Physical Regimes Accessible to the Ignitor Experiment and Relevant Theoretical Developments*

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Abstract. The Ignitor machine can access a significant variety of plasma regimes, thanks to its high magnetic fields and plasma currents and to the flexibility of its poloidal magnetic field system, with a characteristic "split central solenoid" that can produce both an extended limiter configuration and a divertor-like double X-point configuration. The machine design is guided by the criterion of maximizing the average poloidal field to ensure macroscopic plasma stability at ignition. The path to ignition conditions was simulated with the JETTO transport code for both L-mode and H-mode regimes. It is also shown that with a modest injection of ICRH power, ignition can be reached earlier than by ohmic heating alone, thus allowing the investigation of the relevant burning plasmas over times that exceed the current redistribution time. Near ignition, internal modes close to ideal marginal stability could be excited, according to linearized theory, under the most pessimistic conditions, but their development is shown to be strongly influenced by non linear effects, even at very low values of the mode amplitude. The BALDUR transport code was used to simulate the approach to ignition when reversed shear conditions with peaked density profiles are produced through appropriate current ramping. The importance of particle density profile control is confirmed, and the optimal auxiliary heating power to accelerate ignition is evaluated.

1. Ignitor Physics and Operation

Ignitor is the first magnetic confinement experiment proposed and designed to reach conditions where the onset and control of the “thermonuclear” instability associated with the initiation of self-sustained fusion burning can be investigated [1]. Ignitor indeed remains unique among the burning plasma experiments that have been proposed so far in having the capability to demonstrate ignition, that is, the condition when $K_f = P_\alpha/P_{Losses}=1$, where P_α is the power carried by the fusion α-particles and P_{Losses} is the rate of total energy loss from the plasma. The main characteristics of the machine that allow it to attain this objective are the high plasma current, poloidal field, and plasma densities that it can produce. The large values of B_T/R_0 ensures at high plasma densities with peak values $n_0 \simeq 10^{21}$ m^{-3} that are well within the known density limits for good plasma confinement.

Ignitor is designed to operate both in regimes where no pressure pedestal is formed at the edge of the plasma column (L-mode) and in regimes where a pedestal is present (H-mode). Both domains must be optimized for ignition in terms of all the necessary plasma characteristics: macroscopic stability, purity, thermal wall loading, etc. For instance, type I ELMy H-modes are not desirable in view of the large fraction of the thermal energy that can be unloaded on the surface near the X-points in a single event. On the other hand, given the modest improvement over the most pessimistic confinement scalings that suffices to reach ignition in Ignitor, type III ELMs or EDA H-modes are more attractive. Ignitor, like the Alcator C-Mod machine, will most likely access these regimes with $q_{95} > 3$. In the L-mode regimes, the density and current profile evolution has long been recognized to play a fundamental role in the possibility to access ignition [2,3]. The concept of an optimal value for the volume averaged density for ignition has long been known [4], and always confirmed in simulations of Ignitor [5]. With Ignitor's high currents it is also easy to generate reversed shear regions with potential enhanced confinement making use of current ramps that are compatible with the existing Ignitor design [6].

In the standard "extended limiter" configuration, Ignitor exploits the full potential of inductive heating, and ignition can be reached by ohmic heating alone. When the defining ignition condition $P_\alpha = P_{Loss}$ is reached, the ohmic heating power equals the rate of increase of the stored energy and is about half the alpha power ($P_\alpha \sim 20$ MW). Thus, at ignition the effective heating power is only equal to the alpha power.

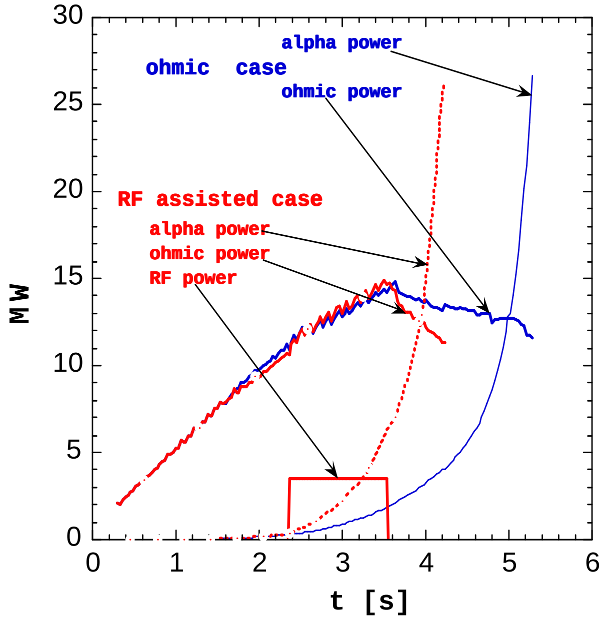

FIG. 1. Comparison of Ohmic and RF assisted ignition scenarios.

