Ignitor: Physics and Progress Towards Ignition

F. Bombarda[1], B. Coppi[2], A.Airoldi[3], G. Cenacchi[1], P. Detragiache[1],
and the Ignitor Project Group
[1] *ENEA UTS Fusione (Italy)*
[2] *Massachusetts Institute of Technology, Cambridge (MA)*
[3] *CNR – Istituto Fisica del Plasma, Milano (Italy)*

Received on 6 February, 2004; revised version received on 6 May, 2004

Thermonuclear ignition condition for deuterium-tritium plasmas can be achieved in compact, high magnetic field devices such as Ignitor. The main scientific goals, the underlying physics basis, and the most relevant engineering solutions of this experiment are described. Burning plasma conditions can be reached either with ohmic heating only or with small amount of auxiliary power in the form of ICRH waves, and this condition can be sustained for a time considerably longer than all the relevant plasma time scales. In the reference operating scenario, no transport barriers are present, and the resulting thermal loads on the plasma facing component are estimated to be rather modest, thanks to the high edge density and low edge temperature that ensure an effective intrinsic radiating mantle in elongated limiter configurations. Enhanced confinement regimes can also be obtained in configurations with double X-points near the first wall.

1 Introduction

Ignitor [1] is the first experiment that has been proposed and designed to achieve fusion ignition conditions in magnetically confined deuterium-tritium plasmas. Demonstration of ignition, the study of the physics of the ignition process, and the heating and control methods for a burning, magnetically confined plasma are the most pressing issues in present day research on nuclear fusion and they are specifically addressed by the Ignitor experiment.

The machine is the natural evolution of the line of high magnetic field, high plasma density experiments started by B. Coppi at MIT with the Alcator machines (Alto Campo Torus, in Latin), and at Frascati with the FT (Frascati Torus) machines. Ignitor is based on an axisymmetric confinement configuration designed to produce high plasma currents and current densities in order to reach the temperature and energy confinement necessary for ignition. This involves the adoption of an elongated cross section, a tight aspect ratio, high magnetic fields, and compact dimensions.

In this paper the main objectives of the Ignitor experiment are described, together with a summary of the principal engineering solutions that are adopted and an update on the ongoing activities. Finally, a brief discussion on relevant time and size scale is presented, which stresses the advantages, for the purpose of this experiment, of the high field solution.

2 The Ignition Goal

Ignition is defined as the condition when the power deposited by the charged fusion products into the plasma compensates for all the losses. The adopted strategy involves the use of compact, limiter configurations with high magnetic fields to reach ignition at low temperature, high density, and trigger the thermonuclear instability [2]. This possibility is the fundamental feature that differentiates Ignitor from all other presently proposed burning plasma experiments. Furthermore, heating methods and control strategies for ignition, burning and shutdown can all be established with this device in meaningful fusion burn regimes, on time scales sufficiently long relative to the plasma intrinsic characteristic times.

The machine parameters, listed in Table I, have been chosen in order to obtain a high peak plasma density ($n_0 \cong 10^{21}$ m^{-3}), a high mean poloidal magnetic field ($\bar{B}_p \cong 3.75$ T) with a correspondingly large toroidal plasma current $I_p \leq$ MA, and a low poloidal beta ($\beta_p = 2\mu_0 <p> / \bar{B}_p^2 \cong 0.2$ at ignition, where $<p>$ is the volume averaged plasma pressure).

The maximum plasma density that can be supported in an ohmically heated toroidal plasma has been observed to correlate roughly with the plasma current density whose maximum value is related to B_T/R_0. A configuration with major radius $R_0 \cong 1.3$ m and toroidal magnetic field $B_T \cong 13$ T should reliably sustain densities of 10^{21} m^{-3}. In fact, peak plasma densities of about $n_0 \cong 10^{21}$ m^{-3} have been obtained by the Alcator C machine [3] and values not far from this by the FTU machine [4], even though the current in these experiments is well below that attainable by the Ignitor device.

A high poloidal field can be sustained due to a combination of strong toroidal magnetic field and optimized plasma shape. Given the low values of β_p at which Ignitor can operate, a paramagnetic plasma current I_θ (up to 9 MA) flowing in the poloidal direction and increasing the toroidal magnetic field B_T at $R = R_0$ up to about 11%, can be produced at the same time as the toroidal current. An estimated bootstrap current $I_{BS} \geq 10\%$ of I_p at ignited conditions slightly reduces the required magnetic flux variation.

