RECENT RESULTS RELEVANT TO IGNITION PHYSICS AND MACHINE DESIGN ISSUES*

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The Ignitor Project Group

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Abstract

The plasma regimes under which ignition can be achieved involve a characteristic range of parameters and issues on which information has been provided by recent experiments. In particular, these results have motivated a new, in-depth analysis of the expected performance of the Ignitor machine as well as of the plasma processes that it can investigate. The main results and recent advances in the design of key systems of the machine are reported.

1. INTRODUCTION

The purpose of the Ignitor experiment is to produce deuterium-tritium plasma regimes where ignition can take place. At ignition all thermal energy losses from the plasma are compensated by the α-particle heating produced by D-T reactions. The main components of the machine are shown in Fig. 1. The reference design parameters of the machine [1], given in Table I, could allow it to reach ignition by ohmic heating alone, but in order to expand the range of experiments that can be performed and to gain more control over the radial profiles of the current density and plasma temperature, an ICRH system has been included. In the present design, this system can deliver a similar power (around 20 MW) as the α-particle heating under projected ignition conditions. Since ignition can occur for low values of β-poloidal, typically $\beta_p \lesssim 0.25$, a considerable paramagnetic poloidal current can be produced. We consider the $m = 1$, $n = 1$ mode involving collisional magnetic reconnection to be of particular concern, given the fact that in these regimes [2] the electron collision frequency, on the $q = 1$ surface, exceeds the ion diamagnetic frequency by a factor 3–4.

Two scenarios of operation, at the design value of the toroidal field on axis, $B_T \cong 13$ T, are quoted in Table I, one corresponding to a plasma current pulse that has a 4 s ramp + 4 s plateau at 11 MA followed by an appropriate ramp-down, and another one in which the plasma current can be raised to 12 MA, with a short plateau followed by a longer ramp-down. The peak plasma pressure at which ignition is expected to be achieved is at least 4 MPa (e.g., $n_0 \approx 10^{21}$ m^{-3} and $T_{e0} \approx T_{i0} \approx 12.5 - 15$ keV). At lower toroidal magnetic fields the plasma current pulse can be considerably longer.

2. THE INTERNAL MODE AND TRANSPORT ISSUES

In the high current, high field scenarios the onset of internal modes with $n^0 = 1$ and a prevalent $m^0 = 1$ component is of concern. A comprehensive analysis has been undertaken, given the importance that large scale sawtooth oscillations be avoided as they may prevent ignition. Different kinds of $p(\psi)$ and $q(\psi)$ profiles have been considered, including those used to evaluate the typical equilibrium configurations produced by the Alcator C-Mod machine with values of β_p and q_ψ close to those envisioned for Ignitor. In this case, the analysis carried out with the PEST code [3] indicates that the plasma is stable to ideal MHD modes. The sawtooth activity observed in Alcator C-Mod is associated with reconnecting modes. At 11 MA the considered equilibrium configuration for Ignitor has a volume of the $q \le 1$ region that does not exceed 1/10th of the total plasma volume. Thus, the excitation of sawteeth with similar characteristics of those observed in Alcator C-Mod, that is limited amplitude and a modest region from which thermal energy is periodically expelled, should not prevent achieving or maintaining ignition. In fact, this configuration is shown to be ideal MHD stable [4] or close to marginal stability for pressure profiles considerably more peaked than those representative of Alcator C-Mod. At 12 MA, a class of pressure profiles can be identified, with realistic gradients, for which these modes cannot be excited. Moreover, when ideal MHD unstable modes are found, these feature a transition layer where the radial profile of the plasma displacement undergoes a sharp variation, which is so narrow that consideration of reconnection and finite ion gyroradius effects, along the lines described below, becomes necessary.