Ignition can be significantly accelerated by applying modest levels of ICRH (less than 5 MW, a fraction of the final fusion heating) during the current rise. In addition, ICRH provides a means to control the evolution of the current density profile [1,2]. An example of RF-assisted ignition scenario obtained by numerical simulations with the 1-1/2 D transport code JETTO is shown in Fig. 1 [7]. The most effective boost to the attainment of ignition is provided by more centrally localized power deposition profiles. These ignition scenarios are particularly important as they leave the 4 s flat top of the 13 T magnetic field pulse at $q_a \simeq 3.5$ fully available to study the evolution of the thermonuclear instability or to investigate the properties of the plasma in steady, slightly sub-ignited regimes. Furthermore, if a lower safety factor can be adopted, such as $q_a \simeq 3$, the magnetic field could be lowered to 11 T and the field flat top phase could be extended to 7 s. We note that in terms of the ratio of the pulse flat top time (≥ 4 s) to the current redistribution time, Ignitor does not rate below other proposed fusion burning experiments such as ITER and FIRE, which consider achieving plasmas well below ignition ($K_f \simeq 2/3$) with magnetic safety factors $q_{95} \simeq 3$.

Equilibrium configurations with double X-points in the proximity of the first wall have also been investigated. Up-down symmetric configurations can be produced by the poloidal field system as presently designed, with plasma currents $I_p \simeq 9$ MA and $B_T \simeq 13$ T, so that $q_\psi > 3$. They can be established near the end of the initial current rise, when the magnetic field, plasma current, and plasma density have almost reached their final values. The possibility of accessing the associated H-mode confinement regime has been investigated with the JETTO code. The heating power required to cross the L-H threshold [8], about 19 MW at the highest field and density, is within the limits of the total rate of plasma heating that can be produced. However, ignition in the X-point configuration involves higher values of β_p than in the extended limiter configuration.

The mean poloidal field $\bar{\bar{B}}_p = I_p /[5(ab)^{1/2}]$ has been maximized to prevent the onset of internal modes with significant amplitudes in the central part of the plasma column, where the peak plasma pressure exceeds 3 MPa at ignition for a density $n_0 \simeq 10^{21}$ m^{-3}. Given the high value of $\bar{\bar{B}}_p$ and low ignition temperatures (e.g. $T_{i0} \simeq$ 10.5 keV) , the number of orbits contained within the minor radius of Ignitor is higher than in other proposed experiments, making it, from this point of view, the "largest machine". Furthermore, an equivalent parameter $I_p A q_\psi / R_0 \propto \bar{\bar{B}}_p$ has recently been found to be an appropriate factor of merit, to gauge the quality of toroidal confinement machines, on the basis of purely engineering considerations [9]. Accordingly, Ignitor is the leading concept for the next generation of fusion burning experiments, since the innovative design that has been adopted allows it to achieve $\bar{\bar{B}}_p \simeq 3.45$ T with reasonable safety factors ($q_a \simeq 3.5$ for $B_T \simeq 13$T, $I_p \simeq 11$MA) in plasmas whose duration exceeds the important plasma time scales. These solutions include "bucking and wedging" of the toroidal magnet and its coupling to the central solenoid, a static and a dynamic horizontal press, the cooling of the copper coils to the optimal temperature of 30 K by helium gas, and a toroidal magnet cavity whose shape closely matches that of the last closed magnetic surface in the "extended limiter" configuration.

