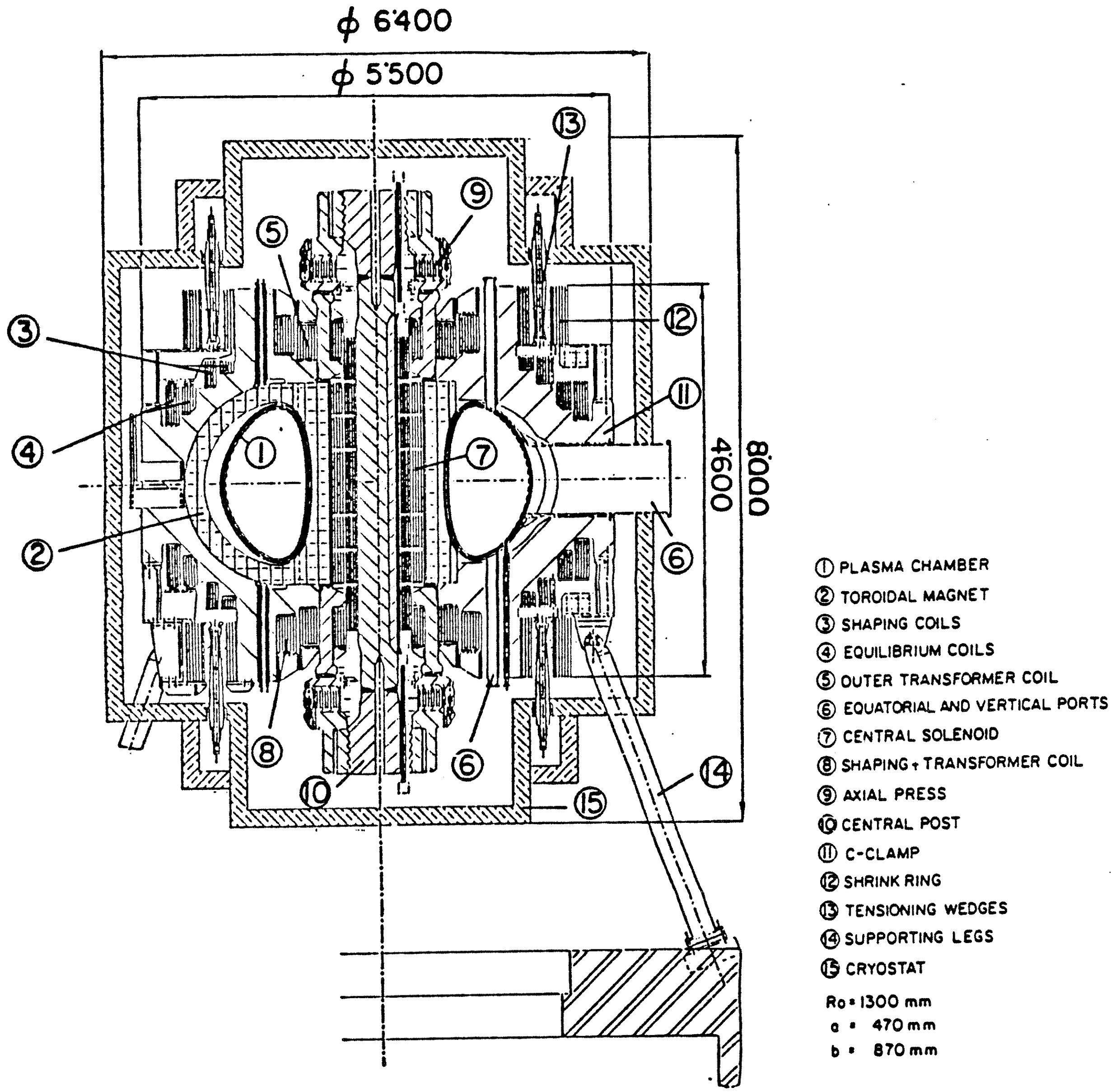

Fig. 1. Ignitor vertical cross-section

to avoid the presence of narrow regions of the first wall where the thermal loading is too high. When the localized thermal wall loading, associated with the x-point configuration, is estimated to exceed desirable limits, the equilibrium is to be made to evolve into a limiter configuration;

- detached limiter configurations that enable the plasma column to maintain its reference dimensions and characteristics while having its outer edge detached from the first wall by a distance larger than $a/10$ that should be sufficient to maintain the onset of the H-regime, a procedure suggested and confirmed by a significant set of experiments[8].

