

Physics of Self-sustained Fusion Burning Plasmas and Relevant Experiments*

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1. Introduction

Ignition in magnetically confined plasmas is defined as the condition where the energy deposited in the plasma by the fusion reaction products can compensate all energy losses. In a D-T plasma, this translates into the requirement that the confinement parameter $n_0\tau_E$ be around $2-5 \times 10^{20}$ sec/m³ (n_0 being the peak density and τ_E the energy confinement time) and that the plasma purity be relatively high (in practice $Z_{eff} \lesssim 1.6$). Moreover, the peak plasma pressure needs to be brought into the range 1.5-4 MPa, without exciting macroscopic instabilities, with a density sufficiently high to ensure effective α -particle heating. The combination of these conditions leads to confinement configurations that feature high plasma currents for good confinement ($I_p \gtrsim 10$ MA) and high magnetic fields, for standard modes of operation in toroidal devices. In large, low field devices, the apparent gain in confinement obtained by increasing the plasma size is offset by the lower density limit that can be reached at low field. More importantly, macroscopic stability of the plasma favors high field. Experiments performed on toroidal devices (tokamaks) have consistently given the best results, in terms of confinement properties, plasma characteristics and operational reliability, for values of the edge safety factor $q_\psi > 3$ with aspect ratios $R/a \lesssim 3$. An approximate criterion against the onset of large scale modes is B_T (T) $> [8\pi\langle p \rangle / \beta_{p,crit}]^{1/2} R / (aG) q_\psi \gtrsim 10 \sqrt{(p_{0,MPa} / 3) / (\beta_{p,crit} / 0.3)}$, where G is a geometrical factor to account for plasma shaping, $R/a \cong q_\psi \cong p_0 / \langle p \rangle \cong 3$, and $\beta_{p,crit}$ is the value of β_{pol} at which the mode becomes unstable.

The Ignitor Experiment

Ignitor has been the first ignition experiment to be proposed and designed. In compact, high field machines, the heating processes that can bring the plasma temperatures to the necessary values are ohmic and RF heating. Thus Ignitor is designed to operate at toroidal magnetic fields $B_T \lesssim 13$ T and peak densities $n_{e0} \cong 10^{21}$ m⁻³, for which high plasma purity has been

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repeatedly demonstrated. The other parameters of the machine, ($I_p \lesssim 12$ MA, $R_0 = 1.32$ m, $a = 0.47$ m, $k \approx 1.8$, $\delta \approx 0.4$), allow Ignitor to remain well below most empirical limits, in particular those for the density and the onset of ideal MHD modes. However, $m=1$, $n=1$ modes involving collisional magnetic reconnection may be of concern. The purpose of the experiment, to produce and investigate deuterium-tritium plasmas where ignition can take place, requires that the pulse length be long relative to the main intrinsic plasma characteristic times. In order to achieve its primary goal, operation scenarios with ohmic heating only or assisted by ICRF auxiliary power are envisaged, with standard plasma characteristics of ohmic or RF L-mode regimes, similar to those investigated by the Alcator C-Mod machine. While the technology of high field, normal conducting cryogenic magnets is suitable for near term experiments, the development of high field superconducting magnets would allow the demonstration of net power production capability in reactors operating in similar regimes. In fact, high field machines lend themselves to the exploration of the fusion burn conditions of tritium-poor plasmas (e.g., mainly D or D-He³), in which physical processes different from those of D-T plasmas play an important role [1].

2. Simulation of Reference Scenarios

The dynamic nature of the path to ignition in Ignitor requires the use of spatially varying time evolution codes. Reference ignition scenarios [2] have been established by carrying out extensive simulations, for the most part with the free-boundary transport code TSC [3]. The results showed that ignition could be reached near the end of the current ramp for plasma parameters characterized by relatively low temperatures and high densities. Similar results have been found using the upgraded version of the free-boundary 1-1/2 D JETTO code [4], with ignition occurring in ohmic plasmas for values of the energy confinement time τ_E typical of L-mode scaling. More recently, we have started a new series of simulations with the fixed-boundary BALDUR code [5] to revisit the operational scenarios, to include minor changes in the Ignitor plasma geometry, and to explore new paths to ignition.

As a start, the shape of the Coppi-Mazzucato-Grüber (CMG) transport model [6] is used to simulate Ignitor ohmic plasmas, as it complies with the principle of “profile consistency” and reproduces quite well the observed temperature profiles. A cutoff temperature is used to simulate a possible degradation of confinement associated with α -particle heating (this may very well be an overly pessimistic assumption). The resulting τ_E is close to the projections of the ITER98 L-mode scaling [7]. A more recent form of an effective thermal transport

