IGNITOR Physics Assessment and Confinement Projections

W. Horton 1), F. Porcelli 2), P. Zhu 1), A. Aydemir 1), Y. Kishimoto 3), T. Tajima 1)

1) Institute for Fusion Studies, The University of Texas, Austin, TX 78712, U.S.A.
2) INFM and Dipartimento di Energetica, Politecnico di Torino, 10129 Torino, Italy
3) Plasma Science and Fusion Center, M.I.T., Cambridge, MA, U.S.A.
4) JAERI, Plasma Theory, Tokai-Mura, Naka-Gun, Ibaraki-Ken 319-11, Japan

e-mail contact of main author: `horton@physics.utexas.edu`

Abstract. An independent assessment is presented of the physics of Ignitor, a physics demonstration experiment for achieving thermonuclear ignition (where fusion alpha heating compensates for all forms of energy losses). Simulations show that a pulse of α particle power up to 10-20 MW is produced for a few seconds. Crucial issues are the production of peaked density profiles over several energy confinement times, the control of current penetration for the optimization of ohmic heating, and sawtooth avoidance. The presence of a 10-20 MW ion cyclotron radio frequency system and the operation of a high-speed pellet injector are considered essential to provide added flexibility in order to counter unexpected, adverse plasma behavior.

IGNITOR [1] is a physics demonstration experiment whose main goal is to achieve thermonuclear ignition. The relevant information that would be gained from such an experiment involves: (i) Improved understanding of plasma turbulence and transport processes, by the exploration of high-plasma-density, high-magnetic-field regimes never accessed before; (ii) alpha particle physics issues - in particular, alpha particle confinement, collective electromagnetic modes excited by the fusion alphas, and the nature of alpha particle heating; and (iii) control of a fusion burning plasma during physically significant time scales.

Ignition is defined as the plasma state where the heating power due to the fusion alpha particles compensates for all forms of power losses (due to anomalous transport and radiation). Consider the power balance equation, $dW/dt = P_\Omega + P_\alpha + P_{\rm aux} - P_{\rm loss}$, where W is the plasma energy content, P_Ω is the ohmic power, P_α is the alpha particle heating power, $P_{\rm aux}$ is the auxiliary heating power, and $P_{\rm loss}$ is the loss power, including radiation losses. In the ignited state, $P_\alpha = P_{\rm loss}$ and the auxiliary power, $P_{\rm aux}$, may be switched off. Thus, ignition is an overheated state with $dW/dt = P_\Omega > 0$. The relevant parameter is $Q^* = P_{\rm fus}/(P_{\rm loss} - P_\alpha)$ where the fusion power is given as $P_{\rm fus} = 5P_\alpha$ for a D-T reacting plasma. With this definition, $Q^* = \infty$ at ignition. Alternatively, using the power balance relation, one may write $Q^* = P_{\rm fus}/(P_{\rm in} - dW/dt)$, where $P_{\rm in} = P_\Omega + P_{\rm aux}$.

The parameter Q^* is the measure of fusion power to the input power, taking into account the transient loading/unloading of plasma energy, $W(t)$. One can see that Q^* becomes equal to the widely used thermonuclear gain parameter, $Q = P_{\rm fus}/P_{\rm in}$, when $dW/dt = 0$; i.e., Q^* is the natural extension of Q under non-steady-state operation. During transient regimes, the difference between Q and Q^* becomes important and should be kept in mind. The simulation uses the IGNITOR parameters given in Ref. [1] for a typical inductive operation scenario at ignition are $R/a = 1.32\,{\rm m}/0.47{\rm m} = 2.8$, $B_T = 13\,{\rm T}$, $I_p = 11\,{\rm MA}$, $\kappa_x = 1.83$, $q_{95} = 3.5$, $n_e(0) = 9.5 \times 10^{20}{\rm m}^{-3}$, $n_e/n_{\rm G} = 0.4$, $T_e(0) = 11.5\,{\rm keV}$, $P_\Omega = 11\,{\rm MW}$, $P_{\rm ICRH} = 0/20\,{\rm MW}$, and $Z_{\rm eff} = 1.2$.

