Optimal Regimes for Ignition and the Ignitor Experiment*

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Abstract. The optimal conditions under which confined plasmas can reach ignition are identified referring in particular to the parameters of the Ignitor machine. The key importance of the radial profiles of the particle density, the thermal energy diffusivity, the plasma pressure, the function $q(\psi)$, etc., is demonstrated. Peaked density profiles, such as those obtained in the Alcator A and C experiments (at about the same central density and magnetic field as in Ignitor), characterized by minimal thermal diffusivities and high plasma purity, are shown to be best suited for ignition. The H-mode regime in Ignitor is accessible but not considered a priority because of the typically flat density profiles. The role of collective modes and their interaction with both high and low energy α-particle populations are assessed. For the modes generating sawtooth oscillations and involving magnetic reconnection the stabilizing effect of "shoulder" $q(\psi)$ profiles is pointed out together with the role of the trapped ion population.

1. Introduction

Ignition in magnetically confined D-T plasmas is defined as the condition where the rate of energy deposited in the reacting plasma by the produced α-particles, P_α, compensates for all thermal and radiative losses, represented by P_L. Hence the relevant parameter to evaluate the plasma fusion performance is $Q_\alpha = P_\alpha/(P_L - P_\alpha)$. Reaching the regime where $Q_\alpha >> 1$ requires that the plasma column be macroscopically stable, that the reacting part of it (central region) be immune to relatively large internal oscillations of the plasma pressure, the density be below the known density limit, the level of plasma purity be relatively high, etc.. Therefore the approach to ignition, in general, cannot be discussed in terms of a two-dimensional diagram, such as $n\tau T$ vs T as is usually done. In fact, the distance in the relevant phase space between present day experiments and those for ignition is usually underestimated.

The need to avoid the onset of relatively large oscillations that can affect the central region of the plasma column, where most of the fusion energy is produced, in practice limits the value of β-poloidal. Since central pressures exceeding 1.5 MPa are in fact necessary, the poloidal magnetic fields need to be relatively high. Thus, considering the present state of knowledge of the relevant plasma physics, the window of parameter space for which ignition can be achieved at this time includes only compact confinement configurations with high magnetic fields. It is possible, in principle, to increase the size of the experiment beyond the values chosen, for example, for Ignitor, but the value of the poloidal field has to be maintained. This rapidly increases the magnetic energies involved and all the problems implied (e.g., magnitude of the cooling system, costs, etc.), to a point where the costs far outweigh the benefits. The choice of parameters made for Ignitor is optimized to establish the basic physics for D-T burning plasmas and of the relevant reactors. In particular, one of its unique characteristics, besides that of being capable of reaching ignition, is that the α-particle slowing down time is considerably smaller than the energy confinement time, a condition that present day experiments are far from attaining and that is not met by the ITER-FEAT concept.

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2. Optimal Plasma Parameters

The most accessible conditions under which a magnetically confined plasma can reach ignition regimes involve density profiles of the peaked type, such as those obtained by the Alcator A and C machines (with pellet injection in the latter), which have led to record values of the $n\tau_E$ parameter in considerably pure plasmas [1]. In that context, peaked density profiles had been suggested to improve the plasma confinement properties by preventing the excitation of ion temperature gradient driven modes. An extrapolation of the confinement time from the Alcator C results to Ignitor with ohmic heating only gives such a high value that a considerable degradation, possibly induced by α-particle heating, is allowed. Recently, the FTU machine has reproduced these ohmic high confinement regimes [2], following the injection of multiple pellets. The Ignitor experiment [3] is designed to achieve ignition conditions by an optimal combination of high magnetic fields ($B_T \leq 13$ T), compact dimensions ($R_0 \simeq 1.32$ m), relatively low aspect ratio ($\simeq 2.8$) and considerable plasma cross section elongation and triangularity ($\kappa \simeq 1.83$, $\delta \simeq 0.4$). The appropriate central density for which ignition can be achieved in Ignitor is about 10^{21} m^{-3}. Given the high value of the volume averaged current density, the corresponding line average density is well below the density limit for the considered plasma currents ($I_p \simeq 11$ MA). The peak temperature is $T_{e0} \simeq T_{i0} \simeq 11$ keV for an energy confinement time $\tau_E \simeq 0.6$ sec (see Table I for the results obtained by a time dependent numerical simulation with the actual machine geometry).