coefficient [8] for high density, low beta plasmas was tested with data available in the ITER L-mode database and found to give a better fit of global parameters for steady state, "clean" discharge, and locally for steady state Alcator C-Mod discharges. However, it does less well, yielding distorted temperature profiles, for ignition experiments and for transient conditions in Alcator C-Mod. With proper programming of toroidal field, plasma current, and plasma geometry, ignition can be reached around the end of the current ramp (Fig. 1) over a relatively large density range. While the details of the temperature and density profile are not critical for the attainment of ignition, the desired control of the current diffusion with ohmic heating only is more difficult. The main problem is keeping the size of the region where the safety parameter q is less than unity small. The evolution of global modes and magnetic reconnection in fusion burning plasmas has been the subject of careful investigation in our group [9, 10] and a general result is that a "sawtooth" type of activity may be tolerated as long as the volume of the region with $q < 1$ is relatively small ($< 10\%$). About 20 MW of ICRF power are included in the machine design and provide a significant control over the current profile if applied during the second half of the current ramp. A considerable benefit obtained with the use of moderate amount of ICRF power is that the resulting q -profiles can be properly tailored [2,11] to have a region near the $q=1$ resonant surface where the profile is almost flat and therefore have more attractive ideal MHD stability properties against $m=1$, $n=1$ internal modes than conventional q -profiles [12].

An important issue to clarify is the validity of the transport model used for non-steady state conditions. Benchmark experiments are being carried out on Alcator C-Mod, the device that most closely resembles a high field ignition experiment. In fact, its geometrical parameters correspond to a "half size Ignitor". Data collected in the early phase of the current ramp, with and without RF heating, are being used to investigate confinement in transient regimes, in combination with transport code simulations. Results so far show that electron temperature "profile consistency" is an important constraint during the ramp, in agreement with results from TFTR [13].

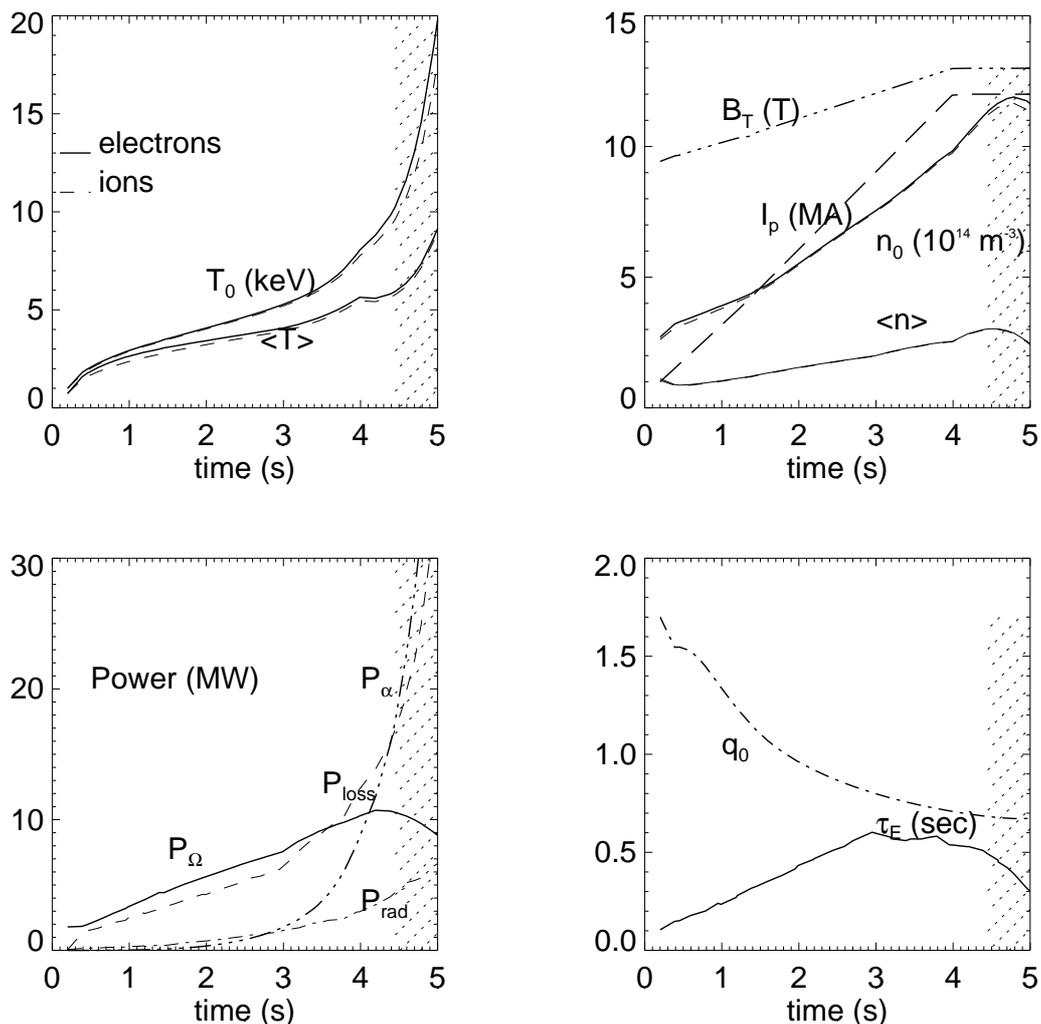


Fig. 1. BALDUR simulation of a possible 12 MA, 13 T ohmic scenario of operation for Ignitor. The ignited regime is shown by the dotted area.

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