Two solutions have been studied to deal with the main issues related to plasma wall interactions in burning plasma experiments: (i) high plasma density limiter configurations with a highly radiative edge, which have produced plasmas with the degree of purity necessary to reach ignition conditions, and (ii) divertors, which have proven effective in low density, high edge temperature devices. Ignitor has chosen an "extended limiter" configuration, with the first wall entirely covered by molybdenum tiles and the plasma closely conforming to its surface. Magnetic configurations with double X-points are also considered maintaining the same first wall system. In this case, the last closed magnetic surface does not closely match the first wall profile, thus the local thermal wall loading and the out-of-plane force distribution in the toroidal magnet are significantly different. The choice of an "all-metal limiter" is considered best suited to the requirements of plasma-wall interaction control in high density plasmas, where most of the energy is released by radiation in the periphery by a small amount of intrinsic impurities (additional impurities can also be injected to enhance radiation). In high density regimes, the low temperature at the edge reduces physical sputtering from the wall and medium/ high Z impurities are effectively screened from the plasma core (screening is less effective for low Z impurities). Furthermore, particle recycling in the main chamber and cross-field diffusion in the scrape-off layer become predominant, thus reducing the effectiveness of a divertor as the dominant power and particle sink [10]. These observations reinforce the original decision not to insert a divertor chamber within the toroidal magnet cavity, which would also substantially degrade the obtainable plasma parameters. Instead, the design provides space on the low field side of the plasma cavity for alternative pumping concepts to be used in studying long duration burning discharges at lower fields, below ignition conditions. Poloidal detachment and MARFEs can develop at high density. It has been verified that the consequent localized radiative peak loads are still within acceptable limits for the first wall [11]. Nevertheless, these are undesirable events from the point of view of the main plasma characteristics, and means to avoid their occurrence in Ignitor, for example by appropriate tailoring of the density profile, are envisioned.

The Ignitor design incorporates three forms of protection against the onset of strong internal m = 1 modes driven by the plasma pressure gradient, which can cause large scale sawtooth oscillations [12]. Such oscillations could be particularly damaging since they affect the central plasma pressure and therefore the fusion reactivity. The three are:

i. the low values of β-poloidal for which ignition can be reached ($\beta_p \gtrsim 0.2$),

ii. the sufficiently high value of the edge magnetic safety factor $q_a \gtrsim 3.5$, to limit the volume of the region contained within the $q = 1$ surface, and

iii. the stabilizing conducting shell effect exerted by the 2.7 cm thick Inconel plasma chamber, which is protected from the plasma by a first wall of molybdenum tiles.

The resistive time constant of the chamber is about 1.5×10^{-2} s. The ideal MHD growth rates of the modes that can be excited under the worst assumptions for the local pressure profile and magnetic shear are about $\gamma_0 \simeq (v_A/R_0)\lambda_H$, with λ_H in the range 10^{-3} – 10^{-2}, with corresponding growth times in the range 2.2×10^{-5} to 2×10^{-4} s.

We have shown also that near the ideal MHD stability threshold for m =1 modes which may be approached by Ignitor under extreme conditions, the transition layer δ_1 for the relevant radial displacement function $\tilde{\xi}(r)$ is so small ($\delta_1 \sim \lambda_H r_1$, where $q(r=r_1)=1$) that nonlinear effects are shown to become important at very small values of the mode amplitude. Therefore we have developed numerical tools to identify the new effective threshold, building upon the numerical analysis [13] which has shown that the linear growth rate has a different dependence on the parameter $\beta_{p1} = \left(8\pi / B_{p1}^2\right)\int_0^{r_1} r\, dr\left[\, p(r) - \langle p \rangle_1 \right] / r_1^2$ than that obtained by an earlier analytic asymptotic analysis [14].

2. Approach to Ignition with Current Ramping

Peaked density profiles have long been recognized to be favorable for reaching ignition, both to enhance the confinement and to optimize the fusion power balance. Studies for IGNITOR [15] have confirmed that maintaining a peaked density profile for many particle confinement times and avoiding sawtooth crashes in the plasma's reacting core are major physics issues for reaching ignition. The improvement in confinement that has been observed with non-monotonic current profiles (in both neutral beam-heated and RF-heated plasmas) has opened new possibilities for low-temperature, low-power ignition in high-field, ohmically heated devices. Transport simulations [16] of DIII-D and JET with reversed shear show good agreement with the enhanced confinement data. Theoretical studies by means of the drift wave map and PIC simulations [17,18] explain the existence of transport barrier in a reversed shear profile.

Work carried out with the BALDUR transport code suggests that fast current ramping could provide a scheme that itself creates peaked density profiles, as a result of the formation of an internal transport barrier due to reversed magnetic shear [19]. The semi-empirical transport model JETTO, containing a mixed Bohm and gyro-Bohm scaling, has been used, as it has been benchmarked with experimental data from different machines. While the maximum rate of current ramping is limited by the design of the Ignitor machine and its connection to the power grid, the simulations suggest a physics path for reaching ignition by ohmic heating.

