Relevant Developments for the Ignitor Program and Burning Plasma Regimes of Special Interest*

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The optimal path to ignition, in the relevant plasma parameter space, that can be followed by experiments based on existing technologies and knowledge of plasma physics is based on the high plasma density regimes (with peak values $n_0 \cong 10^{21}$ m^{-3}) discovered by the high magnetic field experiments. These regimes have both outstanding confinement characteristics and degree of purity. The value of the high density, that is at the basis of the Ignitor design, has been rediscovered recently following the experiments by the helical LHD facility that have 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 the plasma parameters close to those of Ignitor when reaching ignition. While the stellarator solution for a power reactor can solve the problem of the current drive for fusion burning plasmas that afflicts the tokamak approach, near term realistic experiments to investigate ignition regimes are, in fact, possible only by the Ignitor approach. Another significant development of the Ignitor approach is the adoption of recently developed superconducting material (magnesium diboride) for the largest poloidal field coils, producing the necessary vertical field component (4 T), that operate at 15 K and, like all other magnets of Ignitor, is cooled by He gas. The properties of this material make it possible to envision its future adoption for other important coils producing higher magnetic fields and open new options in the design of novel experimental devices. A relevant R&D effort in this direction is being undertaken. In fact this step is one of the results of interactions between the Ignitor program and the effort initiated at Cambridge University for the analysis of compact devices capable of offering near term perspectives in fusion research and the consideration of novel materials.

Clearly, the main purpose of the Ignitor experiment 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 ($R_0 \cong 1.32$ m, $a \times b \cong 0.47 \times 0.83$ m^2, triangularity $\delta \cong 0.4$) is the poloidal field pressure $[B_p^2/(2\mu_0)]$ 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 $\lesssim 13$ T and, when the "extended first wall" configuration is adopted, the plasma current can reach 11 MA, with a magnetic safety factor $q_a \cong 3.5$.

In view of extending the operation of Ignitor to H-regimes where ignition conditions can be attained, a series of double X-point configurations has been identified. These adopt the maximum toroidal fields on axis and a toroidal current of 9 MA when the X-points lay on the first wall or 10 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 $3.45 < q_{95} < 4$.

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 were verified. The H-mode threshold power has been estimated on the basis of the most recent multi-machines scalings and it was found to be consistent with the available Ion Cyclotron Radio frequency auxiliary heating (ICRH) combined with the Ohmic and α-particle heating powers. For these numerical simulations about 5 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. Ignition conditions and plasma parameters that are similar to those expected for the 11 MA scenarios with the extended first wall configuration can be attained. As a complement to the transport analyses, the physics of the ICRH was analyzed for all the operating scenarios of interest. The power deposition profiles on electrons and ions, to be used as input data for the transport analysis, are obtained by using a full wave code in toroidal geometry. In particular, these calculations show that a small fraction of ^{3}He (1-2%) improves the wave absorption on ions near the center of the plasma column, while a substantial fraction of the coupled power is damped on the electrons over a broad radial interval, owing to the $n_{||}$ spectrum radiated by the antenna. The conclusion is that the characteristics of the ICRH system design provide a significant flexibility in order to control the plasma temperature and to stimulate the transition to the H-regime with modest amounts of ICRH power (< 8 MW).

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 on the JET facility in England. 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 also at the highest parameters that the Ignitor experiment can achieve.

The ENEA-Frascati and Oak Ridge National Laboratory collaboration for the development of a four barrel, two-stage pellet injector for the Ignitor experiment, an essential tool to control the density profile evolution, has advanced considerably. The pellets will have to reach velocities up to 4 km/s, in order to penetrate close to the center of the plasma column when injected from the low field side at the temperatures expected at ignition. At ORNL, deuterium pellets, from 2.1 to 4.6 mm in diameter, were launched at low speed. ORNL developed, specifically for this application, the light gate and microwave cavity mass detector diagnostics that provide in-flight measurements of the pellet mass and speed, together with its picture. The ENEA two-stage pneumatic propelling system is being shipped to ORNL. We ran simulations to estimate the penetration depth of pellets from this system into the LHD as the planned substantial increase of the available heating power may require a higher pellet speeds than presently available.

The 3-D nonlinear structural analysis that was carried out of the Central Post, the Central Solenoid and Poloidal Field Coil systems, of the Plasma Chamber and First Wall systems, and of the surrounding mechanical structures (C-clamps), has confirmed that they can withstand both normal and off-normal operating loads, as well as plasma chamber baking operations, with proper safety margins, for all the operating scenarios and magnetic configurations under consideration. Both 3D and 2D drawings of each individual component have been produced using the Dassault Systems CATIA-V software, including the electro-fluidic and fluidic lines which supply electrical currents and helium cooling gas to the coils. At this point, the detailed design of the entire machine core is considered to have been completed. Finally, a study of the tritium system has been carried out with the aim of describing the main equipments and the operations needed for supplying the deuterium-tritium mixtures and recovering the plasma exhaust.

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