PLASMA CHARACTERISTICS FOR A COMPACT D-T IGNITION EXPERIMENT

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ABSTRACT

Compact, tight aspect ratio toroidal configurations offer a set of properties favorable for fusion ignition experiments. High magnetic fields support high particle densities, which increase the fusion reaction rate and improve the plasma purity, as well as high plasma currents, which provide strong ohmic heating and keep the plasma beta low to improve stability. Low temperature D-T ignition, $T_o \leq 15$ keV, at relatively low levels of fusion α-particle heating compared to the ohmic heating, $P_\alpha/P_{OH} \leq 2$, then becomes possible, using predominantly ohmic heating. This minimizes the degradation of plasma confinement caused by injected heating and high beta and also reduces the need for complex divertor systems.

I. INTRODUCTION

High magnetic field experiments to investigate deuterium–tritium ignition conditions have been designed on the basis of known experimental and theoretical understanding of plasma behavior. The most advantageous and least expensive designs incorporate an interlocking set of characteristics[1] — tight aspect ratio, relatively small size with significant vertical elongation, high toroidal and poloidal magnetic fields, large plasma currents, high plasma densities, good plasma purity, strong ohmic heating, good plasma and α-particle confinement, and robustness against ideal MHD and resistive plasma instabilities. This paper discusses the basis for these plasma properties, while the design and engineering solutions for attaining the necessary parameters (the Ignitor Ult) are discussed separately[2]. Since ignition depends upon many spatially and temporally varying processes, many of the results are based upon the numerical simulation of a free boundary plasma (the Ignitor[1-4]) from the current ramp through ignition, using the TSC code[5].

II. BASIC CONSIDERATIONS FOR IGNITION

The ignition of a 50:50 deuterium–tritium plasma requires a minimum value of the parameter $n_o\tau_E \simeq 4 \times 10^{20}$ sec/m^3 in order to achieve ignition with $T_{eo} \simeq T_{io} \lesssim 15$ keV, where n_o is the peak plasma (electron) density, T_{eo} the peak temperature, and τ_E the energy replacement time. Here ignition is defined to be the point when the plasma heating due to fusion α-particles, P_α, equals the plasma thermal losses P_L. Relatively high values of the plasma density, $n_o \simeq 10^{21}$m^{-3}, then require only moderate values of τ_E, whose magnitude is less easy to predict with certainty. Both these values should be achievable, based on the favorable confinement properties of high density plasmas that have been demonstrated by a series of high field experiments, the Alcator A and C at MIT and the FT/FTU devices at Frascati, Italy. Experimentally, the maximum plasma density n_o that can be supported correlates with the ratio B_T/R_o, where B_T is the toroidal magnetic field at the center of the plasma column, at major radius $R = R_o$. On the basis of the Alcator C machine, where $n_o \simeq 2 \times 10^{21}$m^{-3} was achieved with $B_T \simeq 12.5$ T and $R_o = 0.64$ m, and the TFTR machine at Princeton, where even larger ratios of n_oR_o/B_T were achieved, a configuration with $R_o \simeq 1.3$ m and $B_T \simeq 13$ T should be able to sustain reliably densities of 10^{21}m^{-3}.

A strong toroidal magnetic field also supports a high poloidal field B_p and correspondingly large plasma current I_p. A significant vertical elongation, e.g., $\kappa \simeq 1.8$, substantially increases the plasma current that can be carried for a given B_T and R. If the density correlates with the (volume) averaged toroidal current density, $\langle J_\phi \rangle$, then experimental results suggest that somewhat less than 1 kA/cm^2 should offer considerable margin to attain the desired peak density $n_o \sim 10^{21}$m^{-3}. High values of B_p produce a strong rate of ohmic heating, while large currents I_p tightly confine the fast α-particles produced by the fusion reactions, so that they deposit their energy in the center of the plasma. The degradation of the plasma energy confinement, that is commonly observed when injected (nonohmic) heating is applied, is reduced at higher plasma current. In addition, the poloidal plasma beta β_p can be kept small at ignition, to improve the plasma stability and in particular to stabilize the ideal MHD modes with mode numbers $m = 1$, $n = 1$ that are associated with sawtooth oscillations.

