Critical Physics Issues for Ignition Experiments: Ignitor

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Abstract

The crucial physics issues related to fusion burning plasmas and potential fusion reactors can only be studied in a burning plasma experiment. The Ignitor experiment is designed to take the most conservative approach to the near term study of the physics of fusion burning plasmas, using an optimal combination of compact dimensions and high magnetic fields to support high plasma particle densities and high plasma currents. The values of its geometrical parameters, plasma current, and magnetic field have been chosen based on current knowledge of ignition physics, so that ignition is most likely to be achieved. This article presents the most important ideas behind its design.

1 Introduction

Demonstration of fusion ignition is a major scientific and technical goal for controlled fusion. Until the fundamental physics of fusion burning have been confirmed by experiment, the defining concepts for a fusion reactor must remain uncertain. Other factors would also have to be taken into account, such as the method for extracting fusion energy. Nevertheless, two major areas can be addressed in a near term ignition experiment. The *ignition process* will be similar for any magnetically confined, predominantly thermal plasma. Heating methods and control strategies for ignition, burning, and shutdown can also be established.

These three issues, demonstration of confined ignition, the physics of the ignition process, and heating and control of a burning plasma, are specifically addressed by the Ignitor experiment [1][2][3][4][5]. Its design has been driven more closely by physics considerations than that of any other existing design. The associated physics studies have gone beyond simple identification to include interaction of the physical processes involved in ignition. Ignitor is part of a line of research that began with the Alcator machine at MIT in the 1970's [6][7], which pioneered the high magnetic field approach to plasma magnetic confinement and has been continued by the Alcator C/C-Mod and the FT/FTU series of experiments. The idea for a high field D-T ignition experiment was formulated at about the same time [8]. Based on present knowledge of fusion physics, high magnetic fields still offer the best path to achieving ignition, when both energetics and plasma stability are taken into consideration. The high field approach also allows a possible development path [9][10] to tritium-poor, relatively low-neutron-production fusion, based on D-^{3}He or perhaps some form of "catalyzed" D-D reactions, which could yield a different kind of fusion reactor.

A large amount of work on the physics of ignition has been carried out over the course of the Ignitor design evolution. Much of it is generally applicable to ignition in a confined plasma, not only at high field. This article presents the basic physics that underlies the Ignitor design, including open questions. It starts with the physics questions that cannot be addressed in present experiments, then discusses the problem of attaining ignition and the advantages of high magnetic field, the dynamic nature of the ignition process and its relation to the initial current rise phase of a discharge, and other issues. Since these questions overlap in many ways, the Appendix summarizes the self-consistent characteristics of a high field ignition experiment.

2 Advances beyond present experiments

Even without strong assumptions on the possible form of a fusion reactor, it is clear that present experiments do not operate in plasma regimes close to those required for ignition. There are a number of discrepancies, of which one or more always apply:

1. The effective charge Z_{eff} is in general too high, compared to the limiting value for stable ignition, Z_{eff} >1.5–1.6 [1]. High Z_{eff} prevents ignition by allowing excessive radiation emission, so that the ideal ignition temperature is not attained. Although initially demonstrated for Ignitor, this Z_{eff} limit can be shown to be general. Exceeding this value requires large amounts of auxiliary heating power, operation near the β stability limit, and other conditions.

2. The central ion temperature is substantially higher than the electron temperature, $T_i > T_e$. A thermal burning plasma, will have $T_i \simeq T_e$ unless the temperature is very high. Fusion α's, and all other charged particles produced by fusion reactions, have relatively high energies in the MeV or multi-MeV range and therefore primarily heat the electrons by collisional slowing down. In present experiments, the ions used for neutral beam heating have relatively low energy on the order of 100 keV, and primarily heat the ions. In addition, they sustain a large fast ion population, due to the relatively long collisional slowing down times at the low plasma densities.

3. The α-particle slowing down time is long compared to the energy confinement time τ_E, while in an igniting plasma the time should be much shorter.

4. The effective electron collision time is short compared to the diamagnetic frequency, $\nu_e < \omega_*$. This is important for $m = 1$, $n = 1$ mode stability when the plasma poloidal beta β_p approaches the ideal MHD instability threshhold. Most present machines operate at low densities compared to an ignition experiment or reactor, where higher density is desirable to increase the fusion reaction rate and improve plasma purity. The collisionless reconnecting modes seen in present high temperature plasmas are relatively easy to stabilize, but those expected in ignition experiments as diverse as Ignitor and ITER will be at most semi-collisional, with $\nu_{ei} \gtrsim \omega_*$, and are expected to be more dangerous.

