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The High Density Path to Fusion*

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Introduction

The path to ignition chosen for the Ignitor program [1] is based on the outstanding confinement and purity properties of high density plasma regimes. Typically these correspond to peak densities $n_0 \cong 0.7 - 1 \times 10^{21}$ m^{-3} and were discovered and investigated originally by axisymmetric high magnetic field machines. When needed, relevant experiments have been aided by both single and repeated injection of pellets in order to attain peaked density profiles. As is well known, the excitation of modes producing anomalous ion thermal energy transport can be hindered by lowering the temperature gradient relative to the density gradient (i.e. the parameter $\eta_i = d\,(\ln T_i)/d\,(\ln n_i)$).

The importance of these regimes has been rediscovered recently following the experiments by the helical LHD facility [2], that has systematically produced plasmas with $n_0 \cong 10^{21}$ m^{-3} using a multiple pellet injection technique similar to that included in the Ignitor design, showing that the high magnetic field is not a necessary requirement at the low temperatures that have been reached. Moreover, if the confinement characteristics of these regimes can be maintained at considerably higher temperatures than those obtained until now, a reactor capable of reaching ignition and maintaining it over long times becomes conceivable. In particular, conceptual power producing reactors named HDR (Helical Demo Reactor) [3] and ARIES-CS (Conceptual Stellarator) [4], have been envisioned by the LHD (Japan) and the NCSX (Princeton) teams. These reactors would operate with plasma parameters close to those of Ignitor at ignition. While the stellarator solution for a power reactor avoids the problem of the plasma current drive, near term viable experiments to investigate ignition regimes are possible only by the Ignitor approach.

We observe that Ignitor was proposed originally as a physics experiment and a possible material testing reactor. However, ideas have been examined to use sets of high field reactors, based on the physics of Ignitor and on the development of new materials, as possible power stations. We note also that high field experiments to reach ignition with tritium-poor plasmas, based on the physics and technologies developed for Ignitor have been investigated and found to be feasible. In this context, detailed analyses were carried out for the "Candor" concept [5], an experimental device capable of investigating D-He^3 burning plasmas that needs to be updated in the light of more recent results. Ignitor itself could produce a

measurable amount of fusion power from D-He^3 reactions if more additional heating power became available. A D-T burner, called Columbus [6], using the same technological solution as Ignitor and having the same poloidal field but slightly larger dimensions has been proposed as a parallel effort to Ignitor in the US.

The main purpose of the Ignitor experiment is that of establishing the "reactor physics" (i.e. the physics of power producing reactors) in regimes close to ignition, where the "thermonuclear instability" can set in with all its associated non linear effects, in regimes dominated by self-sustaining internal α-heating and, at the same time, sufficiently far from other, well known, operational limits (density and β limits, for example). The experimental achievement of these conditions over significant times (in Ignitor $t_{pulse} >> \tau_E >> \tau_{sd}$) will provide the much needed proof-of-principle that fusion reactors capable of producing net power can indeed be designed. The driving factor for the machine design ($R_0 \cong 1.32$ m, $a \times b \cong 0.47 \times 0.86$ m^2, triangularity $\delta \cong 0.4$) is the poloidal field pressure $[B_p^2/(2\mu_0)]$ that can contain, under macroscopically stable conditions, the peak plasma pressures ($p_0 \cong 3$–3.5 MPa) corresponding to ignition. The maximum magnetic field on axis, excluding the paramagnetic contribution, is $B_T \lesssim 13$ T and, when the "extended first wall" configuration is adopted, the plasma current can reach 11 MA, with a magnetic safety factor $q_a \cong 3.5$. The Ignitor strategy to reach ignition conditions (where the ratio of the α-heating power to the power lost by the plasma is $K_f \cong 1$) relies on the optimal exploitation of Ohmic heating during the plasma current ramp phase with the possible assistance of modest amounts of RF auxiliary power.

In the approach to ignition conditions, various types of instabilities can be expected, ranging from internal modes to micro- and meso-scale modes (i.e., modes involving magnetic reconnection in the presence of a high energy particle population [7,8]. While the plasma parameters for the reference ignition scenario were chosen specifically to avoid unstable macroscopic modes, the wide operational range of Ignitor allows it to cover the plasma parameters at which different types of modes can be excited, providing a sure way to advance toward a power producing fusion reactor. Dealing with D-T burning plasmas is in fact the sole possibility to explore the self-organization processes and stability issues associated with α-particles.