Large plasma density combined with good ohmic heating allows ignition at low plasma temperatures. This reduces the fusion power, and therefore the thermal wall loads. The low beta increases the overall margin of plasma stability.

The plasma purity has been shown to improve with increasing plasma density, that is, the effective charge $Z_{eff} = \sum n_i Z_i / n_e$ decreases monotonically with n_e, in an extensive series of experiments starting with the Alcator A[6]. The major effect of impurities is to dilute the concentration of fusing nuclei, while a secondary effect is the increase the power lost due to bremsstrahlung radiation. If auxiliary heating is not used, Z_{eff} cannot exceed about 1.6 for D-T ignition in the Ignitor, as shown in Section III.

Relatively high plasma edge densities also help to confine impurities to the scrape off layer, where the induced radiation helps to distribute the thermal wall loading more uniformly over the plasma chamber surface. The low ignition temperatures associated with high density further help to keep the plasma clean, by reducing the thermal wall loading.

Peaked plasma density profiles should be maintained, by external means such as a pellet injector if necessary. Peaked profiles maintain stability to η_i modes that enhance the ion thermal transport[7]. Since the neoclassical (Ware) inward particle pinch is relatively strong in a tight aspect ratio, high field configuration and an anomalous inflow is also present, pellets that penetrate partway into the plasma can be successfully used to raise the plasma density and produce peaked profiles near ignition[8].

Plasma configurations, such as x-points, that concentrate the thermal (particle) heat flux on localized areas of the vessel wall, limit the amount of fusion power that can be handled. In addition, a more limited plasma current can be sustained. However, x-points and detached plasmas can be obtained with relatively little sacrifice in the plasma and magnet parameters and they may prove desirable to limit the degradation of the plasma confinement caused by nonohmic heating, by creating the conditions known to produce "H-mode" operation.

Divertors represent a more severe compromise, since they alter the design of the plasma chamber and the toroidal magnet. The major radius must be increased to accomodate a reliable divertor, reducing the ratio B_T/R and therefore the maximum plasma density. The magnetic fields are also reduced, lowering the plasma current and the ohmic heating, and increasing β. A large injected heating system becomes necessary to replace the ohmic heating and the resulting degradation of the plasma confinement makes low temperature ignition difficult. The divertor plates must then handle large thermal heat fluxes. There is no demonstrated advantage to using divertors in high density plasmas, while the cumulative disadvantages make ignition difficult to attain. Their use would remove much of the rationale for using a compact, high field machine.

III. TIME DEPENDENT IGNITION

III.A. Transient Processes and the Current Density Evolution

The transient nature of ignition cannot be overlooked. The initial current ramp, when I_p, n_e, B_T, and the plasma cross section are increased simultaneously, has important effects on the plasma energy balance and stability at ignition[1,4]. These effects arise from the relatively slow inward diffusion of the plasma current compared to the growth of the central temperature. The current ramp generates a inhomogeneous toroidal electric field in the plasma that is peaked near the plasma edge and allows large values of ohmic heating at high central temperature. The magnetic safety factor q can be easily maintained above unity or held to a very small $q < 1$ region during the current ramp, and a more careful study[1,4] shows that it can also be kept small after the ramp, at least until the central temperature reaches high values and fusion α-particles begin to appear, both of which are stabilizing effects for $m = 1$ modes. Furthermore, small amounts of injected heating (e.g., $P_{INJ} < P_{OH}/2$) during the current ramp

TABLE I

Reference Discharge for the Ignitor Ult

	End Ramp	Ignition	
t	3.0	4.3	time (sec)
$\ell_i/2$	0.32	0.38	internal inductance
β_p	0.08	0.13	poloidal beta
β	0.8	1.26	toroidal beta (%)
$q_{\psi a}$	3.3	3.6	edge magnetic safety factor
W	7.5	11.7	plasma kinetic energy (MJ)
T_{eo}	4.0	11.0	peak electron temperature (keV)
τ_E	710	660	energy confinement time (msec)
P_{OH}	13.0	9.5	ohmic heating (MW)
P_α	2.0	17.8	α-particle heating (MW)
$n_{\alpha o}$	1.5	12.0	peak α-particle density (10^{17} m^{-3})
P_B	3.2	4.1	bremsstrahlung radiation (MW)
P_{IC}	0.4	0.5	cyclotron and impurity radiation (MW)
$V_{q=1}$	1.4	5.8	volume where $q \leq 1$ (% of total)
$\Delta\Phi$	29.2	31.4	magnetic flux variation (V sec)
I_{BS}	0.6	1.0	bootstrap current (MA)