5. Present experiments have relatively low peak pressure. The ignition figure of merit $n_i(0)T_i(0)\tau_E$ requires a minimum absolute pressure with peak value $p_o \gtrsim 1.5 - 4$ MPa. For D-T fusion, $n_i(0)T_i(0)\tau_E \simeq 70$ (in units of $10^{20}\mathrm{m}^{-3}$, keV, sec). More accurate figures of merit, for example $n_H(0)T_e(0)\tau_E\epsilon_{sd}\epsilon_p F(T_e/T_i)$, could take into account the slowing-down-time of the fusion α's, through $\epsilon_{sd} = 1/(1 + \tau_{sd}/\tau_E)$, the plasma purity through $\epsilon_p = (5/4)/(1 + Z_{eff}^2/4)$, and the ratio of the electron and ion temperatures.

6. The sub-ignited D-T experiments performed so far have been ballooning unstable. High fusion yield discharges have been terminated consistently by plasma instabilities, TFTR by $n = 1$ kink-driven edge ballooning modes and JET also by MHD instability.

7. The known improved confinement regimes are transient and/or nonthermal (significant non-Maxwellian particle distributions). Improved confinement regimes tends to be associated with modified, transient q-profiles, while most high confinement experiments using NBI heating have a nonthermalized ion population due to the relatively low bulk-plasma densities.

One further criterion, that the electron-ion energy equilibration time be short, $\tau_{ei} < \tau_E$, is satisfied in present experiments. The remaining points must be addressed by a burning plasma experiment.

3 The ignition dilemma

The goal of an ignition experiment is to reach the ideal ignition temperature at which fusion heating begins to dominate the bremsstrahlung radiation losses (peak temperature $T_o \simeq 6$ keV for typical centrally peaked profiles), under conditions in which the fusion heating can continue to rise. The basic problem is that plasma confinement is still not understood well enough to predict performance reliably in these regimes. For ignition experiments, this creates a problem. To study ignition and true fusion burning, experiments must operate in regimes with high levels of fusion power relative to other inputs, e.g. $Q_\alpha \geq 2$, where $Q_\alpha \equiv P_{\alpha h}/(P_L - P_{\alpha h})$, P_L represents the total power loss from the plasma, and $P_{\alpha h}$ the fraction of the D-T fusion power in α-particles that actually heats the plasma. Effective plasma heating must also be provided to reach this state. (Recall that the plasma power balance is $dW/dt = P_{\alpha h} + P_{Aux} + P_{OH} - P_L$, where W is the plasma kinetic energy and P_{Aux} and P_{OH} the externally applied and ohmic heating powers, respectively. The definition of ignition used in the early Ignitor work was $P_{\alpha h} = P_L$, which when first reached in a time evolution sequence corresponds to an over-heated state with $dW/dt > 0$, where the temperature will first make an upward excursion before settling at a steady state level.) To guarantee ignition, experiments may also consider using relatively high levels of input power. This approach, however, leads to several difficulties, including that of ensuring plasma stability.

This uncertainty must be resolved by the design of an ignition experiment. Ignitor uses high toroidal magnetic field in a compact size, which allows ignition at relatively low fusion power levels and low plasma beta, with relatively strong ohmic heating. These are not the only considerations that favor a high field approach and a strong argument can be made that high magnetic field is the only real solution for the ignition dilemma (Section 4). High field introduces an interlocking set of requirements [1], which are summarized in the Appendix. The maximum value of the field and plasma current that can be generated and the length of time over which they can be sustained in a given magnetic configuration is thus a strong constraint on ignition capacity. Maximizing these values constitutes the major goal for the engineering design. For reference, the basic parameters of the Ignitor are given in Table 1. Flattop periods vary significantly with B_T, ranging from 4 sec at 13 T (reference value) to 10–15 sec at 9–10 T. Ignition scenarios at varying density are given in Table 2.

4 Physics conditions to ensure ignition: High B_T

Many of the physics limitations and uncertainties regarding ignition (see also the Snowmass Burning Plasma report [11]) lead to the statement that "High magnetic field is the most advantageous approach to ignition using the present knowledge of the physics and technology of high temperature plasmas." This conclusion also emphasizes the importance of continuing technological

Table 1: Ignitor Reference Design Parameters

major radius	R_o	1.32 m
minor radius	$a \times b$	0.47×0.86 m
aspect ratio	A	2.8
elongation	κ	1.83
triangularity	δ	0.43
toroidal field	B_T	≤ 13 T
toroidal current	I_p	$\lesssim 12$ MA
mean poloidal field	$\overline{\overline{B}}_p \equiv I_p/5\sqrt{ab}$	≤ 3.75 T
poloidal current	I_θ	$\lesssim 9$ MA
edge safety factor ($I_p \simeq 11$ MA)	q_ψ	3.6
magnetic flux swing	$\Delta\phi$	36 Vs
plasma volume	V_o	≈ 10 $\mathrm{m}^{\mathbf{3}}$
plasma surface	S_o	≈ 36 $\mathrm{m}^{\mathbf{2}}$
auxiliary heating	P_{RF}	18–24 MW