TABLE I. Machine parameters

Major radius R	1.32 m
Minor radii $a \times b$	0.47 × 0.86 m
Elongation κ	1.83
Triangularity δ	0.4
Plasma volume V	10 m^3
Plasma surface S	36 m^2
Pulse length	4+4 s
Plasma Current I_p	11 MA
Toroidal Field B_T	13 T
Poloidal Current I_θ	8 MA
Average Pol. Field $\langle B_p \rangle$	3.5 T
Edge Safety factor q_ψ	3.5
RF Heating P_{icrh}	<18 MW

TABLE II. Typical plasma parameters at ignition

Peak temperature T_{e0}, T_{i0}	11.5, 10.5 keV
Peak density n_{e0}	10^{21} m^{-3}
Peak α density $n_{\alpha 0}$	1.2×10^{18} m^{-3}
Total α power P_α	19.2 MW
Plasma stored energy W_{pl}	11.9 MJ
Ohmic power P_{OH} = dW/dt	10.5 MW
Total radiated power P_{rad}	6 MW
Poloidal and toroidal beta $\beta_{pol,}$, β	0.2, 1.2%
Edge and on-axis safety factor q_ψ, q_0	3.5, $\sim$ 1.1
Energy confinement time τ_E	0.62 s
α's slowing down time τ_{sd}	0.05 s
Effective charge Z_{eff}	1.2

Ignition is expected to be reached near the end of the current rise, taking full advantage of a strong rate of ohmic heating (Fig. 1). This is accomplished by programming the initial rise of the plasma current and density while gradually increasing the cross section of the plasma column. By the end of this relatively long (3 to 4 s) transient phase, the electric field is strongly inhomogeneous. It is low at the center of the plasma column, where it is consistent with relatively high values of the plasma temperature, and remains high at the edge of the plasma column. The burning phase starts when the temperature reaches about 5-6 keV, and should last for the whole flat top. The pulse duration is limited by the magnets heating, but should operation at a lower value of the safety factor prove to be feasible, then the pulse length can be extended considerably.

The α-particles produced by the fusion reactions experience a good confinement in the central part of the plasma column (a current $I_p \cong 3$ to 4 MA is sufficient to confine the orbits of the 3.5 MeV α-particles within the plasma column), and given the low temperature and high density, their slowing down time is much shorter than the energy confinement time ($\tau_E > 10\tau_{sd}$).

In a burning plasma a high degree of purity is needed to prevent dilution of the reacting nuclei and loss of internal energy from the plasma core by radiation. In practice, Z_{eff} should not be higher than about 1.6. Experiments performed so far have confirmed that Z_{eff} is a monotonically decreasing function of the plasma density. The high values of B_T and the low thermal loads on the first wall expected in Ignitor under low-temperature ignition conditions are also favorable to low values of Z_{eff}. The relatively high plasma edge density helps to confine impurities to the scrape-off layer, where the induced radiation contributes to distributing the thermal wall loading more uniformly on the first wall.

The approach to ignition in Ignitor was extensively simulated [2,5] by means of 1 1/2 D transport codes (TSC [6], BALDUR [7], JETTO [8]), using different transport models. The results shown in Fig. 1 are obtained by applying the Coppi-Mazzucato-Gruber model (as detailed in [5]) in the JETTO code. The optimal conditions under which confined plasmas can reach ignition, according to four different transport models, were identified [9] and summarized in [10].