Flattop parameters $I_p = 12$ MA, $B_T = 13.5$ T, $R = 1.3$ m, $a = 0.48$ m, $b = 0.87$ m, $\delta \simeq 0.4$, $n_{eo} = 1.1 \times 10^{21}$m^{-3}, $n_{eo}/\langle n_e \rangle = 2.2$, $Z_{eff} = 1.2$.

can maintain a very small size (or nonexistence) for the $q < 1$ region until well past ignition, if central temperatures approach 10 keV by the end of the current ramp, through the freezing-in of the central current density at low resistivity. Injected heating also reduces the magnetic flux consumption required to reach ignition, particularly if ignition occurs during the current ramp. These characteristics are illustrated in Tables I (reference case for the Ignitor design parameters, maximum $B_T = 13.5$ T, $I_p = 12$ MA, $R = 1.3$ m, $a = 0.48$ m, $\kappa = 1.8$, and $n_{eo} = 1.1 \times 10^{21} \mathrm{m}^{-3}$, at 50:50 D:T ratio and $Z_{eff} = 1.2$) and Table II (degraded conditions and injected heating). These cases started with small, nearly circular plasmas at $t = 0.2$ sec into the current ramp, with $R = 1.07$ m, $a = 0.26$ m, I_p=1 MA, $q_o = 1.75$, $q_{\psi a} = 4.2$, $T_{eo} = 1$ keV, and $n_{eo} = 2.5 \times 10^{20} \mathrm{m}^{-3}$.

It has been shown that it is simultaneously possible to maintain monotonically increasing q profiles without large low shear regions, and with with edge values $3 < q_{\psi a} < 4$ during the current ramp, to beyond ignition. These conditions should prevent instabilities associated with internal plasma modes (e.g., "locked" or quasistationary modes) that can be triggered during the current ramp and often lead to disruptions[4]. Since hollow q profiles are usually associated with the excitation of internal macroscopic modes and enhanced, "anomalous" current penetration, while ignition is aided by a slow current penetration that keeps $q_o > 1$ for as long as possible, these precautions are not superfluous.

III.B. Energy Confinement at Ignition

A major question for all ignition experiments is the degree of degradation expected in the plasma energy confinement near ignition, since D-T ignition is easily achieved if the confinement remains at the optimal, ohmic heating level. One strategy for a high field experiment is to maintain a high level of ohmic heating up to ignition, $P_\alpha \leq 2P_{OH}$, to reduce the degree of degradation. Since α-particle heating possesses two important characteristics of ohmic heating that are not shared by any presently available form of injected heating — axisymmetric deposition and generation in the center of the plasma column — we expect that the degradation should not be as severe.

The requirement of relatively low edge q (high plasma current) means that special care must be devoted to maintaining $q > 1$ up to ignition. If only ohmic heating is contemplated, the steadily increasing size of the $q < 1$ region after the end of the current ramp imposes a more severe limit on the time in which the plasma can ignite and on the required energy confinement level, than the energy balance alone, if it is assumed that sawtooth oscillations large enough to destroy the central peaking of the temperature cannot be avoided. Then ignition in the Ignitor reference case, at $T_o \simeq 11$ keV, requires $\tau_E \simeq 0.66$ sec and must occur within approximately 1.5 sec of the end of the current ramp (Table I). Our theoretical analysis, on the other hand, indicates that Ignitor remains, in all regimes, within the stability limits of the ideal MHD and resistive $m = 1$, $n = 1$ modes. In addition, moderate amounts of auxiliary heating, P_{ICRH}~10-15 MW started during the current ramp, allow ignition down to the limits predicted by $n_o\tau_E$, i.e., $\tau_E \lesssim 0.4$ sec, while maintaining very small $q = 1$ regions well beyond ignition. Similarly, in the ohmic case, if the requirement of small $q < 1$ region is dropped, either on the basis of the theoretical analysis or by externally stabilizing the sawtooth oscillations, ignition can also occur at these τ_E's and times of $t_I \simeq$ 5-5.5 sec (Table II).