Table 2: Effects of Different Density Profiles for Ignitor

Density Profile	Narrow	Reference	Broad	Broad*	Almost Flat**
n_{eo} ($10^{20}\mathrm{m}^{-3}$)	11	11	11	8.5	8.4
$n_{eo}/\langle n_e \rangle$	2.9	2.2	1.5	1.5	1.1
t_{IGN} (sec)	4.1	4.3	4.7	4.3	4.5
β_p	0.12	0.13	0.15	0.15	0.15
W (MJ)	10.7	11.7	13.4	12.6	13.7
T_{eo} (keV)	11.2	11.0	11.1	13.0	13.3
τ_E (sec)	0.61	0.66	0.70	0.68	0.74
P_{OH} (MW)	8.8	9.5	9.9	9.1	8.9
P_α (MW)	17.4	17.8	19.0	18.7	18.6
P_B (MW)	3.2	4.1	5.8	4.2	5.4
P_C (MW)	0.4	0.5	0.8	0.6	1.1
$Vol_{q=1}$ (%)	4.0	5.8	> 10	$4.8^\dagger$	10.2

*Lower density; $n_{eo} = 6.5 \times 10^{20}\mathrm{m}^{-3}$ at end of current ramp ($t = 3$ sec), increasing after.

**Lower peak density; optimum value is lower than this.

†Large low shear region for $q \simeq 1$.

P_α is fusion α-heating, B bremsstrahlung loss, C cyclotron radiation loss. $P_{Aux} \equiv 0$.

progress, such as the development of superconductors capable of sustaining fields of 20 T or more. In fact, experience with the Ignitor and other designs very strongly points to the conclusion "High magnetic field is the only possible approach to ignition at this time."

A simple argument shows why a high toroidal magnetic field is so indispensable. Consider the possible values of the edge safety factor q_ψ, at the required values of the central pressure and plasma β for ignition and for plasma stability. Since the actual q is a complex function of the plasma fields and shape, define an "engineering" $q_E = (5ab/R)(B_T/I_p)$, which satisfies $q_E \propto q_\psi$ and $q_E < q_\psi$. A corresponding "engineering" poloidal field can be defined by $\overline{\overline{B}}_p = I_p/(5\sqrt{ab}) = (\sqrt{ab}/R)(B_T/q_E)$. Plasma stability can be measured by the poloidal plasma beta, $\beta_p = 8\pi\langle p\rangle/\overline{B}_p^2$, where $\overline{B}_p$ is the actual average poloidal field. At ignition, the minimum central pressure p_o must be in the range of $1.5 \lesssim p_o \lesssim 4$ MPa for 50:50 D-T (1 MPa $\simeq$ 10 atm), because of the minimum limit on the ignition parameter $n_i(0)T_i(0)\tau_E \simeq 70 \times 10^{20}\text{m}^{-3}\text{keV}\cdot\text{sec}$.

There are two possible ignition regimes, at low and high q_ψ. At low edge $q_\psi \lesssim 3.3$ (an approximate value), the regions where $q < 1$ and $q < 2$ are large. Then large scale internal modes with dominant $m = 1$ and $m = 2$ harmonics, extending to r_1 and r_2 respectively, will exist unless β_p is also small. Since the volume average pressure $\langle p\rangle$ cannot be too low at ignition, the plasma stability requires a minimum B_T that depends on the critical $\beta_{p,crit}$ of the modes. Starting from the definition of q_E and using the definitions of $\overline{\overline{B}}_p$ and β_p gives the limit

$$B_T > q_E \frac{R}{\sqrt{ab}} \left(\frac{\overline{\overline{B}}_p}{\overline{B}_p}\right) \left(\frac{8\pi\langle p\rangle}{\beta_{p,crit}}\right)^{1/2} .$$

The definition of β_p in terms of inverse I_p^2 also shows why trying to increase q_ψ by lowering the current relative to a fixed B_T is a poor idea at low q_ψ.

At high $q_\psi > 5$, the plasma current must be relatively low, since

$$I_p = \left(\frac{\sqrt{ab}}{R}\right) \sqrt{ab}\, B_T \frac{5}{q_E}.$$

Assuming that the confinement time is $\tau_E \propto I_p$, as is typical of the L-mode, then larger values of the confinement improvement factor H over L-mode are required to reach ignition. In practice, H is observed to be limited to values of 2–3, so that the remaining factor $\sqrt{ab}\, B_T$ cannot be too small. In the opposite limit, if $\sqrt{ab}\, B_T$ is increased by expanding the radius, the average poloidal field $\overline{B}_p$ remains low as long as B_T is low, and β_p becomes large. Pressure-gradient-driven ballooning modes then become a problem.

Applying the actual values from experiment and theory shows that these criteria give fairly stringent practical limits on B_T. Intermediate values of $q_\psi \sim 4$ correspond to the least restrictive conditions and are the best choice for ignition. This is the Ignitor reference value. On the other hand, limits on the achievable B_T with present day magnets tend to force q_ψ somewhat lower in most high field designs (e.g., down to $\simeq 3.6$ in the Ignitor design, that uses normally conducting, cryogenically cooled magnets).

