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Relevant Advances of the Ignitor Program*

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1. Introduction

The main purpose of the Ignitor experiment [1] is to establish the "plasma reactor physics" in regimes close to ignition, as required for net energy producing reactors, where the "thermonuclear instability" can set in with all its associated non-linear effects. The driving parameter of the machine design ($R_0 \cong 1.32$ m, $a \times b \cong 0.47 \times 0.83$ m^2, triangularity $\delta \cong 0.4$) is the poloidal field pressure [$\overline{B}_p^{\,2}/(2\mu_0)$] that can contain, under macroscopically stable conditions, the peak plasma pressure $p_0 \cong 3 - 3.5$ MPa needed for ignition with central densities close to 10^{21} m^{-3}. The maximum design magnetic field on axis, excluding the paramagnetic contribution, is 13 T, and the plasma current $I_p \lesssim 11$ MA, with a magnetic safety factor $q_\psi \cong 3.5$. That reactor relevant plasma regimes require $Q > 50$ is well understood by now [2]. The only appropriate solution at this time to reach this objective is the adoption of normal-conducting magnets. Furthermore, experiments without a divertor chamber as Ignitor is, can sustain, for equal overall sizes and magnetic field values, higher currents and therefore achieve better confinement parameter [2]. The broader range of accessible plasma regimes, which include extended limiter and double-null configurations, is presented in the context of a "science first" approach to the development of a fusion energy program. In fact, since the process of attaining ignition has been investigated extensively [1], the most recent efforts have been devoted to identify the conditions where the thermonuclear instability is barely prevented over the entire length of the current pulse, to define the parameter space that can be covered in H regimes, and to simulate the plasma regimes that can be produced at lower field and currents than the design values. While tritium is the necessary step forward of any advanced fusion facility, Ignitor can provide novel and important results even when limited to operate with H, D, and He plasmas in the early phase of its experimental life.

2. Steady State Operation, H-mode Regime, and Reduced Parameters Regimes

In addition to the reference parameters for which Ignitor is designed in order to reach ignition conditions, we have investigated nearly stationary, slightly sub-ignited regimes where the thermonuclear instability is not allowed to develop and the relevant plasma parameters are maintained by a modest amount of ICRH injected heating [3]. Moreover, the possibility for Ignitor to access the H-mode regime has been re-analyzed in view of the latest, more favorable, scaling laws [4] of the power threshold, for configurations with double X-points. Adopting $B_T \cong 13$ T and $I_p \cong 9$ MA (that is compatible with reasonable safety factors) ignition can be achieved as the relevant power threshold is overcome by the combined contributions of Ohmic, α-particle and ICRH heating. The operating space corresponding to $Q \cong 10$ is found to be relatively broad, even considering the pessimistic case, in terms of maximum average reactivity, of rather flat density profiles. Moreover, considering experimental results such as those from JET [5] indicating that relatively peaked density profiles (e.g. $n_0/\langle n \rangle \cong 1.5$) can be obtained in the H-regime, values of Q considerably larger than 10 can be attained. Note that the adoption of recent scalings [6] with a weak dependence on β does not change the overall operating space significantly in the case of Ignitor.

Long pulse regimes at reduced parameters are considered for "preparatory" experiments and are directed at surpassing the (significant) ideal ignition condition at high plasma densities where α-particle heating compensates bremsstrahlung radiation emission. Two scenarios with magnetic fields up to 9 T and appropriate levels of injected ICRF heating were investigated by the JETTO code, which is capable of taking into account self-consistently the free-boundary plasma equilibrium evolution. The first is an "extended first wall" (no X-point) configuration with plasma currents up to 7 MA; the second involves double X-point configurations with plasma currents up to 6 MA. By decreasing the peak density below the optimal value for ignition, and maintaining the plasma temperature by modest amounts of ICRH heating (below 5 MW) during the rise of the plasma current, steady state conditions are attained in the presence of sawtooth oscillations. Peak temperatures around the ideal ignition temperature (6 keV $\lesssim T_{e0} \cong T_{i0} \lesssim$ 8 keV), at which the plasma density can be increased without encountering a bremsstrahlung barrier, and a significant amount of α-particles are produced.