The importance of ohmic heating during the ignition sequence at high field and density means that a model for the electron thermal transport should, like the one adopted here, include a diffusion coefficient that simulates ohmic regimes and reproduces typical toroidal

TABLE II
Degraded Conditions and Injected Heating

	$Z_{eff} = 1.6$		Large Thermal Transport	
Heating	Ohmic	Injected	Ohmic	Injected
P_{ICRH} (MW)	0	5*	0	15†
Z_{eff}	1.6	1.6	1.2	1.2
γ_i‡	0.5	0.5	1.5	1.5
t_I (sec)	5.3	3.3	5.0**	3.0
β_p	0.14	0.15	0.14	0.19
W (MJ)	12.8	14.0	12.9	16.6
T_{eo} (keV)	13.0	13.2	13.4	15.1
τ_E (msec)	570	555	470	425
P_{OH} (MW)	8.7	8.8	8.1	6.9
P_α (MW)	22.5	25.2	24.3	39.2
P_B (MW)	4.9	5.4	4.2	4.9
P_{IC} (MW)	1.0	1.1	0.5	0.7
$V_{q=1}$ (%)	> 10	2.3	> 10	1.4

* $P_{ICRH} \simeq 5$ MW for $t > 1.2$ sec.

† $P_{ICRH} \simeq 5$ MW for $1.2 < t < 1.8$ sec, 10 MW for $1.8 < t < 2.4$ sec, and 15 MW for $t > 2.4$ sec.

‡ Ion thermal diffusion coefficient $\chi_i = \chi_i^{neo} + \gamma_i \chi_e^{nOH}$, where $\chi_e = \chi_e^{OH} + \chi_e^{nOH}$, reference $\gamma_i = 0.5$.

** Subignited; never reaches ignition.

loop voltages in steady state ohmic experiments, that are observed to be about a "universal" constant. In addition, the total diffusion coefficient should increase with injected heating and reproduce the degraded confinement observed in present experiments that are dominated by injected heating.

III.C. Plasma Density

A second major question for ignition is the effect of variation in the plasma density and its profile, since pellets injected to raise the density are unlikely to fully penetrate a high density plasma.

For a given level of thermal transport, there is an optimum density for fastest ignition. A higher density is more favorable under degraded conditions. Higher density, however, accelerates the toroidal current penetration at a given time by lowering the T_e, producing larger $q < 1$ regions earlier than at lower density. This effect also operates in the outer part of the plasma radius when density profiles are broadened, as shown in the first three cases of Table III. Thus, for $n_{eo} = 1.1 \times 10^{21}\mathrm{m}^{-3}$ profile peaking factors $n_{eo}/\langle n_e \rangle \geq 1.9$ where $\langle n_e \rangle$ is the volume average, give relatively similar results for ignition. Broader profiles rapidly lead to degraded ignition, e.g., $n_{eo}/\langle n_e \rangle = 1.5$ requires longer t_I and higher τ_E, and yields a significantly larger $q = 1$ radius. Lower central density, e.g., $n_{eo} = 6.5 \times 10^{20}\mathrm{m}^{-3}$ at the end of the current ramp increasing to 8-9 $\times 10^{20}$ by ignition, allows broader profiles, $n_{eo}/\langle n_e \rangle = 1.5$, as shown by the last case in Table III.

For related reasons, increasing the plasma density after the current ramp is more advantageous than increasing the density during the ramp.

At high density, a region of low magnetic shear at $1 < q < 2$ develops in the mid-region of the minor radius. This region becomes seriously unstable when its value of q approaches unity, since ideal MHD instabilities with $m = 1$ can occur. This is one of the major limits on the broad density profile cases.

III.D. Burning Conditions

Fusion ignition is thermally unstable in the low temperature interval, due to the temperature dependence of the fusion reaction cross section. At ignition, by definition, $P_\alpha = P_L$, so that the plasma thermal energy W is increasing as $dW/dt = P_{OH} + P_{INJ}$. If necessary, provision should be made to limit possible temperature excursions. There are intrinsic processes, such as the rise of the central pressure, that can overcome the stability threshold for $m = 1, n = 1$ modes and limit the temperature naturally. Marginal ignition and sustained subignited states, partly supported by ohmic heating, are also of interest for studying fusion burning. These greatly expand the operating parameter range for the Ignitor[1].