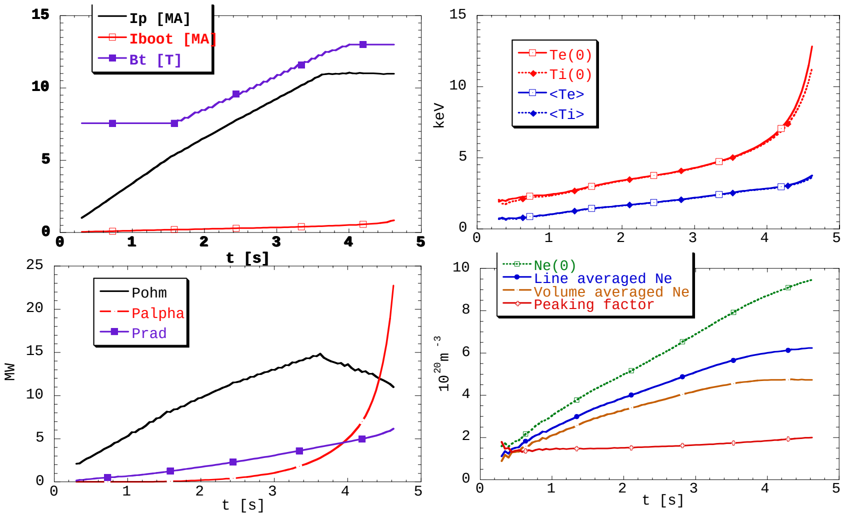

Figure 1. Time evolution of plasma current and toroidal field, plasma temperatures, density, and ohmic, alpha, and radiated powers for a reference ohmic discharge at 13 T and 11 MA simulated by the JETTO code [8] using the Coppi-Mazzucato-Gruber transport model.

The most accessible conditions for ignition involve relatively peaked density profiles. Peaked plasma density profiles can be maintained by external means such as a pellet injector, which is planned as an integral part of the Ignitor facility. In fact, peaked profiles are beneficial for fusion burning plasmas from several perspectives. In particular, they can provide a stability edge against the so-called η_i modes that enhance the ion thermal transport.

A characteristic feature is the *consistency* of the plasma pressure profile at ignition [9]. The word *consistency* means that, although the plasma evolution is determined by different expressions for the electron thermal diffusivity χ_e, at ignition the pressure profiles turns out to be nearly of a unique type.

The confinement regimes associated with peaked density profiles have been found experimentally to be better than the so-called L-regime, but do not fit the characteristics of the H-regime. Frequently considered global scalings for energy confinement time are based on experimental data that involve a large diversity of plasma regimes and conditions, many of which are not appropriate for extrapolation to fusion burn regimes. In fact, if the appropriate selection criteria are applied (i.e., $T_e \simeq T_i$, $Z_{eff} \lesssim 1.6$, thermalized plasmas, proximity to the density limit), a dramatic reduction in the number of data points and machines has to be considered. Clearly, this undermines the validity of statistical analyses, typically performed on a large number of parameters, to predict the confinement properties of meaningful burn experiments. We consider the combined database of well confined plasmas with n_0 above 10^{20} m^{-3} provided by the Alcator A, C and C-Mod machines, and FTU, to provide a solid and reliable foundation for the extrapolation to Ignitor.

High magnetic field and plasma density experiments have shown that extremely low thermal diffusivities can be produced in the central part of the plasma column. In particular, we refer to the historical experiments carried out by the Alcator C machine where confinement times slightly exceeding 50 msec were obtained with a plasma radius of 16 cm, peak plasma densities $\simeq 2 \times 10^{21}$ m^{-3}, $T_e \simeq T_i$, and $Z_{eff} \simeq 1$ [3]. The FTU machine obtained an improved confinement regime with an enhancement factor of about two following the injection of multiple pellets in ohmic plasmas [4], resulting in higher central densities and more peaked density profiles. The analysis of these discharges showed that the ion thermal conductivity was reduced to nearly neoclassical values, whereas the electron thermal conductivity was essentially suppressed in the region inside the $q = 2$ surface.

3 RF assisted regimes and burn control

While the Ignitor experiment is designed for a most effective exploitation of ohmic heating, a fair amount of auxiliary power in the form of ICRH waves is also planned, to provide an additional knob to turn on ignition, and to expand the range of accessible plasma regimes. The RF system will use up to six of the twelve large horizontal ports, and is being designed to operate in a frequency range between 70 and 120 MHz, to allow either H or ^{3}He minority heating in all the envisaged operating scenarios. According to the results reported in [11], the D(^{3}He) scheme is suitable for high field operation in DT plasmas. Absorption effects by the fusion α-particles have been considered and found to be negligible. The antenna design is being carried out by the Politecnico di Torino in collaboration with the Oak Ridge National Laboratories.