5 Ignition criteria: Natural density for ignition

One aspect of advantages due to high B_T can be illustrated by the limitations on time-dependent ignition. An idealized "natural density" for an ignition experiment can be defined as a measure of

Table 3: Natural Densities for Ignitor (volume-averaged)

	$\langle n_N \rangle$ (10^{20}m^{-3})	T_{io}/T_{eo} (keV)	R/a (m/m)	B_T (T)	I_p (MA)	$\overline{n}_G$ (10^{20}m^{-3})
Reference	5	$\lesssim$ 15/15	1.32/0.47	13	12	17.3
RevShear	3	17/19	1.32/0.47	12	7	10.1

the absolute ignition margin and the difficulty of achieving desired performance that includes cost and complexity.

The "natural density" n_N for D-T ignition in a given device is the density at which a pure ($Z_{eff} = 1$) 50:50 D-T plasma ignites most readily for the nominal machine parameters. It is a characteristic property of a given machine, i.e., the achievable plasma size and shape, magnetic field, plasma current, and auxiliary heating power, and it can also be defined for each operating scenario within a machine. Since there are maximum and minimum density limits on ignition in a given experiment, determined by a balance between radiation power loss, available heating power, and energy confinement (and other factors, see [23]), there is also the possibility that n_N may not exist for a given case. When it does, it indicates the best possible ignition performance for that device, since the required heating and plasma confinement at n_N are the absolute minimal requirement and every real plasma will be at least slightly contaminated and thereby suffer degraded performance. It provides a measure of the potential plasma performance at the design operating conditions, even though these may be very different from the ideal conditions used to determine n_N. The difficulty of achieving the desired operating parameters (cost, complexity, physics ignition margin) depends on the degree of improvement needed in the heating power, confinement, etc., over the ideal level, based on the expected degree of contamination (Z_{eff}), which is a sensitive function of density.

The natural density must be determined using, at a minimum, a 1 1/2 D transport simulation. Heating during the initial current ramp phase must be included. Unless the design specifies otherwise, the current ramp is chosen to have the minimum duration required to reach the design current I_p without developing nonmonotonic current density profiles J_ϕ, at the optimum programming of the time evolution of the plasma size, shaping, and ramp rates $\dot{I}_p$, $\dot{B}_T$, $\dot{n}$, etc. Given a standard thermal transport model, the combination of the minimum required enhancement factor over a standard confinement scaling that allows ignition and the minimum amount of external heating required (using an idealized heating profile) is determined. The optimum or expected density transport/fuelling or a given profile shape may be used. Sawtooth oscillations can be ignored, since they usually increase the difficulty of ignition.

Different operating regimes in Ignitor can be used as an example. Table 3 shows results for the volume-averaged n_N for the reference scenario at full field and full current and for a reversed shear, improved confinement regime at reduced current, both with relatively flat density profiles. The maximum confinement was constrained as far as possible to approximately H-mode, i.e., 2–3 times the ITER89-P L-mode scaling. The reference scenario, based on Refs. [1] and [2] and Table 2, shows ignition at low central temperatures, $T_{eo} \simeq T_{io} \sim$ 12–15 keV, with confinement slightly above L-mode (ITER-89P) and ohmic or almost entirely ohmic heating. These results (actually obtained for $Z_{eff} \simeq 1.2$, but very similar to $Z_{eff} = 1$) are close to expected operating conditions. In comparison, the reversed shear case at 12 T and 7 MA [12], has approximately $\langle n_N \rangle \sim 3 \times 10^{20}$ at a maximum $P_{Aux} \simeq 8$ MW during the current ramp and $H = 2.5$–3 (again at $Z_{eff} \gtrsim 1.2$). The reversed shear field and current are fairly similar to the FIRE parameters, and the Ignitor result, along with its larger dimensions, implies a lower natural density for that machine, relative to the reference Ignitor.

At fixed maximum plasma size and shape, when the density rise occurs primarily during the current ramp, the natural density varies approximately proportionately to plasma current I_p. At varying minor radius and current, it varies roughly like the Greenwald density, line-average $\overline{n}_G = I_p/(\pi a^2)$, although with a somewhat weaker dependence in minor radius. This occurs because the density rise and the rate of current penetration are inter-dependent, the magnitude of the density affecting the local temperature for a given heating rate, and the local temperature in turn determining the resistive diffusion rate of the current. The relationship is less direct when substantial plasma fuelling occurs outside the current ramp.

6 The transient nature of the ignition process

In a contained burning plasma, the approach to ignition is a transient process, where both spatial and temporal effects are important [13]. The strong positive dependence of the fusion cross sections on the kinetic energy of the reactants also allows the possibility of a "thermonuclear instability" phase near the ignition point, where the plasma temperature and fusion power can rise rapidly.