The reduction in turbulent transport across the reversed shear region, resulting in the formation of an internal transport barrier, is incorporated in the JETTO model by reducing the transport coefficients in the region where the magnetic shear is negative. In the simulation, the global design parameters of Ignitor are those given in [15]. The key procedure is a fast plasma current ramp combined with a gradual growth of the volume-averaged density. For a given current ramp rate there is an upper limit on the density ramp rate above which the desired density peaking and ignition will not occur. If density is increased too slowly, ignition will also be delayed or prevented. A staged current ramp with an appropriate rate of increase for the density results in central peaking of the density profile and ignition.

The density profile peaking is a consequence of the formation and dynamics of the internal transport barrier and the neutral particle physics that allows inward penetration of particles from the edge particle source. If the initial current ramp is sufficiently fast, the plasma current accumulates in the outer part of the plasma column. The reversed magnetic shear in the outer region is assumed to lead to the suppression of both particle and thermal transport, forming steep gradients in the density and temperature profiles. As the plasma heats, the reversed shear region and the transport barrier move inwards, causing central density peaking. Ignition, defined as the condition when the alpha-heating power balances the total thermal loss P_L, is reached a few seconds after the end of the current ramp, before sawteeth occur. If the current is ramped more slowly, a sawtooth oscillation begins earlier and may prevent ignition. Non-monotonic current density profiles generated during the current ramp may lead to MHD instabilities, such as resistive interchange and double tearing modes, which would lead to a faster current penetration and may prevent or destroy the barrier. On the other hand, if the reversed shear configuration could be sustained at least transiently, this would be sufficient for the successful ignition.

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[1] COPPI, B., NASSI, M., SUGIYAMA, L.E., Physica Scripta **45** (1992) 112.
[2] SUGIYAMA, L.E., and NASSI, M., Nucl. Fusion **32** (1992) 387.
[3] AIROLDI, A., and CENACCHI, G., Fusion Technology **25** (1994) 278.
[4] COPPI, B., and TANG, W.M., Phys. Fluids **31** (1988) 2683.
[5] AIROLDI, A., and CENACCHI, G., Plasma Phys. Control. Fusion **33** (1991) 91.
[6] SUGIYAMA, L.E., "Reversed Shear Ignition in a High Field Toroidal Experiment", Proc. E.P.S., Kiev (1996), MIT RLE Report PTP-95/3 (1995).
[7] AIROLDI. A., et al., Bull. Am. Phys. Soc. **46** (2001) 271.
[8] SNIPES, J.A., et al., Plasma Phys. Control. Fusion **42** (2000) A29.
[9] SCHULTZ, J.H., "Advanced Magnets and Implications for BPX", BPS Wrksp II, GA (San Diego, CA) May 2001, http://fusion.gat.com/bps2/presentations/plenary/.
[10] LABOMBARD, B., et al., Nucl. Fusion **40** (2000) 2041.
[11] PITCHER, C.S., Contract ENEA-PSE, Ref # 00/58/21/88 (2001).
[12] MANICKAM, J., "m=1 Mode: Ideal MHD Stability", Fusion Science Summer Study (Snowmass, CO), July 2002, http://web.gat.com/snowmass/working/mfe/physics/p3/ .
[13] SUGIYAMA, L.E., Phys. Plasmas **6** (1999) 3276.
[14] DETRAGIACHE, P., Plasma Phys. Control. Fus. **40** (1998) 1501.
[15] HORTON, W., PORCELLI, F., ZHU, P., AYDEMIR, A.Y., KISHIMOTO, Y., and TAJIMA, T., Nucl. Fusion **42** (2002) 169.
[16] ZHU, P., BATEMAN, G., KRITZ, A. H., and HORTON, W., Phys. Plasmas, **7** (2000) 2898.
[17] KWON, J.-M. , HORTON, W., ZHU, P., et al., Phys. of Plasmas, **7** (2000) 1169.
[18] KISHIMOTO, Y., KIM, Y.-J., HORTON, W., et al., Nucl. Fusion **40** (2000) 667.
[19] HU, B., ZHU, P., HORTON, W., PORCELLI, F., to appear in Phys. Plasmas (2002), (http://orion.ph.utexas.edu/~starpower).