C. Radial and Vertical Control

The radial feedback system is mainly used to:

- control the plasma current density distribution and the magnetic safety factor evolution during the ramp phase of the discharge by changing the plasma radial dimensions;
- keep the plasma in the desired position relative to the first wall and, possibly, control the transition between x-point configuration and limiter configuration;
- control the radial position during vertical disruption or during the rapid change of plasma parameters, such as the internal inductance (l_i) or the poloidal beta (β_p).

The elongated plasma configuration in Ignitor is potentially unstable to vertical motion. An extensive numerical simulation[9] of the plasma dynamics has been carried out using the TSC code. The stability behavior of the plasma/vacuum vessel/poloidal field coils system has been analyzed, taking into account, in a two dimensional space, the geometry of the machine, the position of the diagnostic magnetic pick up coils and the characteristics of the power supplies in terms of voltage limitations and time delay in the response. The minimal plasma vertical growth time (τ_v), defined as the reciprocal of the linear exponential growth rate of the plasma vertical position, has been estimated to be about 15 ms when the presence of the thick vacuum vessel is taken into account and the poloidal field coils are connected in such a way that antisymmetric current can be induced in the up and down symmetric coils. The toroidal magnet coils can be expected to have an additional beneficial effect in slowing the plasma motion. This factor will be considered in the next analysis.

The best results in terms of fast plasma position control and lower power requirement use a combination of one inboard coil (number 4 in Fig. 2) and one outboard coil (number 12 in Fig. 2). The inboard coil is less coupled to the plasma and cannot control the plasma motion by itself. However, it can produce a radial magnetic field that diffuses rapidly into the plasma and slows the vertical motion, reducing the power requirement on the outboard coil. Both proportional and derivative gains are used in the feedback algorithm for the current in the inboard and outboard coils, while a simple proportional gain is used to determine the voltage.

Some simulations have been carried out to evaluate the influence on τ_v of the small variation around the reference value of some plasma parameters, such as β_p, l_i and κ. The results show that β_p and κ have a very weak effect on the plasma vertical motion. The relatively mild influence of κ (for variation $\Delta\kappa = \pm 10\%$) on τ_v is due, as explained in ref. 10, to the presence of a close-fitting vacuum vessel. In particular, if κ is increased, a larger field index ($n_v \equiv -(R_o/B_z)(\partial B_z/\partial x)$) is required for the equilibrium and the plasma becomes more unstable. However, at the same time a more elongated plasma is closer to the vacuum vessel and its stabilizing effect is therefore stronger. Instead, lower values of l_i give rise to lower values of τ_v, as already found in ref. 10, because narrow toroidal plasma current distributions mean that the plasma current lies on average farther away from the vacuum vessel. Furthermore, the equilibrium configuration at lower l_i requires a larger value of the field index for the same elongation.

III. TOROIDAL FIELD SYSTEM

In order to make Ignitor Ult suitable for relatively long plasma current pulses that can exceed 10 τ_E, the toroidal magnet has been designed with lower values of the starting temperature (30 K) and of the current density (< 100 MA/m^2) compared to the case of the Alcator-C machine (temperature ~ 80 K and design current density up to 220 MA/m^2).