Experience from Alcator C-MOD [3] and FTU [4] indicates that the worst-case discharges in these machines have a confinement time that follows the ITER89P L-mode scaling, both in ohmic discharges and with auxiliary heating at relatively high densities, while the neo-Alcator scaling is followed at lower densities. Regimes of improved confinement at high plasma density have been observed. H-modes have been observed in limiter as well as divertor configurations, and in ohmic as well as in auxiliary heated discharges. Enhanced confinement in L-mode operation, such as the Improved Ohmic Confinement (IOC) regime observed in ASDEX-U [5], has also been observed in Alcator C [6] at relatively high density in plasmas with peaked density profiles. Recently pellet-assisted ohmic discharges with very good confinement have been obtained in FTU [7], with a line-averaged density $\bar{n}_e \approx 4 \times 10^{20}\,\mathrm{m}^{-3}$ and energy confinement time $\tau_E \approx 0.1\,\mathrm{s}$.

1. Transport considerations and formulas

The IGNITOR team bases its confinement predictions on a combination of empirical and theoretical 1-D flux-surface-averaged transport models [1]. While such 1-D models are intellectually appealing, the unfortunate reality of tokamak physics is that we do not have a generally valid model of transport. Thus, the confinement issue for IGNITOR should be addressed with various methodologies and from many different perspectives. In this section, we first examine the predictions based on empirical scaling laws. Next, we discuss the possibility of enhanced confinement regimes. Finally, we examine heat diffusivity models and present our own 1-D simulations of Ignitor discharges.

1.1 Confinement time based on L-mode scaling laws

The L97 scaling law has been compared with confinement in Tore Supra [9]. The Tore Supra database has 50 discharges with Fast Wave ICRH that deposits its energy into the electrons, $P_{\mathrm{ICRH}} = P_0 \exp\left(-r/L_p\right)$, in a highly localized core with $L_p \approx a/5$. Thus, the fast wave ICRH heating approximately simulates alpha power heating of the electrons. In addition, Tore Supra operates routinely in L-mode and exhibits various levels of enhancement over the ITER-97 L-mode scaling law as a function of density profile peaking. Thus, even though not a high field tokamak, Tore Supra is relevant to IGNITOR considerations. The best discharges have an enhancement factor of $H = 1.4$ to 1.7 with respect to the ITER-97 L-mode formula, which is a conservative calculation of τ_E.

1.2 Improved confinement regimes with peaked density profiles

As is well known, the linear ohmic confinement mode is a regime of ohmic confinement (LOC) with a linear relationship between energy confinement time and density. Unfortunately, at regular conditions with increasing density, the LOC regime makes a transition either into a saturated ohmic confinement (SOC) mode or into the L-mode with Goldston confinement scaling. Experiments with high fields and pellet injection have been carried out by the FTU [7] machine in Frascati. Estimated confinement times of about 90-100 msec have been reached with a magnetic field $B \approx 7\,\mathrm{T}$, a line-average density $\bar{n}_e \approx 4 \times 10^{20}\mathrm{m}^{-3}$ and a current $I_p \approx 0.8\,\mathrm{MA}$.

Peaked density profiles reduce the two dimensionless profile parameters η_i and η_e that represent driving terms for the instability of ion and electron temperature gradient modes and their associated plasma turbulence for peaked density profiles. For flatter density profiles, the ITG stability condition is that L_{Ti}/R exceed a critical value, which is typically not compatible with the overall required temperature difference between the edge and the core. Theoretical investigations of ITG modes have concluded that the improved confinement in Alcator C pellet fueling experiments [6] was correlated in time with the drop of the η_i parameter. Numerous other machines have shown discharges with improved confinement due to density peaking. For instance, Ref. [10] predicts a suppression of the ion thermal flux due to ITG turbulence going from L-mode to the RI-mode in TEXTOR [11]. As far as the electron temperature gradient driven turbulence is concerned, there are two theoretical forms of the anomalous electron thermal diffusivity that are depressed by high density: the dissipative trapped electron turbulent diffusivity and the short wavelength electromagnetic diffusivity with mixing length proportional to the collisionless skin depth [2, 8, 9].

1.3 Heat diffusivities

Let us examine the question of confinement in IGNITOR from the point of view of the heat diffusivity value needed for ignition relative to models that are known to work well in other tokamak experiments.