III.E. Plasma Stability

High field, tight aspect ratio configurations have more favorable plasma stability characteristics than lower field ignition experiments, because of the intrinsically low plasma β. A major concern for ignition is the stability of the plasma to central, sawtooth oscillations. The stability of modes with dominant poloidal mode number $m = 1$ has been discussed previously[1,3]. Additional considerations for instabilities driven by the current density profile have been discussed above. Other instabilities, such as shear Alfvén modes destabilized by fusion α-particles, have also been discussed[1,9].

IV. CONCLUSIONS

The set of features that make a high field, tight aspect ratio toroidal plasma suitable for an deuterium-tritium ignition experiment have been discussed. Ignition at relatively high density, making the most effective use of ohmic heating, has been shown to be the simplest and most reliable. The time evolution of the plasma to ignition has been shown to play a significant role in de-

TABLE III
Effects of Different Density Profiles

Density Profile	Narrow	Reference	Broad	Broad*
$n_{eo}/\langle n_e \rangle$	2.9	2.2	1.5	1.5
n_{eo} ($10^{20}\mathrm{m}^{-3}$)	11	11	11	8.4
t_I (sec)	4.1	4.3	4.7	4.3
W (MJ)	10.7	11.7	13.4	12.6
T_{eo} (keV)	11.2	11.0	11.1	13.0
β_p	0.12	0.13	0.15	0.15
τ_E (msec)	615	660	705	675
P_{OH} (MW)	8.8	9.5	9.9	9.1
P_α (MW)	17.4	17.8	19.0	18.7
P_B (MW)	3.2	4.1	5.8	4.2
P_{IC} (MW)	0.4	0.5	0.8	0.6
$V_{q=1}$ (%)	4.0	5.8	> 10	4.8†

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

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

termining the ignition requirements. In particular, the transient effects produced during the initial phase when the plasma current is ramped to its final value affect the plasma stability and heating at ignition.

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REFERENCES

1. B. COPPI, M. NASSI, and L.E. SUGIYAMA, "Physics Basis for Compact Ignition Experiments," *Physica Scripta*, in press (1992).
2. B. COPPI, M. NASSI, and L.E. SUGIYAMA, "Engineering Characteristics of the Ignitor Ult Experiment," *10th Topical Meeting on the Technology of Fusion Energy*, Boston MA, 1992, to be publ. in *Fusion Technology*.
3. B. COPPI, R. ENGLADE, M. NASSI, F. PEGORARO, and L. SUGIYAMA, "Current Density Transport, Confinement, and Fusion Burn Conditions," in *Plasma Physics and Controlled Nuclear Fusion Research*, Washington D.C., 1990 (I.A.E.A., Vienna), paper CN-53/D-4-14 (1991).
4. L. SUGIYAMA and M. NASSI, "Free Boundary Current Ramp and Current Profile Control in a D-T Ignition Experiment," *Nucl. Fusion*, in press (1992).
5. S.C. JARDIN, N. POMPHREY, and J. DELUCIA, "Dynamic Modelling of Transport and Positional Control of Tokamaks," *J. Comp. Phys.* **66** 481 (1986).
6. G.J. BOXMAN, B. COPPI, L.C. DEKOCH, et al., "Low and High Density Operation of Alcator," *Proc. 7th Eur. Conf. on Plasma Physics*, Lausanne, 1976 (Ecole Polytechnique Fédérale de Lausanne, Switzerland) Vol. 2, p. 14 (1976).
7. B. COPPI, P. DETRAGIACHE, R. KULSRUD, F. PEGORARO, and W.M. TANG, "Physics of Plasmas Close to the Lawson Limit and Under Fusion Burn Conditions," *Plasma Physics and Controlled Nuclear Fusion Research*, London, 1984 (I.A.E.A., Vienna), Vol. 2, p. 93 (1985); B. COPPI and W.M. TANG, "Ignition Density Bounds and Collective Modes of Fusing Nuclei," *Phys. Fluids* **31** 2683 (1988).
8. W.A. HOULBERG, private communication (1991).
9. R. BETTI and J.P. FRIEDBERG, "Stability of Alfven Gap Modes in Burning Plasmas," submitted to *Phys. Fluids* (1991).