For magnetically confined plasmas, the transient nature of the approach to ignition becomes more important because the most efficient approach to ignition is to use the initial phase of the discharge, when the plasma current is being raised to its final value (the current ramp phase), to heat the plasma towards ignition and to help control the development of the plasma profiles, in particular the toroidal current density J_ϕ, for plasma stability (initial current ramp studies [14], integration of heating and plasma stability effects for Ignitor [15][16][1]). An important constraint is the final edge safety factor q_ψ allowed by the plasma field, current, and shape. A great deal of work for the Ignitor has been done to confirm that this procedure can be effective and to study its limitations, e.g., [1][2][12][17]. Much of this work predated later successful control of the current ramp to produce improved confinement regimes (the early Ignitor work did not consider such regimes and actually imposed the condition that the the q-profile remain monotonically increasing toward the plasma edge; reversed shear and improved confinement was considered in [12].)

Understanding the transient approach to ignition is a complex problem, since a large number of independent or semi-independent time-varying parameters must be optimized. A numerical transport simulation model containing at least the radial (flux-surface) coordinate is required for quantitative results. The basic principles are clear, however, are clear.

For a high field experiment with a high plasma current, transient effects can be exploited to use ohmic heating to give a substantial boost toward ignition [16][1]. This is a major factor used in the Ignitor experiment. When the current ramp phase is considered, the plasma current is increased by adding "skin layers" of current to the outer surface of the plasma column that do not have time to diffuse inward. The plasma loop voltage peaks at radii near the edge of the plasma, a region of relatively large volume (cf. the figures in [1]). Since the resistivity $\eta_{\|} \propto T_e^{-3/2}$, a relatively large ohmic heating power $I_p V_{\|}$ can be produced even when the central plasma temperature is high. The ohmic heating rises continuously during the current ramp, at a rate $\dot{P}_{OH} \propto \dot{I}_p$. For the Ignitor reference scenario, this can be on the order of 10 MW or more at the end of the current ramp, somewhat less at ignition, when roughly $P_\alpha \gtrsim 2P_{OH}$. Due to the high field and current, self-sustained burning states can be reached and maintained by the residual ohmic heating $P_{OH} \simeq 1-2$ MW at reduced levels of confinement, even if full ignition ($P_\alpha = P_{Loss}$) is never reached.

7 Confinement and Thermal Transport Models

The inability to predict even the global level of plasma transport (energy and particle confinement) for a given plasma configuration with a high degree of reliability is the single most troublesome question for the design of an ignition experiment. In all cases, the degree of extrapolation from the existing experimental database is enough to raise concerns as to its accuracy. High field experiments at high density require the least extrapolation, but still lie outside existing experimental data.

A number of important considerations for predicting transport and performance in ignition experiments exist. First, 0D (global, volume-integrated) steady-state models are not sufficient to predict ignition. At a minimum, 1 1/2D time-dependent transport simulations are needed because the energy balance is intimately tied to the plasma profiles (including q and current) and therefore to plasma stability [14][15][16][1]. A 0D steady state model gives only a rough idea of global power requirements for ignition. It gives a functional relationship between input power and loss, but does not predict the optimal point for operation, and says little about the achievability of a given operating point in practice. Transport simulation is needed for prediction and for real-time control.

Second, present widely accepted global scalings for energy confinement time are based on a set of criteria and an experimental database [18] that have been chosen to apply to a particular design, the ITER EDA [19], whose requirements are different from those of high field designs. One result is the ITER89-P scaling for the L-mode confinement time [20] that predicts that the energy confinement time τ_E degrades with the total heating power as roughly $\tau_{E,L} \propto P_H^{1/2}$, or even more strongly [22][18]. An important question is whether different selection criteria, more suited to high field ignition conditions, would yield different results.

In fact, such criteria can lead to different confinement predictions. A case can be made that the degradation of τ_E with the heating power P_H stops above a certain power level. This is the prediction of the Coppi-Daughton effective thermal diffusion coefficient [24][25]. A global τ_E dependence was initially derived from the observed behavior of β_p in Alcator C-Mod ohmic and RF-heated discharges [21], where for OH heating $\beta_p \simeq$ constant (0.25), while with additional ICRH, β_p increases linearly with P_{ICRH}. The resulting τ_E does not have a power law dependence on the plasma parameters, but an offset relation that suggests that the confinement ceases to degrade with heating power above a certain power level,

$$\tau_E \simeq 0.031 R q_E^{2/3} I_p \left(1 + f_3 \frac{I_p \mathcal{V}_o}{P_H}\right) \left(\frac{d_i}{a}\right)^{1/2} \left(\frac{\omega_{pe}}{\Omega_{ce}}\right)^{1/3} \tag{1}$$

in MA, MW, and mks units. Here the coefficient is $f_3 \simeq 1.4(r/4a)^{1/2}(R/20d_i)^{1/2}$, $d_i = c/\omega_{pi}$, ω_{pj} is the plasma frequency for species j, Ω_{cj} the gyrofrequency, q_E a characteristic safety factor parameter, $q_E = 2\pi a^2 \kappa B_T/(\mu_o I_p R)$, and $\mathcal{V}_o$ is an expression for a characteristic voltage, given below. All numerical coefficients were determined from Alcator C-Mod data. The resulting expression for τ_E was then shown to fit the global energy confinement times of a specific subset of the ITER L-mode and OH database (as it existed in 1997), with no additional free parameters. The subset, 1088 cases, was chosen to be more applicable to high density, high field experiments than the general ITER database. It consisted of all the datapoints satisfying

- OH or L-mode
- clean: $Z_{eff} < 2$
- $T_i \simeq T_e$: $0.7 < W_i/W_e < 1.3$

- mostly thermal: $W_{th}/W_{tot} > 0.7$
- steady state: $(dW/dt)/P_H < 0.1$.

