Novel Developments for Fusion Research and the Ignitor Approach*

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Introduction

The optimal path to ignition, in the relevant plasma parameter space, that can be followed by experiments using existing technologies and knowledge of plasma physics, relies on the high plasma density regimes (with peak values $n_0 \cong 10^{21}$ m^{-3}) discovered first by the line of high magnetic field experiments [1]. These regimes have both outstanding confinement characteristics and high degree of purity and are at the basis of the Ignitor design. Their value has been rediscovered recently following the experiments by the helical LHD facility that has systematically produced plasmas with $n_0 \cong 10^{21}$ m^{-3}. Consequently, conceptual power producing reactors named HDR (Helical Demo Reactor) and ARIES-CS (Conceptual Stellarator), have been envisioned by the LHD (Japan) and the NCSX (Princeton) teams that would operate with plasma parameters close to those envisioned for Ignitor when reaching ignition (see Table I). While the helical solution for a power reactor can solve the problem of the current drive for fusion burning plasmas that is connected to the tokamak approach, near term realistic experiments to investigate ignition regimes are, in fact, possible only by the Ignitor approach. In fact, the main purpose of Ignitor is that of establishing the "reactor physics" in regimes close to ignition, where the "thermonuclear instability" can set in with all its associated non linear effects. The driving factor for the machine design (R_0≅1.32 m, $a\times b$≅0.47×0.83 m^2, triangularity δ≅0.4) is the poloidal field pressure $[B_p^2/(2\mu_0)]$ that can contain, under macroscopically stable conditions, the peak plasma pressures (p_0≅3–3.5 MPa) needed for ignition. The maximum magnetic field on axis, according to the machine design and excluding the paramagnetic current contribution, is $\lesssim$ 13 T. When the "extended

TABLE I: PLASMA PARAMETERS WHEN OHMIC IGNITION IS REACHED (JETTO CODE)

Toroidal Plasma Current I_p	11 MA
Toroidal Field B_T	13 T
Central Electron Temperature T_{e0}	11.5 keV
Central Ion Temperature T_{i0}	10.5 keV
Central Electron Density n_{e0}	9.5×10^{20} m^{-3}
Central Plasma Pressure p_0	3.3 MPa
Alpha Density Parameter n_α*	1.2×10^{18} m^{-3}
Average Alpha Density $\langle n_\alpha \rangle$	1.1×10^{17} m^{-3}
Fusion Alpha Power P_α	19.2 MW
Plasma Stored Energy W	11.9 MJ
Ohmic Power P_{OH}	11.2 MW
ICRF Power P_{ICRH}	0
Bremsstrahlung Power Loss P_{brem}	3.9 MW
Poloidal Beta $\langle \beta_p \rangle$	0.20
Toroidal Beta $\langle \beta_T \rangle$	1.2 %
Central "safety factor" q_0	≅ 1.1
Edge safety factor $q_\psi = q_\psi(a)$	3.5
Bootstrap Current I_{bs}	0.86 MA
oloidal Plasma Current	≅ 8.4 MA
Energy Replacement Time τ_E	0.62 sec
Alpha Slowing Down Time $\tau_{\alpha,sd}$	0.05 sec
Average Effective Charge $\langle Z_{eff} \rangle$	1.2

first wall" configuration is adopted, the plasma current can reach 11 MA, with a magnetic safety factor $q_a \cong 3.5$.

Double X-point Configurations

In order to investigate H-regimes under fusion burning conditions and close to ignition, a series of double X-point configurations have been analyzed and a pair of optimal configurations has been identified. One of this adopts the highest toroidal field on axis ($B_T \cong$ 13 T) and a toroidal current of 9 MA when the X-points lay on the outer surface of the plasma chamber but still relatively close to the edge of the plasma column. The relevant magnetic safety factors are in the range $3.45 \leq q_{95} \leq 4$. Transport analyses using the JETTO code have been carried out. The stability consistency of the current density evolution for the required magnetic configurations, and the possibility of accessing the high confinement (H-mode) regime have been verified. The H-mode threshold power has been estimated on the basis of the most recent multi-machines scalings and found to be consistent with the available total heating power that includes the Ion Cyclotron Frequency, the Ohmic and the α-particle heating. For the last numerical simulations about 2 MW of ICRH power absorbed by the plasma have been considered. The H-regime is modeled by a global reduction of the thermal transport coefficient used for the L-regime. When no sawtooth activity is included in the simulation, ignition conditions and plasma parameters that are similar to those expected for the 11 MA scenarios with the extended first wall configuration are attained. A quasi-stationary condition can be obtained when a mechanism for the re-distribution of temperature/pressure profiles, such as sawteeth, is adopted.