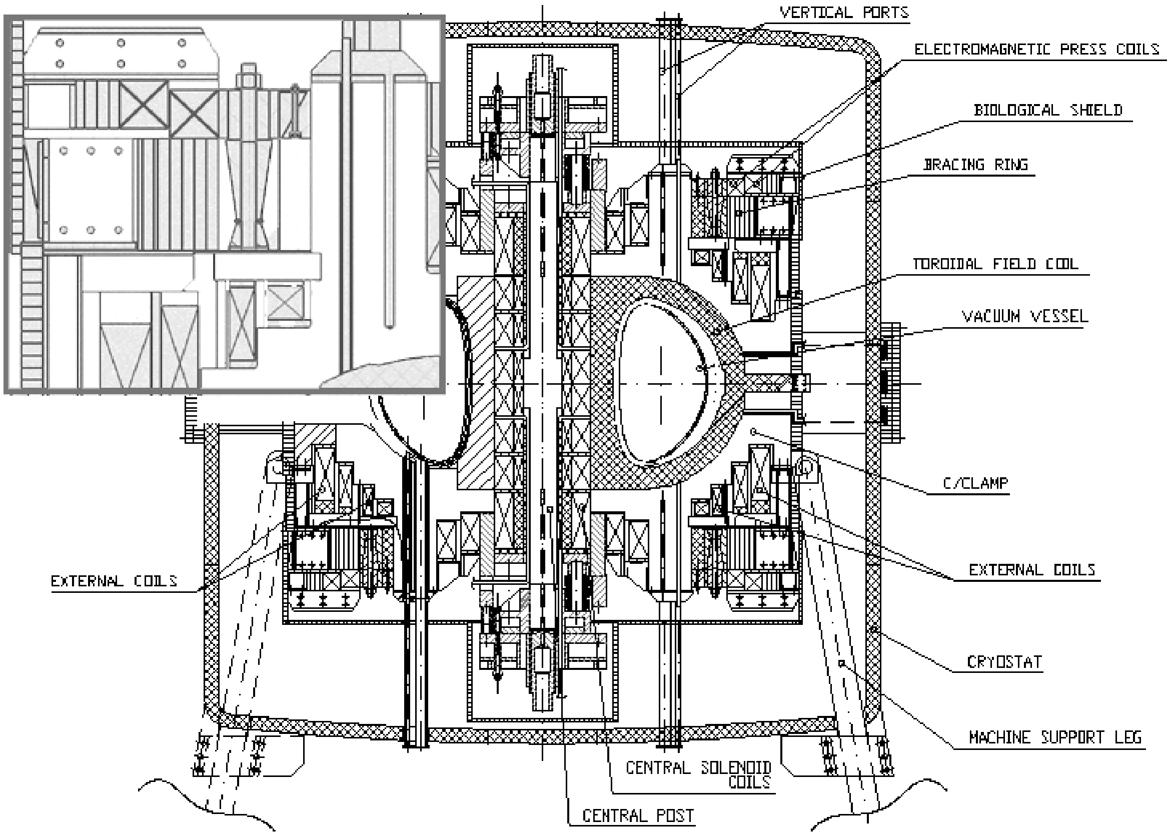

FIG. 1. *Main components of the Ignitor-Ult machine. The electromagnetic press system, enlarged in the inset, involves two concentric coils surrounded by a bracing ring.*

In order to include all relevant physical effects, a parallel analytical effort has been developed where the MHD stability parameter $\lambda_{H,tot} = \lambda_{H,MHD}(\beta_{p1,c} + \beta_{p1,\alpha}) + \lambda_{K,\alpha}(0)$ is computed for general equilibrium profiles [5, 6]. The effects due to the shaping of the plasma cross section and to the presence of α-particles are thus considered. High-energy α-particles have both a stabilizing effect, through the kinetic term $\lambda_{K,\alpha}(0)$ [7] (evaluated here in the small frequency limit) and a destabilizing one, due to their contribution $\beta_{p1,\alpha}$ to the poloidal–β parameter [5] β_{p1}. The quantity $\lambda_{H,tot}$ is then used as a boundary value for the equations describing the plasma dynamics inside the transition layer. Model equations including finite resistivity, finite diamagnetic frequencies and the full finite gyroradius ion response have been formulated, adapting those discussed in [8] for the collisionless regime, to the electron collisional regime that is appropriate for ignition experiments. The resulting eigenvalue problem has been solved numerically. We find that, when $\lambda_{H,tot} < 0$ or close to zero, the relevant reconnecting modes are typically stabilized by finite ion diamagnetic frequencies effects. Fulfilling this condition depends on the shape of the q-profile (and, through β_{p1}, on the steepness of the pressure profile), and we note that q-profiles with a "shoulder" between the $q = 1$ and $q = 2$ resonant surfaces have optimal stability properties. We have considered plasma pressure profiles $p(\rho) = p_0(1-\rho^2)^{\nu_p}$, where ρ is a normalized radius, with $\nu_p = \nu_n + \nu_T = 1 + 1.5$ so that $p_0/\langle p\rangle = 3.5$, a peak density $n_0 = 1.1 \times 10^{21}$ m^{-3}, and different values of the peak temperature T_0 (12 and 15 keV). This analysis shows that, for a standard parabolic q-profile, $\lambda_{H,tot} > 0$ (indicating ideal instability) even for small values of ρ_1. On the other hand, when considering a q-profile with a "shoulder", stability improves dramatically, and $\lambda_{H,tot} < 0$ even for relatively large values of ρ_1. While the conditions under which such "optimal" q-profiles can be generated need to be more thoroughly investigated, it is interesting to note that, in the Ignitor simulations reported in [9], q-profiles of this type can be obtained by properly programming the current ramp and the application of RF heating.

The evolution of the plasma configuration and parameters from startup to ignition has been simulated recently by the JETTO code [10, 11]. The reference operation scenarios considered have plasma current up to 11–12 MA. Many parameters, such as density, impurity content, plasma shaping, and current density profile, are shown to play an important role on the path to ignition. In addition, detailed studies of the approach to ignition have underlined the importance of the choice of the temperature at the boundary [9, 11].