The low ignition temperature strategy of Ignitor is self-evident from FIG.1: this regime can be reached over a rather broad range of τ_E (from different simulations, τ_E can be as low as 0.4 s). The arrows indicate the confinement time at the reference temperature of 11 keV and one degraded by 1/3, that corresponds to a temperature of about 14.3 keV and to a substantially higher fusion power. This is to show that Ignitor can fulfill its objectives even if the energy confinement time is seriously degraded relative to current expectations, before the value of the peak pressure becomes a problem.

3. Confinement Issues and Pressure Profile Consistency

High field experiments at high density require the least extrapolation from the available experimental database, but represent a step forward in terms of confinement characteristics. For instance, in Ignitor $B_p^2/8\pi$ is about 50 times that reached in JET. Volume-integrated, 0D steady-state models are not sufficient to predict ignition, as they give only a rough idea of global power requirements. The confinement regimes associated with peaked density profiles are better than the so-called L-regime, but do not fit the characteristics of the H-regime. Frequently considered global scalings for energy confinement time are based on a set of criteria chosen in view of a particular design, the ITER EDA [4], whose requirements are different from those of high field designs. The experimental database used to propose these scalings involve a large diversity of plasma regimes and conditions. In fact, if the appropriate selection criteria are applied (i.e., $T_e \simeq T_i$, $Z_{eff} \lesssim 1.6$, thermalized plasmas, proximity to the density limit), the dramatic reduction in the number of data points and machines undermines the validity of statistical analyses, typically performed on a large number of parameters, to predict the confinement properties of Ignitor or other meaningful burning experiments. We consider the combined database of well confined plasmas with n_0 close or exceeding 10^{21} m^{-3} provided by the Alcator A, C and C-Mod machines, and FTU, to provide a solid and reliable foundation for the extrapolation to Ignitor.

TABLE I: EXAMPLE OF PLASMA PARAMETERS AT IGNITION

Plasma Current I_p	11 MA
Toroidal Field B_T	13 T
Central Electron Temperature T_{e0}	11.5 keV
Central Ion Temperature T_{i0}	10.5 keV
Central Electron Density n_{e0}	9.5×10^{20} m^{-3}
Central Plasma Pressure p_0	3.3 MPa
Alpha Density Parameter n_α*	1.2×10^{18} m^{-3}
Average Alpha Density $\langle n_\alpha \rangle$	1.1×10^{17} m^{-3}
Plasma Stored Energy W	11.9 MJ
Ohmic Power P_{OH}	11.2 MW
ICRF Power P_{ICRH}	0
Alpha Power $P_{\alpha H}$	19.2 MW
Bremsstrahlung Power P_{brem}	3.9 MW
Poloidal Beta β_p	0.26
Toroidal Beta β_T	1.2 %
Central $q(\psi)$ q_0	~ 1.1
Edge q_ψ	3.5
Bootstrap Current I_{bs}	0.86 MA
Energy Confinement Time τ_E	0.62 sec
Alpha Slowing Down Time $\tau_{\alpha,sd}$	0.05 sec
Average Effective Charge $\langle Z_{eff} \rangle$	1.2

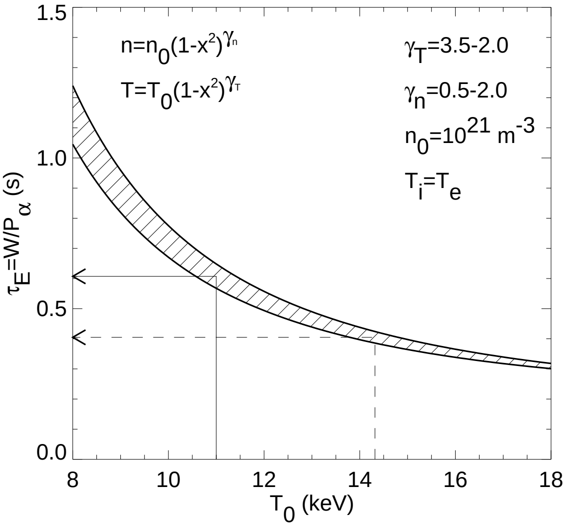

FIG. 1. Confinement time at ignition as a function of the peak temperature, for a range of density and temperature peaking factors. The plasma stored thermal energy is $W = 3\int dV n_e T_e$ *and the fusion power is* $P_\alpha = \varepsilon_\alpha / 4 \int dV n^2 \langle \sigma v \rangle_{fus}$.

