Main Issues on the Approach to Ignition in Deuterium-Tritium Plasmas*

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Introduction

Physics issues that can affect the possibility to reach full ignition in deuterium-tritium plasmas are investigated by extensive simulations of the evolution of the plasma parameters that can be produced by the Ignitor machine [1]. The main design parameters are a toroidal field up to 13T, a plasma current up to 12MA, tight aspect ratio (R_0~1.32m, a~0.47m) and considerable elongation (k~1.83) and triangularity (δ~0.4). The optimal regimes in which full ignition can be achieved correspond approximately to peak densities around 10^{21} m^{-3}. This value is well below the known density limit that is among the most severe conditions to be fulfilled in low magnetic field, larger machines [2]. The high densities allowed by the high toroidal field have been proven to lead to a small impurity content, which is another issue heavily affecting the fusion performances. Ignitor is designed to exploit the beneficial effects of the simultaneous increase of the toroidal magnetic field, the plasma current and the particle density. From a series of simulations under similar conditions, it was found that fusion power production and ignition depend both on the plasma average density and its radial profile [3]. Here the optimal density value is adopted and the influence of other parameters on the global performance is investigated for the 11MA scenario. The evolution and control of the current density profile is a primary issue. As a matter of fact a concern remains for the excitation of m=1, n=1 modes associated with magnetic reconnection, in view of the relatively large sawtooth oscillations which they can produce. While ohmic heating is adequate to reach ignition, the ICRH system can be usefully employed to control the evolution of the current density profile and shorten the time needed to achieve ignition.

Simulations

The current rise phase plays a crucial role in such a machine and requires to be carefully planned. Therefore reliable and consistent numerical simulation of this phase is mandatory. The code here used has the required features. The simulation set-up has already been illustrated in Ref. [3], where the current ramp and plasma cross-section expansion in a limiter configuration followed by a condition of constant I_p were analyzed for the 12MA scenario. The “*nominal*” parameters for the plasma current and the magnetic field are here considered in a set of simulations starting at t=0.3 sec (corresponding to I_p =1MA and B_t =7.6T) and lasting till the ignition attainment in the flattop conditions (I_p =11MA, B_t =13T). The working gas is a 50-50 deuterium-tritium mixture. The cross-section expansion is controlled so as to hold $q_\psi>3$ and to avoid the disruption boundaries in the (l_i,q_ψ) diagram. This criterion can require to tailor the growth of the plasma poloidal cross-section in a way slightly different from the nominal one. The chosen (electron/ion) thermal diffusion coefficients are a combination between the Coppi-Mazzucato-Gruber expression and a power depending contribution that accounts for the heating source due to the alpha particles, as detailed in Ref. [3]. Neoclassical electrical resistivity is adopted. Our layout is somewhat conservative, as the energy confinement time is maintained about the ITER96 L-mode [4] along the ramp. The high toroidal field assures a large margin with respect to the beta limit.

The line-averaged density, due to the high current density, is always lower than the Greenwald limit written in the form:

$$\bar{n}_e = I_p / (\pi \langle a \rangle^2) \qquad [10^{19}\ \mathrm{m}^{-3}, \mathrm{MA}, \mathrm{m}]. \qquad (1)$$

The ignition attainment is pointed out by the unity value of the parameter:

$$f_{ign} = \frac{P_\alpha}{P_{th} + P_{rad} + P_{brem} + P_{sync}} \qquad (2)$$

The f_{ign} value is in any case an important marker of the obtained performances.

Results

Here we consider $\langle n_e \rangle \sim 5\times10^{20}\mathrm{m}^{-3}$ and $\langle Z_{eff} \rangle \sim 1.2$ and analyze how the adopted rate of increase of the density affects the attainment of ignition. Two different growths are represented in Fig.1. The second choice is adopted in other simulations which explore the possibility of obtaining better performances by exploiting the use of additional heating during the current rise. Table I summarizes the results obtained both in purely ohmic regimes and in additionally heated discharges. The RF pulse is simply modeled by a step power input to ions lasting from t_{ON} to t_{OFF} , with a uniform spatial distribution between $\rho_1/\rho_{max}=x_1$ and $\rho_2/\rho_{max}=x_2$. The power input is chosen to be ~10 MW that is of the same order of the ohmic input at the injection time.