Using a volume-averaged β_{p*} gave excellent results, with an RMS error of 13.1%, compared to 23.6 % for the ITER96 L-mode scaling [22] restricted to these cases. (The ITER96 scaling had a lower error than the original ITER89-P scaling.) Only 7 of the 14 machines represented in the full ITER database appear under these criteria.

A possible radial dependence for a thermal diffusion coefficient was also derived and shown to fit a wide variety of steady state ohmic and RF-heated discharges from Alcator C-Mod [25]

$$\begin{aligned}
\chi_{eff}^{CD97} &= \mathcal{V}_o^o \frac{I_\phi(\rho)}{n(\rho)T_e(\rho)} \mathcal{F}_D \frac{V_a}{\langle|\nabla V|^2\rangle} \qquad (2)\\
\mathcal{V}_o^o &= \left[\frac{\nu_*}{1+\nu_*} + \left(\frac{n_o^o}{n}\right)^{1/3}\right]\mathcal{V}_o \\
\mathcal{V}_o &= \alpha_v \frac{T_e}{e}\left(\omega_{pi}\frac{c^2}{\omega_{pe}^2}\frac{\nu_e}{v_{the}^2}\right)^{2/5}, \qquad \left(\frac{n_o^o}{n}\right)^{1/3} \equiv C_1\left(\frac{\omega_{pi}}{\nu_e}\right)^{2/3}\left(\frac{c}{4\pi v_{the}}\right)^2 \frac{m_e}{m_i} \\
\mathcal{F}_D &= C_2\left(\frac{a}{d_i}\right)^{1/2} f_{C3}, \qquad f_{C3} = \begin{cases} C_3\left[\frac{10\beta_{p*}}{q_E^{2/3}}\left(\frac{\Omega_{ce}}{\omega_{pe}}\right)^{1/3} - \frac{R}{4a}A_i^{1/2}\right] & \text{if} > D \\ D & \text{otherwise} \end{cases}
\end{aligned}$$

using a poloidal beta based on the maximum interior pressure gradient $\beta_{p*} = 8\pi p_{e*}/\langle B_\theta^2\rangle$, $p_{e*} = \max(dp_e/d(\rho/a))$. The coefficients were derived from the previously determined global fits to Alcator C-Mod, $C_1 = 0.24$, $C_2 = 0.0833$, $C_3 = 1.7$, $D = 0.25$, and $\alpha_v = 0.18$. (Here V is a volume inside a flux surface, V_a within the entire plasma, $\nu_* = \nu_e(q_E R/v_{the})(R/a)^{3/2}$ is the trapped electron collisionality with ν_e the electron-electron collision time, v_{the} the electron thermal velocity, and A_i the average ion atomic mass.)

The radial form of a transport coefficient is important for predicting ignition, which is a strongly dynamic and non-local process. Even if global confinement is accurately described, a derived transport coefficient may give poor results. Numerical transport simulation consistently indicates that a coefficient that preserves temperature profile shape in some manner ("profile consistency" [26]) is required to fit many present-day experiments, especially their transient phases, as well as having a strong effect on ignition predictions. For example, the CD97 coefficient described above does not work as well for transient conditions, including Alcator C-Mod current ramps and ignition simulations, because the strong dependence on gradient in β_{p*} tends to produce an artificially steep gradient at mid-radius. A profile-consistent coefficient, such as the original CMG [27] scaled to match a desired global confinement, does much better, suggesting that the radial form of CD97 should be modified.

8 Transport and Control

8.1 Thermal transport questions

Other open questions about thermal transport in burning plasmas remain. For example, the heating of the plasma due to collisional slowing down of the charged particles produced in fusion reactions is isotropic in velocity space an axisymmetric in real space, with its magnitude centrally localized in the plasma. Does it then cause degradation of confinement time with increasing input power, $\tau_E \sim P_{Heat}^{1/2}$, in the same way as most existing methods of injected heating, which are anisotropic in velocity space, non-axisymmetric in space, and often concentrated off-axis? This empirical rate of degradation with power exerts perhaps the most crucial influence on current designs for ignition experiments and potential reactors. Evidence that some heating methods, such as ECH, do not degrade confinement in this way should also be explored.

A further consideration for fusion burning is that the electron thermal transport is important at higher density, unlike present-day lower density, mainly ion-heated experiments with $T_i < T_e$, that are dominated by the ion thermal transport due to toroidal ion temperature gradient (ITG) modes. Relatively little has been done for electron transport, even for global scalings. The theory of electron transport processes is poorly understood and the connection between fluctation and transport is much more difficult to simulate numerically than for ions.