In high density plasma regimes the level of impurity contamination has consistently been observed to be low, thanks to higher neutral density and lower temperatures at the edge, therefore a divertor has not been included in the Ignitor design. The first wall, covered with molybdenum tiles, acts as an extended toroidal limiter and the resulting power loads do not exceed 1.8 MW/m^2 [3]. We observe that the H-mode, usually accessed with X-point configurations, is not an efficient regime to reach ignition, because of its characteristic broad and flat density profiles. According to the latest proposed scaling for the L-H transition threshold power [5], approximately 19 MW of total input power would be necessary at full parameters, less during the current and toroidal field ramp up. The available heating power in Ignitor (18-24 MW of Ion Cyclotron Heating plus the ohmic power) is above this value. The Poloidal Field System of Ignitor can produce X-points configurations in addition to the standard limiter ones, but at lower parameters, e.g., reduced current and smaller cross section. For example, double X-points just outside the first wall, the preferred option, at 10 MA and $q_{95} \simeq 3$ are feasible. The thermal loads at the strike points with X-points inside the first wall have also been analyzed, and preliminary results indicate that they may be manageable with the first wall as presently designed.

The optimal ignition conditions for Ignitor have been determined by a series of complex 1½-dimensional simulations performed under a variety of assumptions regarding the thermal transport plasma properties [3,6]. A recently observed feature is the *consistency* of the plasma pressure profile *at ignition*. The word *consistency* means that, although the plasma evolution is determined by different expressions for χ_e, at ignition the pressure profiles turns out to be nearly of a unique type. The comparison concerns simulations of the 11 MA scenario using four electron thermal diffusivity models. All simulations evolve the density profiles assuming a particle (main ions and impurities) diffusion coefficient $D_p = \alpha_p \chi_e$, with $\alpha_p \simeq 0.2$.

The various approaches to ignition are shown in FIG. 2, where the trajectories $n_{e0}(t)\tau_e(t)$ vs $T_{i0}(t)$ are traced together with the curve that represents the ignition condition: $P_\alpha = P_{loss} + P_{brem}$, where P_α, P_{loss} and P_{brem} are the alpha power, the thermal and bremsstrahlung losses respectively. At the time of ignition, which is specific of each case, the plasma *pressure* assumes a privileged shape that is independent of the path followed to reach ignition, but is biased by the time spent before reaching it: as the ignition time gets longer, the pressure profile becomes slightly more peaked. The consistency of the pressure profiles is evident from FIG. 3, where the normalized profiles at ignition are shown for all cases, together with two analytical fits.

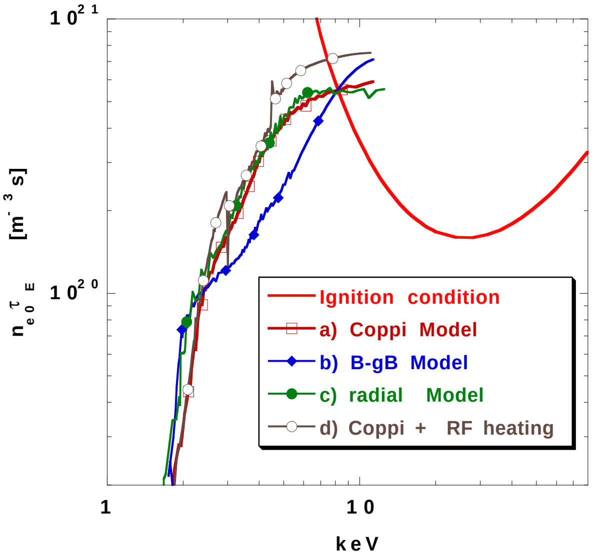

FIG. 2. Trajectories of $n_0\tau_E$ vsT_0 relevant to simulations using different transport models.