A. Structural Solution

A feature maintained throughout the evolution of the design of Ignitor is that of toroidal magnets made of copper plates, connected in series externally and supported by an appropriate steel structure so as to withstand both the vertical (axial) and the horizontal (radial) electrodynamic forces. In particular, the loads on the inner leg of the toroidal magnet are supported by bucking between toroidal and poloidal coils (a sliding surface is provided at the interface between the toroidal magnet and the air core transformer), by wedging in the inner part of the toroidal coils, and by external structural elements. These consist of:

- A set of steel plates or "C–clamps" surrounding each of the 24 modules of the toroidal magnet. The C–clamps are wedged on the outside to allow the unwedged part to rotate around an effective hinge under the effect of the bracing rings. Thus only a small fraction of the vertical separating force is unloaded onto the central leg of the toroidal magnet.
- Two bracing rings maintaining the plate assembly and transferring the vertical separating force produced by the toroidal magnet to the effective outer shell formed by the steel plates.
- A central post filling the bore of the air core transformer whose main functions are to absorb the centripetal force acting on the inner leg of the toroidal magnet and to be a component of a central press. Radial vertical cuts are made in the post to reduce the effect of the induced currents.
- A vertical electromagnetic press connected with the central post and capable of giving a compression preload on the inner leg of the toroidal magnet to reduce the electromagnetic load. The press is deactivated as soon as thermal expansion due to the temperature rise in the toroidal magnet becomes significant, or whenever the machine is operated with magnetic fields below the maximum considered values.

B. Cooling System

A hybrid cryogenic system[11] is adopted for the cooling of the toroidal magnet, where the warmer part of the plant is operated with liquid N_2 and the colder part with He. After a current pulse, corresponding to the maximum plasma current scenario, the temperature will reach about 230 K in the region facing the transformer (1/3 of its volume) and about 95 K in the remaining part. Cooling of toroidal magnets down to 80 K with the help of liquid N_2 has been done before and the technology is well established. The step from 80 K to 30 K requires the use of He as a cooling and heat transfer medium. Heat transfer from the coils to the coolant takes place through forced convection in conduits within the coils. The same helium stream will go several times through the magnet and will be recooled between the passages. The 24 modules of the toroidal magnet are divided into four sections. Each one has its inlet header and its outlet header. This cooling system has a further advantage: when the coolant temperature at the outlet of the magnet reaches a value below 80 K, the He cooling plant can produce an outlet temperature lower than 30 K and the magnet cooling time will be shortened. The estimated cooling time is shorter than that required by the central solenoid.

IV. PLASMA CHAMBER

The design of the plasma chamber has been carried out to produce a structure capable of withstanding both static and dynamic loads with good reliability, while minimizing the weight, construction and assembly difficulties as well as its overall cost. The result is a relatively thick chamber (17 mm in the inboard side and 26 mm in the outboard side), made of Inconel 625, divided in 24 sectors that can be assembled and joined by welding.

The plasma chamber is mechanically supported and restrained by the C–clamps, with long horizontal port ducts which allow for enough freedom of deformation under electromagnetic and thermal loads. The main consideration in the design of the plasma chamber and its mechanical support has been the ability to withstand both vertical and axysimmetric disruptions with plasma current decay rates from 2.5 to 5 MA/ms. The results of a two-dimensional numerical analysis[12] show that the stresses are below the limit imposed by ASME rules. A three-dimensional code has be used to model the toroidal forces due to the discontinuities introduced by the horizontal ports for symmetric disruptions with plasma current decay rate of 2.5 MA/ms. This situation has been found to produce significant changes in the force distribution on the plasma chamber, as was already found in BPX[13], but the corresponding mechanical stresses are still well below the maximum values that can be applied to the Inconel 625.

The plasma chamber acts as a support for the first wall system. Vertical and equatorial access ports for the plasma diagnostics systems, the vacuum system, the pellet injector, and the auxiliary heating are provided for in its design. In particular, six of the twelve equatorial ports (0.8×0.165 m^2) connect to a "pocket" (0.8×0.5 m^2) facing the plasma whose function is to house the antennae of the r.f. heating system (ICRH).