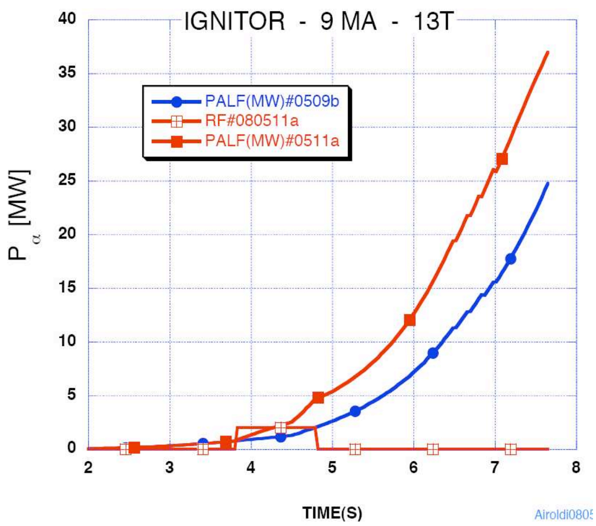

Fig.1 H-mode ignition with and without RF heating, in the case with no sawtooth activity.

Intermediate Temperature Superconducting Coils

The adoption of normal superconductors for the external coils of Ignitor that operate at relatively low magnetic fields has been considered in the past but not pursued as it would have required a separate liquid-He cryogenic system. The cooling system chosen for the optimal operation of the high field coils for which Copper is the best option, uses gas-He at 30 K. Recently a new superconducting material, MgB_2, has been developed that can operate with the same kind of cryogenic system adopted in the Ignitor design and magnetic field values (4-5 T) that are consistent with those of the largest, vertical field coils having a diameter of about 5 m. Another attractive feature of MgB_2 is that it lends itself to be developed for magnets capable of reaching high fields and it opens new perspectives for the design of new kinds of fusion burning devices. Therefore a collaboration has been undertaken with Columbus of Genoa for the design and construction of the (large) vertical field coils, given the expertise that the group has acquired in the construction of MgB_2 magnets with considerable dimensions as well as of normal superconducting magnets such as those for Tore Supra. At the same time a broader collaboration with material science laboratories (including Edison, INFM, Frascati and Cambridge University) to pursue further fusion relevant developments is being initiated.

Fast Pellet Injector and Advanced Diagnostics Systems

The process of achieving ignition conditions the plasma density rise requires to be properly controlled, with particular reference to the ideal ignition condition that for reasonable density and temperature profiles corresponds to peak temperatures $T_{e0} \cong 6$ keV. For this reason, a pellet injector program has always been included in the Ignitor design, for the purpose of controlling both the central density and the density profile evolution. ENEA-Frascati and Oak Ridge National Laboratory are collaborating on the development of a four barrel, two-stage pellet injector for the Ignitor experiment. The pellets will have to reach velocities up to 4 km/s, in order to penetrate near to the center of the plasma column when injected from the low field side at the temperatures expected for ignition. The injector features innovative concepts regarding the optimal shaping of the propellant pressure pulse to improve pellet acceleration, and the use of fast closing valves to drastically reduce the expansion volumes of the propellant-gas removal system. Final assembly of the two subsystems built by ENEA and ORNL respectively is under way in Oak Ridge, where a series of tests, including the formation and sequential launch of pellets of different sizes at speeds up to about 2 km/s, have been carried out successfully very recently [2].

The Ignitor program includes a considerable effort in the development of new diagnostics and essential auxiliary systems suitable for the thermonuclear plasmas that the machine is expected to produce. For example, an advanced neutron spectrometer employing a detector proposed by H. Enge at M.I.T. was initially designed for Ignitor and later constructed and operated for the JET facility. Special attention has been devoted to the development of specific diagnostic systems to be integrated with the control system for the plasma equilibrium configuration. In particular, prototype coils of the electromagnetic diagnostics have been manufactured, in collaboration with Università di Lecce and SALENTEC of Italy, by adopting innovative methods to improve the ceramic insulator resilience to neutron and gamma radiation. An alternative method to monitor the plasma position and shape, based on the diffraction and detection of the soft X-ray radiation emitted at the plasma edge, is under study to provide the necessary information even at the most advanced parameters that the Ignitor experiment can achieve [3].

Fig. 2 A first layer of insulated Ni wire is wound around an alumina core, an insulation layer of MgO is applied. After a second layer of wire is wound, the casing is closed and sealed.

Completion of the Detailed Machine Core Design, Follow-ups, and Siting

The detailed design of the machine has been completed. This includes the toroidal and poloidal magnet systems, the central solenoid, the plasma chamber, the first wall system, the remote handling system, and all the structural support elements (C-clamps, central post, etc.) of the machine. The emphasis given to the operation with a double X-point configuration has motivated the start of a new structural analysis of the toroidal magnet in which the out-of-plane forces are increased relative to the case where the “extended first wall” configuration is adopted. At the same time preparations are being made for the construction of the key components of the ICRH system that are housed inside the dedicated horizontal access port and the plasma chamber.

The activities concerning the installation of Ignitor at the Caorso site have included the preliminary redesign of the “cold machine shop” building in order to fit the core of Ignitor in it. The results of this analysis that aims at minimizing the relevant costs are positive.

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