The range of predictions for IGNITOR performance may be assessed by comparing the results of the empirical transport models of Taroni-Bohm and the mixed Bohm-GyroBohm (Erba *et al.* 1998 [12]) contained in JETTO, with the multiple mode model MMM95 (Bateman, 1998 [13]). The first simple model is a thresholdless parameterization defined as Taroni-Bohm $\chi_e^{\mathrm{TB}} = \alpha_B \, q^2(r) a T_e / B_T L_p$ along with an additional gyro-Bohm contribution where the constant α_B is calibrated with certain JET discharges and validated on other discharges. The model has good predictive power for JET, Tore Supra, and JT60U. The theoretical basis in particle simulations is given in Refs. [14] and [15] for Bohm scaling. Power balance $P_L = q_r^{\mathrm{TB}} S = P_{\mathrm{aux}}$ with the heat flux q_r and surface area leads to a global τ_E scaling with exponents close to those of the ITER97L formula.

The highest performance discharges are obtained with the mixed Bohm/gyro-Bohm JETTO model. Figure 1 shows the time traces of several key parameters in an Ohmic ignition discharge simulation. The time interval where $P_\alpha(t)$ raises above $P_{\mathrm{loss}} = W/\tau_E$ is $t_{ig} = 4 - 5\,\mathrm{s}$. After $t = 6\,\mathrm{s}$ the discharge approaches a quasi-steady burning state with $Q^* = 5\times$ (60 MW)/(5 MW $+0_{\mathrm{aux}}$) $\simeq$ 60 where $P_\alpha \approx$ 60 MW and $P_\Omega \simeq 5\,\mathrm{MW}$. To obtain the regime requires the current ramp shown in frame (a) from 7 MA to 12 MA in $\Delta t_{I_p} = 2\,\mathrm{s}$ and in frame (b) the density rise of $\langle n_e \rangle$ from $80 \times 10^{19}\,\mathrm{m}^{-3}$ to $\lesssim 100 \times 10^{19}\,\mathrm{m}^{-3}$ in the time interval $t_1 = 1\,\mathrm{s}$ to $t_2 = 6\,\mathrm{s}$. Frame (c) shows the rising $P_\alpha(t)$ and falling $P_\Omega(t)$ and the sum of the total input power to the plasma heating $P_{\mathrm{in}} = P_\Omega(t) + P_\alpha(t)$. Frame (d) shows the two-type local energy confinement time $\tau_E(t) = W(t)/(P_\Omega + P_\alpha)$ and $\tau_E^*(t) = W(t)/(P_\Omega + P_\alpha - dW/dt)$. The radiated power is too small, compared with the uncertainties in transport, to warrant inclusion in $\tau_E(t)$. Frame (d) shows that the two definitions give the same basic descriptions except for the time interval around the ignition time. In the quasi-steady state there are fluctuations in $W(t)$ about a mean value that produce the sharp spikes in $\tau_E^*(t)$. In frame (e) the fusion gain parameters Q^* and Q are shown as functions of time, where Q^* approaches 40-75, strongly suggesting the occurence of ignition.

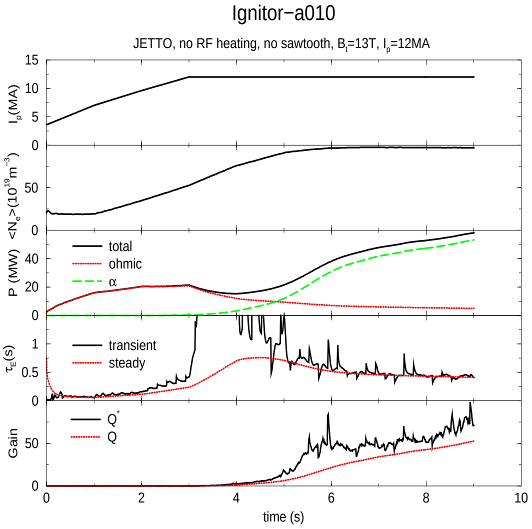

FIG. 1: Time traces of a) plasma current, b) line-averaged electron density, c) heating powers, d) confinement times, and e) fusion gains in the simulation of the JETTO Ohmic heating of IGNITOR without sawtooth.

