

The Ignitor Experiment

Demonstration of fusion ignition is a major scientific and technical goal for contemporary physics. Until the fundamental physics issues of fusion burning have been identified and confirmed by experiment, the defining concepts for a fusion reactor will remain uncertain. An important value of a basic ignition experiment is that the ignition process will be similar for any magnetically confined, predominantly thermal plasma. In such an experiment, heating methods and control strategies for ignition, burning, and shutdown can also be established. These three issues, demonstration of ignition in a magnetically confined plasma, the physics of the ignition process, and heating and control of a burning plasma, are specifically addressed by the IGNITOR experiment. Its design has been driven primarily by physics considerations since its inception. The associated physics studies have gone beyond simple identification to include the interaction of the physical process involved in ignition. IGNITOR is part of a line of research that began with the Alcator machine at [MIT](#) in the 1970's which pioneered the high magnetic field approach to plasma magnetic confinement, and continued with the Alcator C/C-Mod at MIT and the [FT/FTU](#) series of experiments. The idea for the first D-T ignition experiment proposed on the basis of existing technologies and knowledge of plasma physics was formulated at about the same time as the first results of the Alcator experiment were produced. Subsequent developments have confirmed the fact that high magnetic fields combined with an optimised compact geometry offer, at present, the only path to achieving ignition, when both plasma energetic and stability are taken under consideration. The approach involving the combination of appropriate geometry and high magnetic fields also allows a possible development path to tritium-poor, reduced-neutron-production fusion, which could yield interesting kinds of fusion reactors.

Table 1: [Plasma parameters at ignition](#)

Parameters	Symbol	Value	Unit
Plasma current	I_p	11	MA
Toroidal magnetic field	B_T	13	T
Central electron temperature	T_e^0	11.5	keV
Central ion temperature	T_i^0	10.5	keV
Central electron density	n_e^0	1.0×10^{21}	m^{-3}
Central plasma pressure	p_0	3.3	MPa
Average effective charge	$\langle Z_{eff} \rangle$	1.2	
Plasma stored energy	W	11.9	MJ
Ohmic power	P_{OH}	11.2	MW
Auxiliary power (ICRH)	P_{ICRH}	0	MW
Bremsstrahlung losses	P_{brem}	3.9	MW
Alpha power	P_a	19.2	MW
Energy replacement time	t_E	0.62	s
Poloidal beta	β_p	0.20	
Toroidal beta	β_T	1.2	%
Central beta	β_0	5.0	%
Edge q_y	q_a	3.6	
Bootstrap current	I_{bs}	0.86	MA
Alpha density parameter	n_a	1.2×10^{18}	m^{-3}
Average alpha density	$\langle n_a \rangle$	1.1×10^{17}	m^{-3}
Alpha slowing down time	$t_{a, sd, 0}$	0.05	s

IGNITOR [1] has been the first experiment proposed and designed to achieve ignition conditions. The machine is characterized by an optimal combination of high magnetic fields ($B_T = 13$ T), compact dimensions ($R_0 @ 1.32$ m), relatively low aspect ratio ($A = 2.8$) and considerable plasma cross section elongation and triangularity ($k=1.83$, $d=0.4$). The appropriate central density for which ignition can be achieved in IGNITOR is about 10^{21} m^{-3} . Given the high value of the volume averaged current density corresponding to a plasma current $I_p @ 11$ MA, the relevant line average density is well below the density limit and ignition can be achieved by ohmic heating alone. The peak ignition temperature is about $T_e = T_i = 11$ keV for an energy confinement time $t_E = 0.6$ s (see Table I). When only ohmic heating is present, ignition is reached shortly after the end of the current ramp (≈ 4 s). The first wall, covered with molybdenum tiles, acts as an extended toroidal limiter and the resulting peak power loads do not exceed 1.8 MW/m^2 [1]. In high density plasma regimes, which involve higher neutral density and lower temperatures at the edge, the level of impurity contamination is expected to be low, consistently with an extensive series of experiments. A system for the injection of RF power at the Ion Cyclotron frequency ($\approx 70 - 140$ MHz) up to $18 - 24$ MW is included in the machine design using 6 of the 12 equatorial ports. With this system the band of accessible interesting plasma regimes can be extended and more control over the evolution of the temperature and current density profiles, relative to the case where only ohmic heating is used, can be gained, e.g. the time needed to reach ignition can be shortened. Relatively low levels of RF power are appropriate to optimize the process of reaching ignition, but these will be needed during a phase of varying magnetic field, requiring antennas tuned at various frequencies to operate in sequence.

A pellet injector, producing pellets with velocities $@ 4$ km/s, has always been considered an integral part of the machine design in order to have: i) fast core fueling; ii) density profile control; iii) time-dependent burn control. Besides the controlled fuelling of particles, the pellet injector can be used to promote the formation of internal transport barriers [2], and for diagnostic purposes.

The machine is characterized by a complete integration among the different major components (toroidal field system, mechanical structure, poloidal field system and vacuum vessel). A split central solenoid is adopted to provide the flexibility to produce the sequence of plasma equilibrium configurations through the envisioned plasma current and pressure rise. The structural performance of the machine relies upon an optimized combination of "bucking" between TF coils, the central solenoid with its central post, and "wedging" in well defined areas of the TF magnet and of the magnet reinforcing mechanical structure (C-clamps). The necessary mechanical strength has been obtained by designing the copper coils and its structural elements (C-clamps, central post, bracing rings) in such a way that the entire system, with the aid of an electromagnetic press when necessary, can withstand the forces acting on it. The set of stainless steel C-clamps form a complete shell, which surrounds the 24 TF coils. These are pre-stressed through the C-clamps by means of two bracing rings. The combination of these two elements gives an appropriate degree of rigidity to the central legs of the coils to handle the electrodynamic stresses, while allowing enough deformation to cope with the thermal expansion. The entire machine is enclosed by a cryostat. A detailed design of the machine core has been complemented by the construction of full size prototypes of the key components of the machine by well known European industrial groups.

The Poloidal Field System of Ignitor can produce internal X-points configurations in addition to the standard "limiter" ones, but at reduced parameters, in particular lower currents and smaller cross sections. For example, configurations with double X-points just outside the first wall, the preferred option, at 10 MA and $q_{95} = 3$ can be obtained. Less than 5 MW of additional heating power, combined with the ohmic power, are sufficient, according to the latest proposed scaling [3], to access the H-mode regime. A preliminary analysis of the thermal loads at the strike points with X-points inside the first wall indicates that they are acceptable with the first wall as presently designed. Internal divertor coils are not included in the Ignitor design, as the easier accessibility to the H-mode does not compensate for the reduction in the plasma cross section and the complexities that a full divertor within a high magnetic field environment would involve. In addition, experiments have shown that attaining high density regimes is more important for good impurity screening than the existence of a divertor.

A considerable amount of work on the physics of ignition has been carried out over the course of the IGNITOR design. Much of it is generally applicable to ignition in a confined plasma, not only at high fields. At present IGNITOR is one of the three proposed burning plasma experiments with [FIRE](#) and the international thermonuclear reactor [ITER-FEAT](#).

References

- [1] B. Coppi, A. Airoidi, et al., "Critical Physics Issues for Ignition Experiments", MIT RLE Report PTP 99/06 (1999).
- [2] L. R. Baylor, T.C. Jernigan, et al., *Physics of Plasmas* **7**, 1878 (2000).
- [3] J. A. Snipes, et al., *Plasma Phys. Contr. Fusion* **42**, 381 (2000).