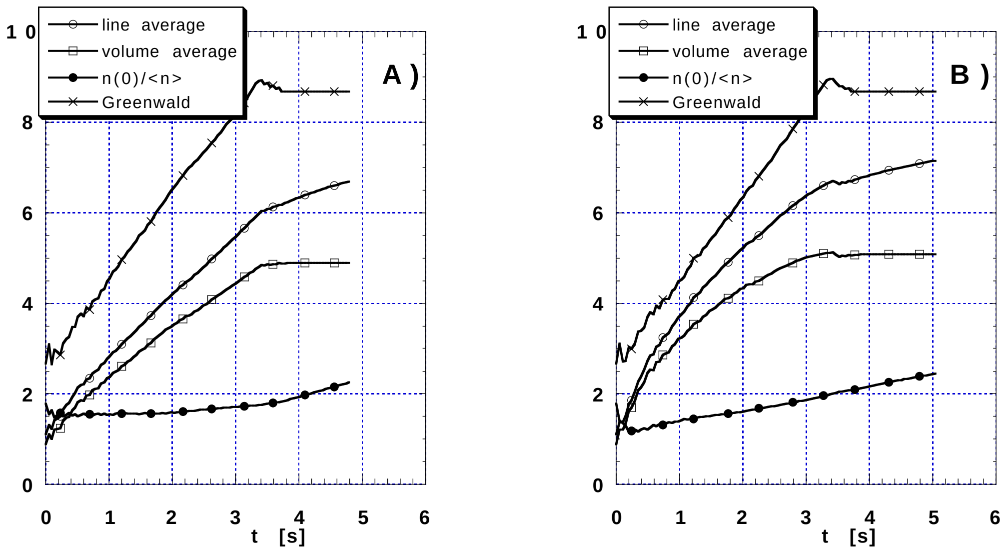


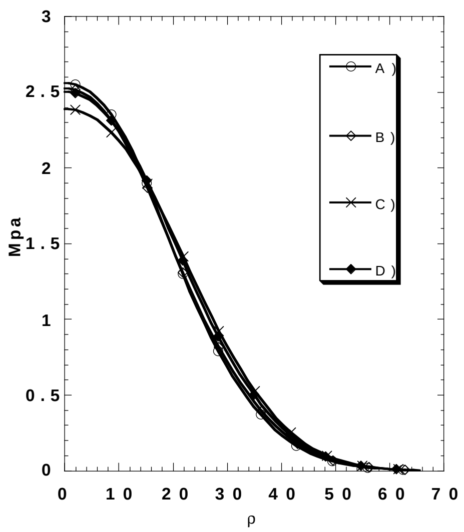
Fig.1.- Time evolution of line/volume averaged electron density in $10^{20}m^{-3}$ for cases A) and B) in Table I. The peaking factors and the relevant Greenwald values are also plotted.

The different increase in the density produces different temperatures, but the pressures at ignition are very similar (See Table I and Fig.2), even if the ignition times are not the same. This “preferential” pressure profile at ignition is also underlined by the simulations performed in the presence of auxiliary heating, as cases C) and D) in Table I. The ignition time is shortened by the RF injection when the same degradation with power is assumed (f_{UB}=1). The safety factor profiles look markedly different, remaining completely over unity in the presence of additional heating; the pressure profiles maintain similar shapes. The invariance of the electron pressure profile at ignition was already observed in simulations relevant to the 12MA scenario and based on a different transport model calibrated so as to produce comparable confinement times [5]. An enhanced f_{UB} , case E), delays the ignition, lowers the confinement time and modifies the pressure profile.

Table I

Shot	A	B	C	D	E
f_{UB} factor	1	1	1	1	1.6
t_{ign}-t_{EOR} [s]	1.09	1.33	0.99	1.24	1.57
$<n_e>$ in $10^{20}m^{-3}$	4.89	5.03	5.34	5.16	5.45
$n_e(0)/<n_e>$	2.3	2.4	2.2	2.3	2.4
P_Ω [MW]	10.5	10.3	10.0	10.0	10.5
P_α [MW]	25.4	23.7	26.9	26.9	29.8
t_{ON}-t_{OFF} [s]			1.5-2.9	1.8-3.2	1.5-2.9
x_1 - x_2			0.59 - 0.84	0.69 - 0.94	0.59 - 0.84
I_{boot} [MA]	0.80	0.87	0.98	1.00	0.95
β_p	0.28	0.26	0.28	0.28	0.28
$T_e(0)$ [keV]	14.5	12.2	12.7	12.9	13.5
$T_i(0)$ [keV]	12.6	11.0	11.3	11.4	11.9
q(0) at t_{EOR}	1.10	1.05	1.23	1.10	1.20
q(0) at t_{ign}	0.87	0.80	1.08	0.94	0.92
$p_e(0)$ [MPa]	2.56	2.42	2.39	2.50	2.82
f_{ign} at t_{EOR} [s]	0.18	0.15	0.18	0.18	0.15
τ_E at t_{ign} [s]	0.57	0.60	0.61	0.61	0.54
$<n_\alpha>/<n_{DT}>$ [%]	0.054	0.033	0.036	0.038	0.039

Table I - f_{UB} is an enhancement factor for ubiquitous mode contribution in the thermal diffusivity; t_{EOR} marks the end of ramp time , i.e. the time when Ip=11MA and Bt=13T. All quantities are listed at ignition, if not otherwise specified.