V. FIRST WALL SYSTEM

A. Material

The first wall is made of graphite tiles, 20 mm thick, covering the entire inner surface of the plasma chamber. A set of 16 tiles is brazed on appropriate (double curvature) support plates that can be replaced by a remote handling system. Thus, in principle, the whole first wall functions as a completely extended limiter. The major advantage of this solution is the large contact area on which the heat load may be spread. This area ranges from the total first wall surface ($\simeq 36$ m^2), for a plasma limiter configuration filling the entire cavity, to the area of the inner part ($\simeq 12$ m^2), for plasma detached from the outside wall.

Graphite reinforced by carbon fibers has been selected as first wall material, taking into account both thermo-mechanical properties and plasma-related properties such as atomic number, sputtering yield, release and inventory of hydrogen isotopes, radiation damage, the relatively large amount of experimental data avaliable on its behavior as first wall material, etc. The major consideration that has led to this choice of material is the expected effect of disruptions.

B. Thermal Wall Loading Analysis

Numerical transport simulation[14,15] have shown that Ignitor can achieve ohmic ignition at low peak temperature ($T_o \gtrsim 11$ keV) with a moderate value of the α-power ($P_\alpha \simeq 18$ MW). About 26 % of this power is lost by radiative processes ($P_R \simeq 4.6$ MW) in the main plasma and the remaining 13.4 MW (74 %) is transfered to the scrape off layer (SOL). From here this power is released to the first wall surface by radiative and convective-conductive energy transfer. The importance of one process relative to the other is determined by the plasma behavior in the SOL. Simple physical models[16,17] and experimental data from high density, high magnetic field experiments confirm the expectation of a high density, low temperature plasma in the SOL. This means that the core plasma will be shielded from the impurities and that this cold and dense scrape off plasma will be characterized by a strong radiative cooling. In particular, on the basis of an extensive series of observations made on high field machines, it is realistic to consider that at least 50% of the power transfered into the SOL will be released by radiation.

In summary we may assume that:

- 63% ($\simeq 11.3$ MW) of the total power is uniformly distributed to the first wall by radiation in the main plasma and in the SOL.
- the remaining 37% ($\simeq 6.7$ MW) is nonuniformly distributed (with an estimated maximum peaking factor of 3) due to convection and conduction processes in the SOL.

We may estimate the maximum thermal wall loading about 0.9 MW/m^2 for a limiter configuration filling the entire plasma chamber and higher values if the plasma interacts only with the inner part of the surface of the first wall. On the other hand, if we assume that the plasma, after achieving ignition, will reach a state at $T_o \lesssim 15$ keV where about 40 MW are supplied by the input powers to maintain the energy balance and the radiative losses from the main part of the plasma column are about $P_R \simeq 6$ MW, the corresponding wall loading is 2 MW/m^2.

VI. AUXILIARY SYSTEMS

A. Injected Heating System

Since ignition can be attained by ohmic heating alone, injected heating systems in compact high field experiments such as Ignitor have the role of backups; to be available, if needed, to suppress the possible onset of sawtooth oscillations, to control the temperature evolution and the current density profiles, and to accelerate the attainment of ignition.

Among the options considered, an ICRH system with a frequency $f \simeq 130$ MHz and a maximum power delivered to the plasma $P_J \simeq 15$ MW, has been adopted for Ignitor because of the experimental evidence of its effectiveness with relatively high density plasmas. The relevant antennae are placed in six housings inserted into the vacuum chamber and connected to the large horizontal ports. The power that can be delivered through each housing is estimated in the range 2.5 to 4.0 MW.

B. Pellet Injector

An injector of deuterium or deuterium-tritium pellets (~ 4 mm diameter) is considered, in addition to the well-tested technique of gas injection ("puffing")[2], to create and maintain the desired density profile. Pellet velocities of 2 km/s or higher that are required to reach the central region of the plasma column have, in fact, been already achieved with existing technologies. Another use for a pellet injector that has been demonstrated recently is to condition the first wall by launching lithium pellets into the plasma column prior to regular hydrogenic discharges[18].

VII. CONCLUSIONS

The design of a machine that can produce and confine D-T plasmas to reach fusion burn conditions has been carried out adopting the high field magnet technology, started with the Alcator experiment, that uses cryogenically cooled normal conductors.

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