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The Ignitor Experiment

Ignitor [1] is the first experiment that has been proposed and designed to achieve physical regimes where ignition by nuclear fusion reactions occurs under controlled conditions. At the present time, it is the only one to have a design capable of attaining these regimes. Ignitor is conceived by the criterion that the burning phase exceeds all the intrinsic physical time scales and it addresses the main issues that should be resolved in present day research on nuclear fusion - demonstration of ignition, the study of the physics of the ignition process, and the relevant heating and control issues.

The machine is characterized by an optimal combination of high magnetic fields ($B_T \lesssim 13$ T), compact dimensions ($R_0 \cong 1.32$ m), relatively low aspect ratio ($R_0/a \cong 2.8$), and considerable elongation and triangularity ($\kappa \cong 1.83$, $\delta \cong 0.4$) of the plasma cross section. The optimal central density of the fusing nuclei to achieve ignition is estimated to be about 10^{21} m^{-3}. The corresponding line-averaged density is well below the known density limit (related to the average plasma current density) for magnetically confined plasmas, as the plasma current I_p allowed by the machine design can reach 11 MA. Ignition can be achieved by ohmic heating alone shortly after the end of the plasma current rise. The peak temperature at ignition is expected to be about $T_{e0} \cong T_{i0} \cong 11$ keV for an energy confinement time $\tau_E \cong 0.6$ sec (see Table I); the relatively low ratios of the plasma energy density (pressure) to the poloidal magnetic field energy density are consistent with favorable conditions for macroscopic plasma stability.

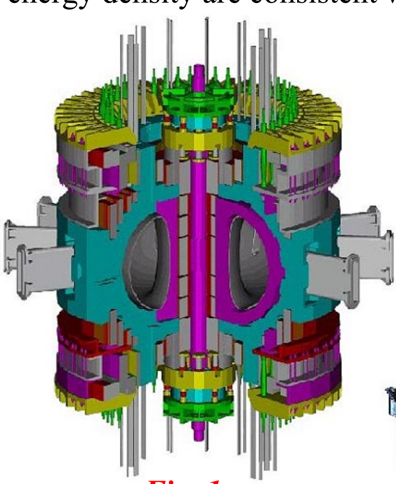

Fig. 1

The “first wall” facing the plasma is made of molybdenum tiles lining the entire plasma chamber, and acts as an extended toroidal limiter. The expected peak thermal power loads on the first wall do not exceed 1.8 MW/m^2 [1] in the standard extended limiter configuration. The poloidal field system of Ignitor can also produce magnetic divertor “double nul” configurations with 9 MA and an adequate safety factor against macroscopic instabilities in order to facilitate the access to the so-called H (enhanced confinement) regime. A preliminary analysis of the thermal loads, when the two up-down symmetric X-points are located near the first wall, indicates that these loads are acceptable with the first wall as presently designed.

Experiments have shown that attaining high density plasmas is more important for good impurity screening than including a divertor system in the machine design [2]. High density plasmas have higher neutral particle density and lower temperature at the plasma edge. In these regimes, in the absence of transport barriers, the level of impurity contamination has consistently been found to be low by a variety of experiments over the last 30 years. In fact, the standard view of the divertor as the dominant power and particle sink has been challenged by definitive experiments [3], where particle recycling from the main chamber and cross field diffusion in the outer region of the plasma column are observed to play an increasingly important role at higher densities.

TABLE I: EXAMPLE OF PLASMA PARAMETERS WHEN 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

$n_\alpha^* \equiv n_D n_T \langle \sigma v \rangle \tau_{\alpha,sd}$

$\tau_{\alpha,sd} \equiv 0.012 T_{e0}^{3/2}(\text{keV})/n_{e0}\ (10^{20}\ \text{m}^{-3})$

A system for the injection of auxiliary heating power at the ion cyclotron frequency (ICRF) in the range 80 – 120 MHz is included in the machine design. Less than 5 MW of absorbed power delivered by antennas using 3 of the 12 equatorial ports are sufficient to gain significant control over the evolution of the temperature and current density profiles, and to shorten the time needed to reach ignition. In non-igniting plasmas, it is also possible to investigate α-particle driven modes by substantially increasing the α-particle pressure gradient and enhancing the virulence of the relevant modes (3.5 MeV α-particles are produced by D-T reactions). This requires operating at higher temperature and lower densities than for ignition, and using a higher level of auxiliary heating power, up to 20 MW with 6 antennas. The first exploration of fusion burn conditions in tritium-poor plasmas can also be conducted, with significant production of power from D-^{3}He reactions [4].