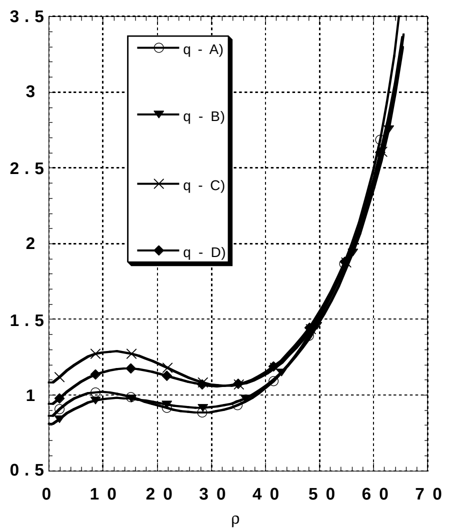


Fig.2.- Electron pressure (left side) and safety factor profiles at ignition for cases A), B), C), D)

The approach to ignition may be followed by the trajectories of $n(0)\tau_E$ vs $T_i(0)$ in a Lawson plot as in Fig.3. The Lawson condition and the ignition margin are evaluated by using Z_{eff}=1.5. Notice that cases B), C) and D) reach the same final point although their paths differ because of the auxiliary heating.

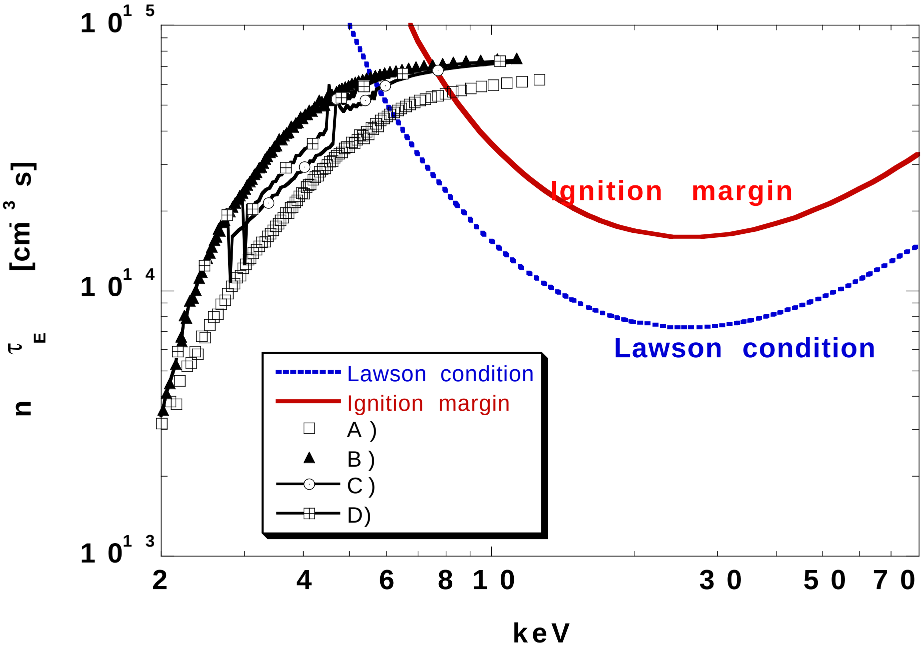


Fig.3.- Evolution of $n(0)\tau_E$ vs $T_i(0)$ for cases A), B), C) and D) in Table I.

Concluding remarks

Plasma density and beta never approach the known limits. The beneficial effects of an appropriate choice of the density, already pointed out in Ref. [3], are confirmed also in these simulations. Additional RF heating during the ramp may be effective for modifying the current profile so avoiding or minimizing the q<1 region. It seems that, under the same global energy confinement time, a “consistent” plasma pressure characterizes the ignition condition, independently of the path followed.

There are still open questions on high field ignition experiments: transport and resistivity during the current ramp are not necessarily the same as in steady state.

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