8.2 Density profile control

The prediction and control of the density profile at high densities is another important transport and edge plasma physics problem for ignition experiments. The basic shape of the density profile cannot be reliably predicted from present knowledge. Peaked density profiles are more favorable for ignition, although the level of degradation with flatter profiles is relatively small, as long as the total number of particles remains roughly the same, e.g., [2] and Table 2. (Note that the flattest profile case in Table 2 probably has a lower optimum density.)

The question of the degree of profile control (peaking) by pellet injection, which translates to the question of the penetration of the pellet particles into the plasma, is a subject of current investigation. Control of the plasma edge density during startup and steady state is also important, since it regulates the current penetration rate as well as being related to the edge temperature. A balance must be struck — high edge density improves impurity screening from the main plasma, but may be less beneficial for other processes, such as plasma heating and/or stability. (High edge densities result in relatively lower edge temperatures, which speed up the rate of the edge current penetration, resulting in lower central safety factors q and potential stability problems, as well as tending to reduce the central plasma temperature.)

8.3 Burn control

Transport simulation readily demonstrates that precise time-dependent burn control through variation of the bulk ion density source is *not* possible in general, since particle confinement times τ_P are generally longer than energy confinement times τ_E. Short-time-scale sensitivity to the fuel-ion particle source rate requires that the confinement τ_E be marginal relative to that needed to maintain the desired level of burning, or that the burning rate is high enough that a strong source of fuel ions is required to sustain it. For a reactor, economical operation dictates that τ_E be significantly above marginal, and a major goal of pre-reactor burning plasma experiments should be to increase this margin. A generalized form of burn control by specifying the concentration of tritium relative to deuterium in a discharge can always be used. Much better control is possible by operating in a slightly sub-ignited state that is driven by a small amount of externally supplied heating.

Emergency methods of burn control include the firing of large "killer" pellets (Ar, Li, etc.) into the plasma to rapidly quench run-away ignition conditions and prevent or mitigate possible disruptions. This method has been adopted in Ignitor. The effects of introducing a large amount of impurities on ignition in the following discharges can be studied.

8.4 Radiating cold mantle

Fusion plasmas deal with relatively large amounts of applied and self-generated power, which must all eventually exit the plasma to its surroundings. An important concern is to reduce the power loading on the physical walls. In the case of Ignitor, the first wall is covered by molybdenum tiles. Among the disadvantages of introducing a divertor is that it becomes a "hot spot" in the plasma-wall interaction system.

A potentially effective method for minimizing and distributing the power loading on the walls is to use a cold mantle of partially ionized plasma to surround the main plasma that is contained within the closed flux surfaces. It has been successfully demonstrated for non-burning plasmas in the RI-mode in TEXTOR [29]. There, impurity injection into the scrape-off layer (SOL) greatly increased impurity line radiation losses from the layer, allowing a relatively large part of the power put into the plasma to be radiated. This has the double advantage that radiation is much less damaging to material surfaces than particles and that since it is relatively evenly distributed throughout the SOL, so is the resulting load on the walls.

This method is particularly well suited to a high field, high density plasma, which can expect to have a relatively high plasma edge density with relatively low edge plasma and SOL temperature (e.g., Ignitor, based on data from the Alcator series of experiments [28]). High plasma edge densities confine outside impurities generated from the walls to the scrape off layer ("cold plasma blanket"[30], DIII-D VH mode [31][32]), while the low plasma edge temperatures allow the formation of a cold radiative mantle.

9 Low-neutron-yield fusion

Fusion reactions with low rates of neutron production ("advanced fuel" D-^{3}He or possibly D-D) may be a more attractive reaction for a reactor than the D-T reaction, which releases 80% of its energy in an energetic neutron. These reactions have their own set of problems, such as the source of quantities of ^{3}He and the attainment of the higher plasma parameters required for burning. To begin to explore their possibilities, however, a D-T burning plasma experiment at high field is much closer to the required parameters than present-day tokamaks. For example, Ignitor would allow initial studies at the level of approximately 1 MW of power in charged particles from the D-^{3}He reaction cycle for beam-injected ^{3}He [33] or somewhat less for thermal ^{3}He in a D-T plasma [34].

10 Summary

The major points driving the design of the Ignitor experiment can be summarized as follows:

- The crucial physics issues related to fusion burning plasmas and potential fusion reactors can only be studied in an experiment capable of approaching ignition.
- The Ignitor experiment takes the most conservative approach to the near term study of the physics of fusion burning plasmas, through an optimal combination of geometrical characteristics, plasma current, and magnetic field. This approach lends itself to important developments that include advanced fuel burning (low neutron yield, e.g., D-^{3}He).