Among the recent experimental results of interest we note that a series of experiments [12] carried out by the FTU machine has employed central electron cyclotron heating (ECH), whose energy deposition, like that of α–particles, is localized near the axis of the plasma column. In discharges with low/negative magnetic shear the effective electron thermal diffusivity was observed to decrease when the MHD fluctuations were transiently reduced, confirming that MHD activity made a significant contribution to transport. These plasmas regimes, characterized by high electron temperatures, low densities, low ion temperatures and high Z_{eff}, cannot be extrapolated to ignited conditions. However, they indicate that it may be too pessimistic to assume, as we have done in our numerical simulations, that α–particle heating, which in addition is axisymmetric, introduces a deterioration in the confinement properties of the same kind as that observed when externally injected heating is present.

3. MACHINE DESIGN ISSUES

The observation of significant, non-axisymmetric halo currents produced during typical Vertical Displacement Events [13] has motivated a full analysis of the stresses generated in the Ignitor plasma chamber, the first wall tiles, and the tile carriers during a reference event of this kind. Structural integrity has been verified by means of a dynamic elasto-plastic analysis [14], modelling the entire plasma chamber. The maximum vertical load on the PC is consistent with a plasma disruption model where the current quench starts when the $q = 1.6$ surface makes contact with the first wall. It has been demonstrated that, according to the ASME III code rules, the Ignitor plasma chamber can withstand in its weakest part, the weld regions, 40000 cycles of disruptions involving an average halo current of 3 MA (25 − 27% of the plasma current) with a peaking factor of 2 in the toroidal direction, at nominal plasma current (11 −12 MA) and magnetic field (13 T at $R = 1.32$ m). These values of the halo current fraction and peaking factor are rather conservative and represent the worse experimental results observed so far. We point out that obtaining good confinement configurations in a machine that incorporates a thick plasma chamber (the Ignitor design was the first one to adopt this solution) has been well demonstrated by the successful operation of the Alcator C-Mod machine.

Significant progress has been made in devising an optimal configuration for the horizontal electrical press, acting on the “flags” of the C-clamps [1], which is employed to relieve the stresses from the inner leg of the toroidal magnet at the maximum field values. The principal feature of the electrical press (see inset in Fig. 1) is that it operates in parallel with a mechanical press (whose main element is a set of two bracing rings) and it makes it possible to perform adjustments on the latter with relative ease. At the same time, the construction, installation and removal of the central solenoids and of the central post system are considerably simplified. In particular, tightening of the bracing ring rams, when the machine is cold, can be avoided. The adoption of a horizontal press relative to a vertical one also allows a greater freedom in the programming of the currents in the central solenoid coils, as the central post can now take up repulsive forces between these coils. In this way, a significant increase in flexibility for the control of the plasma shaping can be gained. In particular, by carefully adjusting the distance between the poloidal field null points and the plasma edge, a good matching of the plasma shape to the first wall can be obtained, thus reducing the possibility of localized heat loads.

Because of the importance of the ion cyclotron resonance heating for high density plasmas an ICRH system in the 70–140 MHz frequency range has been incorporated in the original Ignitor design. A comprehensive analysis of the antenna system performance has been undertaken, in which considerations on the tuning and matching system have been included. The coupling properties of the antenna have been evaluated employing pre-existing codes, as well as a newly developed, self-consistent code [15]. Globally, the analysis demonstrates the feasibility of an ICRH system that fulfills the requirements of the Ignitor experiment, fits within the allocated space and is compatible with the electrical constraints of the machine.

Each of the 6 antennas on the horizontal ports has 4 straps forming a 2×2 poloidal and toroidal phased array; each strap is fed by a radiofrequency power generator via a coaxial cable and a tuning and matching system. The predicted radiation resistance is sufficient to withstand, within the overall mechanical design constraints, 4 MW per port of injected power, so that a total of up to 24 MW can be delivered to the plasma. We notice that the range 18–24 MW is that of the α-particle heating corresponding to the expected ignition conditions. Thus, α-particle heating can be simulated at the same power level in non-reacting plasmas, taking into account that it is radially more localized than the IC heating.

TABLE I. REFERENCE PARAMETERS OF THE IGNITOR MACHINE

Major radius R_0 (m)	1.32
Minor radii $a \times b$ (m^2)	0.47×0.86
Aspect ratio R_0/a	2.8
Elongation $\kappa = b/a$	1.83
Triangularity δ	0.43
Vacuum toroidal field B_T (T)	13
Toroidal current I_P (MA)	11 – 12
Poloidal current I_θ (MA)	$\lesssim$ 8.25 – 9
Paramagnetic field (T) produced by I_θ	$\lesssim$ 1.4 – 1.5
Mean poloidal field $\overline{\overline{B}}_p = I_p / \left(5\sqrt{ab}\right)$ (T)	3.4 – 3.75
Confinement strength $S_c = \overline{\overline{B}}_p I_P$ (MN/m)	38 – 45
Av. toroidal current density $<J_\phi>$ (MA/m^2)	8.5 – 9.3
Maximum poloidal field B_{PM} (T) ($R<R_0$)	5.9 – 6.5
Magnetic flux swing (Vs)	36
Edge magnetic safety factor q_ψ	3.6 @ 11 MA
Plasma volume V_0 (m^3)	≅10
Plasma surface S_0 (m^2)	≅36
Additional heating power P_{ICRF} (MW)	18

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