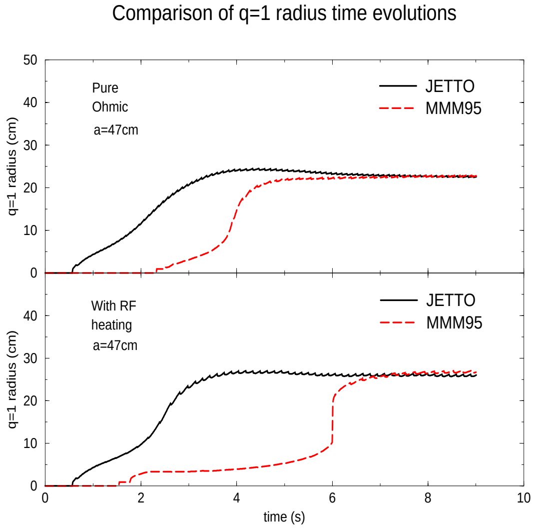

FIG. 2: Time traces of the $q = 1$ radius at sawtooth crash in the simulations with a) pure Ohmic heating and b) 20 MW auxiliary RF heating.

The evolution for the same current and density ramps for the ITG and TEM theory-based transport for the MMM95 we also examined. Here the confinement time is $\tau_E \simeq 0.6\,\mathrm{s}$, higher by $0.6/0.4 = 1.5$ than the ITER97L value of 0.4 s. Auxiliary heating is necessary to achieve a successful experiment with this theory-based model since the pure Ohmic discharge has the ITG turbulence limit $T_i \simeq 7$ keV and T_e is tightly coupled to T_i by the high collisionality of this plasma.

2. Sawtooth degradation of Q and RF power scan

When the sawtooth is allowed in the simulations, the increase of α heating power and the decrease of the Ohmic heating power stop when the first major sawteeth collapse is triggered. After that time, the Ohmic heating power stays at a high level while the α heating power remains at a low level ($\sim 3\,\mathrm{MW}$), indicating no occurrence of ignition. The corresponding movement of the position of $q = 1$ surface is shown in Fig. 2a for both models. The two models give a similar description of the growth of the $q = 1$ radius $r_1(t)$, which saturates at $r_1/\bar{a} = 22\,\mathrm{cm}/64\,\mathrm{cm}$, where $\bar{a} = \sqrt{\kappa}a = 64\,\mathrm{cm}$.

We have studied the effect of auxillary RF heating on the performance of IGNITOR in simulations using the JETTO model and the MMM95 model. 10 MW and 20 MW of ion cyclotron RF heating powers are applied from $t = 1.0\,\mathrm{s}$ to $t = 9.0\,\mathrm{s}$. For the JETTO model the RF power increases the α heating power, but the magnitude of sawtooth oscillation increases at the same time. The fusion gain Q is around 2.2 as the plasma enters steady state. Hence the overall improvement of the heating performance is not significant. For the simulation using the MMM95 model, the RF heating power is found to greatly increase the α heating power until a sawtooth oscillation is triggered. Both Q^* and Q oscillate about the average value of 5 during the steady state. From Fig. 2b, which shows the position of the $q = 1$ surface as a function of time for the 20 MW RF heating power case, one can see the first major sawtooth occurs at $t \sim 3\,\mathrm{s}$ for the JETTO model while the first major sawtooth is not triggered until $t \sim 6\,\mathrm{s}$ for the MMM95 model. In this case, the growth of the $q = 1$ radius is strongly delayed in the MMM95 model till 6 s and then rapidly catches up with that of the JETTO model. The radius saturates at $r_1/\bar{a} = 26\,\mathrm{cm}/64\,\mathrm{cm} = 0.4$.

3. Conclusions

The simulations, although rudimentary, show that control of the sawtoothing and of the density profile are critical elements for achieving the goal of ignition in IGNITOR. These two problems have been identified earlier, but our simulations quantify the degree of the problem. By comparing predictions of an empirical-based transport model with a theory-based model, we highlight the problem of extrapolating from the present, rather limited database to high-field/high-density operation. We also see the need to use more advanced theory models that incorporate the transport suppression from E_r-shear and from optimized magnetic shear current profiles.

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