The appropriate application of ICRH was studied in order to identify the power deposition profiles to be used in the transport analysis. In particular, a parametric study of the power deposition profiles as function of the minority concentration, minority species, frequency band for both configurations, has been carried out by using a full wave code in plane and toroidal geometries. An optimal frequency band is found in the range 85-95 MHz with a delivered power of 8 MW (extended wall configuration) and 5 MW (X-point). The results show that the power is essentially absorbed by the minority and redistributed by collisions to the main ion species of the plasma column.

Burning plasma conditions in Ignitor correspond to low values of the collisionality parameter ν^*, for which relatively peaked density profiles are expected to be beneficial for several reasons, in particular as a stability edge against the so-called ITG modes that enhance ion thermal energy transport. In order to control the density profile during the important current ramp phase, a high speed ($\lesssim$ 4 km/s), multiple barrel pellet injector is under construction in collaboration between ENEA of Italy and Oak Ridge National Laboratory in the US. Our simulations show that good penetration can be achieved for low field side injection even at temperatures close to those at which ignition is expected to take place [7].

3. Design Progress, Tritium System, Plasma Control, Site

The design of the entire Ignitor machine has been completed (Fig. 1). A Finite Element ANSYS model was used to analyze the non-linear mechanical behavior of the entire (machine) structure. The relevant calculations lead to find stresses that remain within the allowable limits at the relevant operating temperatures [8]. Recent detail design activities include those of the in-vessel Remote Handling System, based on the "two port concept" with two operating booms. Moreover, the analysis of the tritium system has been carried out with the aim to describe the equipments and the operations needed for supplying the required deuterium-tritium mixtures and recovering the plasma exhaust [9]. The applicability of a new diagnostic system [10] for the detection of trace amounts of helium isotopes in a hydrogen isotope atmosphere ($^4He/D_2 \sim 2.5\times10^{-7}$) is under assessment. The control of the plasma position and shape is a crucial issue in Ignitor as in every elongated toroidal experiment. The vertical position control strategy has been optimized and the requirements for the plasma cross section

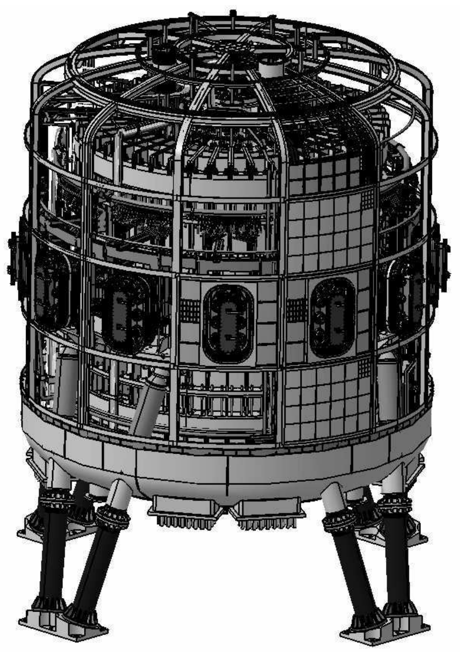

Fig. 1 – The Ignitor machine

shape control have been studied. The development is underway [11] of diagnostics systems directly connected with the control issue, that are based on the expectation of failure of key electro-magnetic diagnostics. A complete analysis of the sequence of equilibria corresponding to the start up and the rise of the plasma current up to its maximum value (11 MA) has been carried out. The main issues concerning this phase have been studied and resolved. Relevant complete simulations by the JETTO transport code have been carried out.

Finally, an in-depth analysis of the connection at Caorso, a former nuclear power site with suitable facilities, of the Ignitor power supply to the European electrical grid was carried out by the appropriate government authority (GRTN). This has shown that the power requirements (max active and reactive power, max active power negative/positive steps) are consistent with the characteristics of the combined two terminals of the 400 kV grid at the site.

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