The achievement of ignition with ohmic heating only relies on the possibility of reaching a critical temperature (about 4 keV), at which the contribution of the α-particle heating compensate for a less effective ohmic heating in the central part of the plasma column as the temperature increases. In order to ensure this event and to provide a faster attainment of ignition, small amounts of ICRF heating (about 3 MW) can be injected during the current rise and turned off before the beginning of the flat top. Thus, ignition is again reached when only ohmic heating is present.

Recent simulations [12] performed with the JETTO code have explored the possibility of keeping the thermonuclear instability under control by means of an appropriate timing of the tritium pulse in combination with a RF pulse (Fig. 2). These evaluations are based on a Bohm-gyroBohm formulation [13] for the electron thermal transport with specific coefficients calibrated so that the energy confinement time is around the value predicted by the ITER97-L mode scaling [14]. The RF heating compensates for a poorer fuel mixture and, as a result, steady state conditions of a burning, sawtoothing plasma can be maintained over the current flat top with values of the ignition factor $K_f \equiv P_\alpha/P_L \cong 2/3$, corresponding to a fusion gain $Q \equiv P_{fus}/P_{in} \gtrsim 10$.

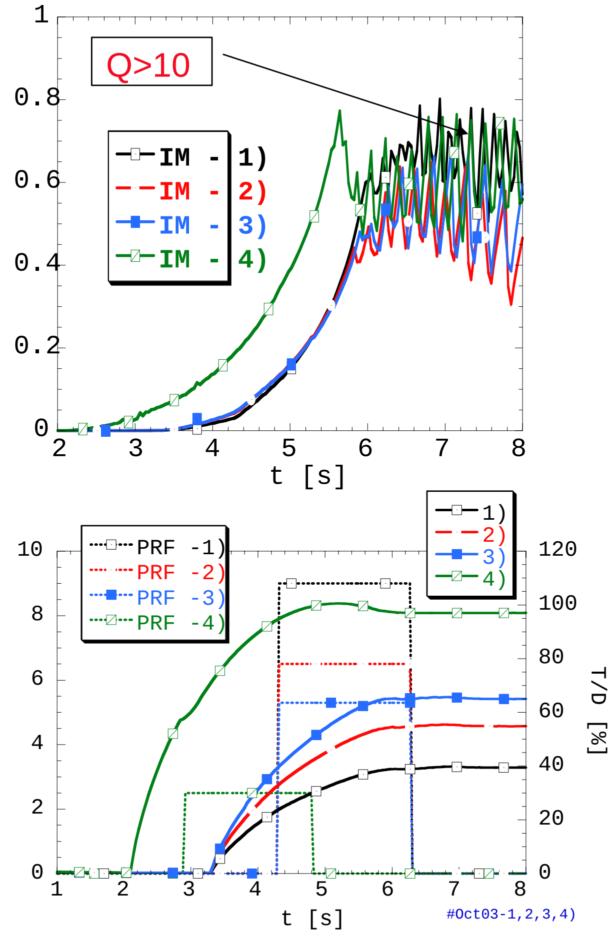

Figure 2. Time evolution of the ignition margin ($IM \equiv P_\alpha/P_{\mathrm{Loss}}$) in a 13 T, 11 MA discharge with separate injection of tritium and an additional ICRH heating pulse [12], simulated by the JETTO code using the Bohm-gyroBohm transport model [13].

The flexibility of the poloidal field system allows the formation of magnetic configurations with double X points, which should provide an easier access to regimes such as the so-called H-mode. The maximum current that can be driven in the plasma without reaching too low a value of the safety factor q_{95} is 9 MA at 13 T. The strike points in this case rest on the first wall, but the plasma is well detached everywhere else. This has proven to be a necessary condition for the attainment of the H-mode, for example on Alcator C-Mod. The estimated power required to enter into the H-mode (15 – 17 MW according to the scaling published in [15]) is still provided mostly by the combination of ohmic and fusion heating, and in smaller amounts by the RF system. It should be noticed that these regimes involve lower peak densities, as the density profile is expected to be considerably flatter, and the energy confinement time higher. On the other hand, the presence of a transport barrier usually includes an impurity accumulation, and this may prove excessive to reach actual ignition. The power load on the first wall is also expected to increase, but our preliminary estimates indicate that the widening of the flux lines around the strike points may be sufficient to keep the heat load on the Molybdenum tiles within acceptable levels [16].