Modest ICRF power levels are also adequate, in combination with the ohmic and fusion α-heating, to access H regimes, according to the available scalings [5]. While these regimes can exhibit longer energy confinement times, they have the disadvantage, for burning plasmas, of featuring rather flat density profiles. Despite the fact that a classic divertor with coils inside the plasma chamber or the toroidal magnet cavity could possibly ease the access to the H-regime, it was not included in the Ignitor design, as it would have involved a degradation of the global plasma parameters that can be achieved. By adopting this solution the maximum plasma current I_p would be seriously sacrificed and a severe complexity in the design and fabrication of the device, that is not warranted by the expected benefits, would be introduced.

Given the importance the evolution of the plasma density has in order to attain ignition, a high speed (~ 4 km/s), multiple pellet injector is included as an integral part of the machine design. In fact, the construction of this system is nearly complete. Injection of pellets is to be used to produce the peaked density profiles that are optimal for fusion burning, to minimize anomalous ion transport, to promote the formation of internal transport barriers [6], and for diagnostic purposes.

One of the main criteria for which Ignitor has been designed is to have mean poloidal magnetic fields $\bar{\bar{B}}_p = I_p/(5a\sqrt{\kappa})$ around 3.5 T (see Table II). This is important for macroscopic stability at the high plasma pressures needed for ignition and for allowing the possibility to reach this regime by ohmic heating alone. $\bar{\bar{B}}_p$ has also been identified as the main parameter of merit to assess the performance of a machine magnet system for the confinement of a toroidal plasma [7]. Therefore, given our present knowledge of the macroscopic stability of well-confined plasmas, any larger Ignitor-like device should also attain similar values of $\bar{\bar{B}}_p$.

The machine (Figs.1 and 2) is characterized by a complete structural integration of its major components (Toroidal Field system, Poloidal Field system, central post, C-clamps and plasma chamber). A "split" Central Solenoid is adopted to provide 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 pre-stressed 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.

An important element of the Ignitor experiment is the site where it will operate. The GRTN-Terna center of Rondissone, near Turin, was selected at first on the basis of its credits. Rondissone is a major node of the European electrical power grid and has been analyzed and authorized to accept loads corresponding to the highest plasma currents and fields in Ignitor. A site with complementary facilities that is being considered as an alternative to Rondissone is Caorso, near Piacenza, that has a weaker but sufficient electrical connection to the electrical grid and houses a former nuclear power station.

References

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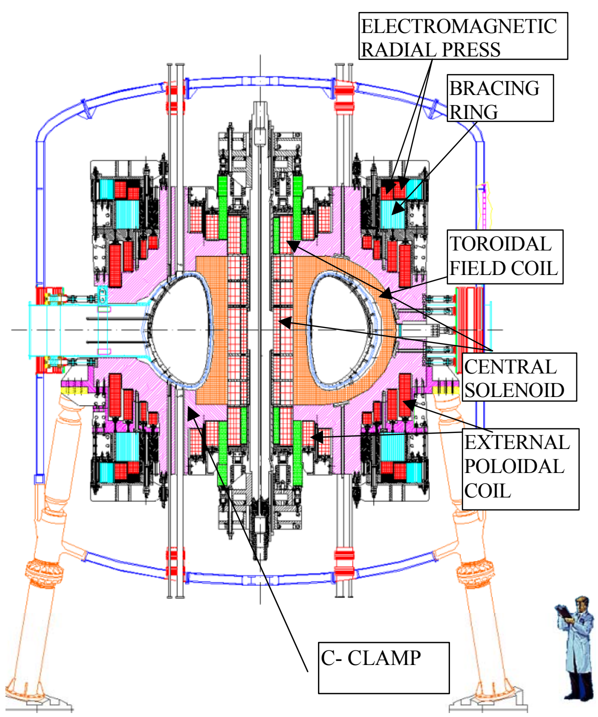

Fig. 2

Table II: REFERENCE DESIGN PARAMETERS

Major radius R_0	1.32m
Minor radius $a \times b$	0.47×0.86 m
Aspect ratio A	2.8
Elongation κ	1.83
Triangularity δ	0.4
Toroidal field B_T	$\lesssim 13$ T
Toroidal current I_p	$\lesssim 11$ MA
Maximum poloidal field $B_{p,\max}$	$\lesssim 6.5$ T
Mean poloidal field $\bar{\bar{B}}_p \equiv I_p / 5\sqrt{ab}$	$\lesssim 3.4$ T
Poloidal current I_θ	$\lesssim 9$ MA
Edge safety factor q_ψ	3.6
Confinement strength $S_c \equiv I_p \bar{\bar{B}}_p$	38 MA·T
Plasma volume	$\simeq 10\,\mathrm{m}^3$
Plasma surface	$\simeq 34\,\mathrm{m}^2$
ICRH heating ($\simeq 100-140$ MHz)	$\lesssim 20$ MW
Optimal ICRH Heating (115 MHz)	3-5 MW

Web site: http://www.frascati.enea.it/ignitor **For more information write to** coppi@mit.edu **or** ignition@psfc.mit.edu

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