Double X-point Configurations

The flexibility of the Poloidal Field Coil System (PFC) in Ignitor allows to establish magnetic configurations with two X-points. A pair of configurations has been identified in order to investigate high confinement regimes under fusion burn conditions and close to

ignition, at the highest toroidal field on axis ($B_T \cong 13$ T) and plasma currents of 9 or 10 MA depending on the position of the X-points relative to the surface of the plasma chamber ($3.45 \leq q_{95} \leq 4$).

Thermal and structural analyses for these configurations show that the stresses are within the allowable values: the more demanding configuration is essentially compensated by the lower value of the currents in the PFC's. The consistency of the current density evolution for the required magnetic configurations with their macroscopic stability, and the possibility of accessing the H-mode regime have been verified using the JETTO transport code for the 9 MA scenario [9]. The H-mode threshold power was found to be consistent with the available total heating power that includes the Ion Cyclotron Frequency, the Ohmic and the α-particle heating [10]. About 2 MW of ICRH power absorbed by the plasma have been found to be adequate (Fig. 1). When no strong 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 process for the re-distribution of temperature/pressure profiles, such as sawteeth, is included in the analysis.

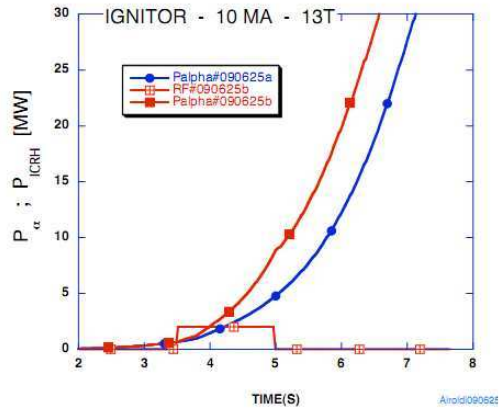

FIG.1 H-mode ignition with and without RF heating, in the absence of sawtooth activity.

The performance of Ignitor in the H regime has been analyzed also using a 0-D power balance code, assuming the energy confinement time to scale as IPB98(y,2) and adopting different scaling expressions for P_{LH}, the power threshold required to access the H regime. The P_{LH}-scaling affects the operating range of Ignitor significantly. Recently proposed scalings [10] lead to more attractive regimes, as the required power may then be reduced by at least 30%. For moderately peaked pressure profiles ($p_0/\langle p\rangle = 2.9$) and rather broad density profiles ($n_0/\langle n\rangle = 1.25$), the operating space for a fusion gain parameter Q=10 is relatively ample. Improved performance ($Q > 50$) is possible when more peaked density profiles are considered, with peaking factors $n_0/\langle n\rangle = 1.60$ in agreement with that resulting from the scaling proposed in Ref. [11].

ICRF Modeling, Antenna Prototype Development and Advanced Diagnostics

In the Ignitor experiment, the Ion Cyclotron Resonant Heating (ICRH) is planned to be

used as a tool to control the plasma temperature, in particular to accelerate the achievement of ignition that may be delayed in the presence of an unbalanced fraction of tritium and deuterium, different spatial profiles, or a higher content of impurities and to facilitate the H-mode transition in the "double X-point" plasma configuration. Another purpose concerns the possibility of controlling the thermonuclear instability that is expected to develop upon reaching ignition conditions. In this case the fusion power tends to diverge and to reach values that may be unsustainable, and ICRH and fuelling rates can be used to keep the plasma in slightly sub-ignited conditions.

A modular configuration of the ICRH system is envisioned, delivering 6 MW at 115 MHz and 12 MW at 80 MHz into the plasma, through four 4-strap antennas. A detailed design of the ICRH antenna has been carried out, including the Faraday shield, the current straps, the vacuum transmission lines and the vacuum feed-through. The mechanical assembly of the relevant components is fully detailed and manufacturing of a full-size prototype is underway.

The Ignitor contribution to fusion research extends to the development of fast fueling techniques (the Ignitor Pellet Injector [12] is designed to reach 4 km/s) and advanced diagnostics. Thus, R&D activities have been undertaken in the area of mineral insulated conductors and gas detectors with higher radiation resilience, in collaboration with INFN and NFRI of Korea. We are working in particular on fast detectors, based on the GEM's concept developed at CERN, for plasma position control and high resolution X-ray spectroscopy. The distinct advantage of GEM gas detectors over solid state ones is the relative transparency to gamma and neutron background, while at the same time providing high counting rates and good energy resolution. A parallel application of GEM detectors for the measurements of fast neutrons is being pursued at Frascati by another group [13], which demonstrates the great versatility of this new type of detectors.

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