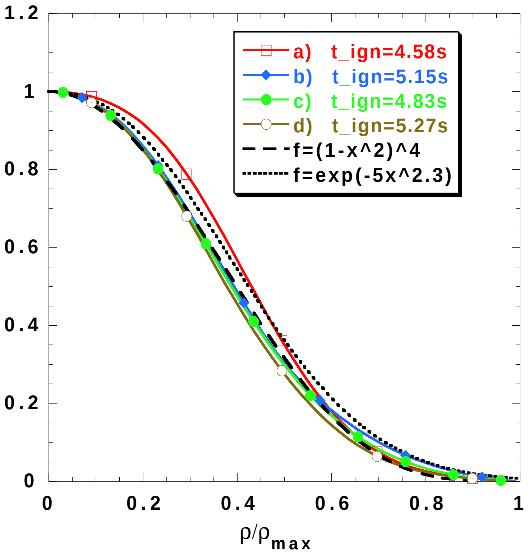

FIG. 3. Normalized plasma pressure profiles at ignition. The dashed and dotted curves represent the analytical fit of the four profiles.

4. Pellet Fueling

In a typical scenario, ignition is reached shortly after the end of the current ramp ($\simeq$ 4 sec). Although comfortably below the density limit, it is conceivable that the peak density value may not be reached sufficiently fast if the plasma is fueled simply by gas puffing from the edge or if the net particle loss is higher than expected. It is also possible that the resulting profiles will not be as peaked as wished for good transport characteristics. Therefore, a pellet injector has always been considered an integral part of the machine design in order to have: i) fast core fueling; ii) density profile control; iii) time-dependent burn control. The controlled injection of tritium, to promote the formation of internal transport barriers [7], and diagnostic purposes can also be envisioned.

A tentative assessment of the fueling requirements for Ignitor has been carried out, based on time-dependent transport simulations. The particle flow required to increase the density is only a small fraction compared to that necessary to compensate for the particle losses at the edge. The interesting results from high field side injection experiments [7] and the very recent ones on vertical injection in DIII-D, suggest that the best solution for Ignitor is that of a vertically mounted, high speed injector, producing pellets with velocities $\lesssim$ 3 km/s.

5. Internal macroscopic modes and high energy particles

An issue that can be resolved only by the experiments is the severity, in terms of limiting the achievable plasma pressure gradient, of the $m^0 = 1$, $n^0 = 1$ modes that can be excited under ignition conditions when the edge safety factor q_ψ is close to the reference value adopted for Ignitor, and $\beta_p \lesssim 0.3$. In a tight aspect ratio configuration, the amplitude acquired by the cou-

coupled $m = 2$ harmonic, which can involve a considerable fraction of the $q \leq 2$ volume, is an additional concern. The amplitudes of the resulting sawtooth oscillations observed in experiments by the Alcator C-Mod machine with similar values of q_ψ and β_p are, in fact, small. In addition, there are significant differences in the plasma microscopic properties from those expected in Ignitor that, according to theory, are favorable. However, the linear theory, which in practice is still the only guidance available, breaks down easily at quite low values of the mode amplitude.

The stability of these modes has been investigated [8] using in particular a combined analytical/numerical approach with the ideal MHD computations performed starting from the analyses given in Ref. [9]. Fast α-particle effects [10,11] as well as finite resistivity, finite drift frequency and finite Larmor radius effects have also been considered. Due to the relatively steep pressure profiles obtained in the transport simulations, strict ideal MHD stability may be difficult to achieve if $q_0 < 1$; moreover, stabilizing fast α-particle effects are too weak to be effective in the standard low-temperature ignition scenario. Thus the best protection is provided by the combined effects of an appropriate choice of q_ψ, to ensure that the $q \leq 1$ region is not a large fraction of the plasma volume, and low β_p. Also, the mode stability was found to be significantly improved when considering a class of q-profiles, characterized by relatively low magnetic shear between the $q = 1$ and $q = 2$ resonant surfaces. Then the relevant modes are either ideally stable or only weakly unstable (and in this case fast α-particle effects turn out to be sufficient to obtain stability). In addition, the remaining resistive modes are stabilized by finite drift frequency effects. Methods to control the q-profile have been envisioned, such as the early application of moderate ICRH power during the current ramp [12].

A worrisome kind of collective modes that has not received sufficient attention outside the Ignitor program is that of macroscopic instabilities involving magnetic reconnection (e.g., $m = 3$, $n = 2$ modes), which are driven unstable by a resonant interaction with the trapped high energy particle population [13]. There is firm experimental evidence for modes of this kind excited in thermal plasmas in the presence of high energy particles produced by different means. The theory that has been developed [13] involves a strong assumption on the factor that breaks the frozen-in law in the collisionless approximation. Thus only meaningful experiments on fusion burning plasmas can shed light on the relevance of the processes involved in the excitation of these modes.

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