- The Ignitor design has been strongly driven by the physics of ignition. A large amount of original and early work on the physics has been carried out during the design process, that is applicable to all magnetically confined burning experiments. This statement can also be extended to the engineering design of the machine and the technology solutions devised for it.
- High magnetic field, high density plasmas have the most favorable characteristics and expectations for ignition, and are the only ones that, given the present knowledge of plasma physics, allow this goal to be pursued realistically.

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A Requirements for a high field ignition experiment

This Appendix summarizes the set of characteristics required for a tight aspect ratio, high field ignition experiment [1]. These provide another way of looking at the physics and engineering requirements for such an experiment.

The requirement of high toroidal field B_T and compact size leads to an interlocking set of characteristics favorable for ignition. The combination of high field and compact dimensions, with significant vertical elongation $\kappa > 1$, allows a relatively large plasma current, toroidal current density, and poloidal magnetic field to be supported. (In Ignitor, the mean poloidal field is $\overline{\overline{B}}_p \leq$ 3.75 T. Also, there is a large paramagnetic current $I_\theta \simeq 9$ MA at the low β of ignition and this increases the central B_T by $\simeq 1$ T.)

High toroidal field supports a high plasma density with $n < n_G = I_p/\pi a^2$, where n_o can be correlated empirically with the ratio B_T/R or with the plasma current density. In Ignitor, densities $n_{eo} \simeq 10^{21}$ m^{-3} should be possible, based on the values of B_T/R obtained by Alcators A and C, FT and FTU, and TFTR. Alcator C obtained $n_o \simeq 2 \times 10^{21}$m^{-3} at $B_T = 12.5$ T. If the maximum density instead correlates with the volume–averaged current density, Ignitor's value of $\langle J_\phi \rangle \simeq 0.93$ kA/cm^2 should again allow $n_{eo} \simeq 10^{21}$ m^{-3} without difficulty.) Therefore, based on the required confinement $n_o \tau_E \simeq 4 \times 10^{20}$s/m^3 for ignition conditions $T_o \sim$ 12–15 keV for 50:50 D-T plasma, only a moderate energy confinement time $\tau_E \sim 0.4$ sec is required.

As a consequence, such plasmas have

- High levels of ohmic heating up to ignition [1] (P_{OH} is high due to highB_p).
- Good confinement of plasma energy and particles (since empirical scalings show that, approximately, $\tau_{E,L} \propto I_p$)
- Good confinement of fast fusion charged particles. ($I_p > 6$ MA will give good central confinement of D-T α-particles.)
- Low temperature ignition ($T_{eo} \simeq T_{io} \lesssim 15$ keV in Ignitor) at relatively low levels of fusion heating ($P_\alpha \lesssim 2P_{OH}$).
- Ignition at low β_p. Ideal MHD and long wavelength resistive $m = 1$ internal modes are expected to be stable, due to low $\beta_p \lesssim 1/4$ (the limit is $\beta_p \simeq 0.3$ for Ignitor [35]).
- Low fusion power and thermal wall loading
- Clean plasmas (since Z_{eff} is a monotonically decreasing function of density)
- High plasma edge densities confine impurities to the scrape off layer ("cold plasma blanket" [30], DIII-D VH mode [31][32]), where line radiation from them helps to evenly distribute the wall loading (RI-mode in TEXTOR [29])

In addition, high field and the ability to ignite at low β gives the capacity for a broad range of operating conditions at less-than-maximum parameters.

These characteristics avoid or reduce the need for

- Injected heating, except to control plasma stability, to extend the operating range, and as a backup to ignition. This avoids serious degradation of confinement before the fusion α-heating regime is reached and allows the possibility that fusion heating may have better confinement characteristics than injected heating, since it is axisymmetric and isotropic like ohmic heating, but unlike injected heating.

- Divertors, which concentrate the thermal wall loading on small regions. Divertors require an expanded volume inside the toroidal field coils to accomodate the magnetic separatrices, the divertor, and the associated shaping coils. For high field designs, relatively small increases in the size of the coils and the major radius have serious consequences through the cascade of relations: larger $R \rightarrow$ lower $B_T/R \rightarrow$ lower n_e, lower $B_T \rightarrow$ lower I_p and P_{OH}, so that β_p is higher at ignition. The I_p is also lower for given B_T because the necessity of squeezing magnetic separatrices and the divertor inside the toroidal field coils reduces the plasma cross sectional area. Divertors introduce additional complexities in machine and magnet design, as well as operational risks associated with the presence of current carrying conductors in regions of high magnetic field.

- X-point configurations, which reduce the plasma cross-sectional area and current carrying capacity for a given toroidal magnet size and capacity. (In Ignitor, X-point configurations with single or double magnetic nulls can be produced for all or part of the discharge if necessary, with relatively little sacrifice in plasma and magnet parameters, i.e., somewhat smaller I_p, estimated as 10 MA for a single lower X-point, and more localized wall loading. The Ignitor X-points can be swept over regions of the wall to further distribute the power load.)

- Current drive to control q, which may be required to control central sawtooth oscillations at low edge q_ψ and/or high β_p.