4 Machine design and engineering

The machine design is characterized by a complete structural integration of its major components (toroidal field system, poloidal field system, central post, C-clamps and plasma chamber) (Fig. 3). A “split” central solenoid provides the flexibility to produce the expected sequence of plasma equilibrium configurations during the plasma current and pressure rise. The structural concept upon which the machine is based involves an optimized combination of “bucking” between the toroidal field coils and the central solenoid with its central post, and “wedging” between the inner legs of the toroidal field magnet coils, and between the C-clamps in the outboard region. The machine core, consisting of the copper TF coils, the major structural elements (C-clamps, central post, bracing rings) and the plasma chamber, is designed to withstand the forces produced within it with the aid of a radial electromagnetic press when necessary. The set of stainless steel C-clamps forms a complete shell, which surrounds the 24 TF coils. These coils are prestressed through the C-clamps by means of a permanent mechanical press system (two bracing rings) that creates a vertical pre-load on the inner legs of the TF coils. This permanent press is supplemented by an electromagnetic press that is activated only at the maximum magnet currents, to maintain as closely as possible a hydrostatic stress distribution in the TF coils in order to minimize the von Mises equivalent stresses. This ensures that the inner legs of the TF coils possess a sufficient degree of mechanical strength to withstand the electrodynamic stresses, while allowing enough deformation to cope with the thermal expansion that occurs during the plasma discharge. The entire machine core is enclosed by a cryostat. All components, with the exception of the vacuum vessel, are cooled before each plasma pulse by means of He gas, to an optimal temperature of 30 K, at which the ratio of the electrical resistivity to the specific heat of copper is minimum.

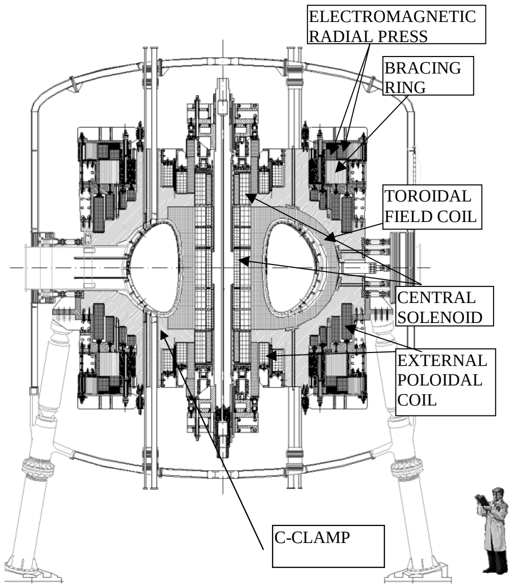

Figure 3. Cross-sectional view of the Ignitor machine.

An important aspect of the machine design is the absence of a separate divertor region. This choice was made on the basis of the observation that, at high density, impurities are effectively screened from the main plasma, the lower edge temperature causes less sputtering from the wall, and radiation, ionization and charge exchange are all important in spreading and reducing the energy of the particles impacting on the walls. Most of the plasma energy is lost by radiation by intrinsic impurities in the outer region of the plasma column. The resulting edge parameters are estimated to be $n_a = 2 - 3 \times 10^{20}$ m^{-3} and T_a = 50 – 60 eV. The plasma chamber is covered by Molybdenum tiles, acting as an extended limiter. The expected peak thermal power loads on the first wall in this configuration do not exceed 1.8 MW/m^2 [17].

Both high and low magnetic field experiments have shown that low thermal diffusivities can be produced in the central part of the plasma column as a result of peaked density profiles, such as those resulting from pellet injection. Therefore, to ensure an efficient refueling and provide density profile control, a pellet injector has always been considered as an integral part of the Ignitor machine design. The compact size of the machine makes injection from the inner wall impractical and, although the port configuration would allow it, it is unclear whether a vertical injection close to the magnetic axis will be beneficial, also considering the relatively low values of the plasma parameter β. A program to design, manufacture and test a prototype high speed ($\leq$ 4 km/s) pellet injector will be carried out by a joint collaboration between the Pellet Injector Group of ORNL and ENEA of Italy. The pellet speed will be sufficient to reach the core of the plasma column during the initial phase of the current rise, when profile control is more important. At a later time, it can be used to tailor the fuel composition and act as a fast burn control system.

Full size prototypes of all the major machine components have been manufactured. The present engineering activities are mostly devoted to the optimization of the electrical power supply system, the detailed design of the plasma chamber and first wall, cooling system, remote handling and other auxiliary systems. 3D immersive imaging techniques are used to assist the design and definition of the assembly procedures of the machine.

5 The ignitor path to fusion and conclusions

What contributions can the Ignitor experiment provide to the physics and technology development path of future fusion reactors? Ignitor is, first of all, a physics experiment. Reaching ignition condition would be a truly remarkable achievement in itself, but it is the collective behavior of a real burning plasma that needs to be explored and understood before the characteristics of a fusion reactor could be drawn. We need to go beyond the present (and past) experiments that do not operate in regimes with characteristics (ion and electron populations closely coupled, low impurity level, good confinement of fusion charged product, etc.) interesting for reactor operation.

Ignitor can sustain a burning plasma over a time longer than any of the physically relevant time scales. In particular, the very short α-slowing down time provides a good margin of stability relative to fast particle induced modes, as well as the low values of beta and of the plasma density relative to the other well known operational limits. Future reactors are more likely to choose these regimes rather than those where transport barriers bring the plasma at the boundaries of the stability limits and edge phenomena challenge the technical feasibility of plasma facing components. Furthermore, if the full complement of RF additional heating is provided, then significant amount of fusion power could be produced in D-^{3}He reactions, thus beginning the exploration of tritium-poor burn experiments.

Ignitor is also the “largest” presently proposed experiments, in that it contains the higher number of orbits of thermal nuclei, for the same value of the edge safety factor q_a, thanks to the high value of the poloidal field B_p and the relatively low temperature at ignition.

Development and testing of high field superconductors, advanced structural materials, tritium breeding, etc., will still need to be conducted in parallel, in appropriate devices, but this applies to all the presently proposed burning plasma experiment. The high field approach has the advantage of relying on well proven technology and physics basis, relatively short construction times, and contained cost. In other words, Ignitor represents at present our best opportunity to satisfy our “yearn to burn” (M. Rosenbluth, 2001).

References

[1] B. Coppi et al., “Critical Physics Issues for Ignition Experiments: Ignitor”, M.I.T. (RLE) Report PTP99/06, Cambridge

MA (1999) and references therein.

[2] B. Coppi, M. Nassi and L.E. Sugiyama, Physica Scripta **45,** 112 (1992).

[3] M. Greenwald, D. Gwinn, S. Milora, et al., Phys. Rev. Lett. **53,** 352 (1984).

[4] Giovannozzi, C. Gormezano, Nucl. Fusion **41**, 1613 (2001).

[5] A. Airoldi and G. Cenacchi, Nucl. Fusion **37**, 117 (1997).

[6] S.C. Jardin, N. Pomphrey and J. Delucia, J. Computational Physics **66**, 481 (1986).

[7] C.E. Singer, et al., Computer Physics Commentaries **49**, 275 (1989).

[8] A. Airoldi and G. Cenacchi, Fusion Technology **25**, 278 (1994).

[9] A. Airoldi, G. Cenacchi, Nucl. Fusion **41**, 687 (2001).

[10] B. Coppi, A. Airoldi, F. Bombarda, et al., Nucl. Fusion **41**, 1253 (2001).

[11] M. Riccitelli, G. Vecchi, R. Maggiora, et al., Fusion Eng. & Design **45**, 1 (1999).

[12] A. Airoldi and G. Cenacchi, CNR-IFP Report FP 03/8 (2003), submitted for publication .

[13] G. Vlad, M. Marinucci, F. Romanelli, et al., Nucl. Fusion **38**, 557 (1998).

[14] S.M. Kaye, M. Greenwald, U. Stroth, et al, Nucl. Fusion **37**,1303 (1997).

[15] J.A. Snipes, et al., Plasma Phys. Control. Fusion **42**, A299 (2000).

[16] C. Ferro, A. Airoldi, F. Bombarda, et al., *Proceed. of the 28th* Conf. on Control. Fusion and Plasma Phys, Madeira, Portugal (2001), paper P5.107.

[17] R. Zanino and C. Ferro, Contrib. to Plasma Phys. **36**, 260 (1996).