High Density Regimes for the Ignitor Experiment*

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Introduction

The high plasma density regimes discovered by the high magnetic field experiments have both outstanding confinement characteristics and degree of purity, and are at the basis of the Ignitor design. The main purpose of the Ignitor experiment is, in fact, 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. Relevant transport simulations [1] show that burning plasma conditions can be attained with "extended limiter" and double X-point configurations, by Ohmic heating only or with modest amounts of ICRH auxiliary heating. The driving factor for the machine design ($R_0 \cong 1.32$ m, $a \times b \cong 0.47 \times 0.83$ m^2, $B_T \cong 13$ T, $I_p \cong 11$ MA) is the poloidal field pressure [$B_p^2/(2\mu_0) \leq 3.5$ T] that can contain the peak plasma pressures corresponding to ignition under macroscopically stable conditions ($p_0 \cong 3.3$ MPa). In all plasma regimes considered, in fact, the plasma density is only about half the density limit, despite having values $n_{e0} \cong n_{i0} \cong 0.5 - 1 \times 10^{21}$ m^{-3}. Gas fueling may be adequate, but density profile shapes and particle penetration cannot be reliably predicted, so a pellet injector has been included in the machine design, to provide (fast) core fueling and control of the density profile shape (and to some extent of the edge density) as peaked density profiles are important for both stability and heating efficiency.

1. High density plasma regimes

It is well known that the maximum plasma density that can be confined correlates with the current density, i.e., $n_{lim} \propto I_p/(\pi a^2)$, which in turn is related to the ratio B_T/R. The volume-averaged current density in Ignitor can be as high as $\langle J_\phi \rangle \cong 0.93$ kA/cm^2. This should allow $n_{e0} \cong 10^{21}$ m^{-3} without difficulty. Therefore, based on the required $n_0 \tau_E \cong 5 \times 10^{20}$ s/m^3 for ignition conditions at $T_0 \cong 12.5$ keV for 50:50 D-T plasmas, only moderate energy confinement times are required.

The series of experiments on record high density plasmas carried out by the Alcator machines that produced plasmas with unexpected high degree of purity have opened the way to the concept that most of the plasma energy can be lost by impurity radiation at the edge of the plasma column. In this case the conversion takes place in a rather narrow layer and does not affect the global energy confinement time. In this case, impurities are, in effect, hindered from entering the plasma column in the regimes with the highest densities. The “cold radiating plasma mantle” idea is supported by the transport analysis given in Ref. [2]. Later experimental observations (in both limiter and divertor machines) have demonstrated the possibility of operating with a radiative mantle which can dissipate up to 90% of the total power lost by the plasma without energy confinement degradation.

Divertors, which concentrate the thermal wall loading on small regions, require an expanded volume inside the toroidal field coils to accommodate the magnetic separatrices, the divertor itself, and in some cases the associated shaping coils. For high field designs, relatively small increases in the size of the coils and the major radius have serious consequences through the cascade of relations: larger $R \rightarrow$ lower $B_T/R \rightarrow$ lower n_e, lower $B_T \rightarrow$ lower I_p and P_{OH} so that β_p is higher at ignition. The plasma current is lower for a given B_T because the necessity of squeezing magnetic separatrices and the divertor inside the toroidal field coils reduces the plasma cross sectional area. Divertors introduce additional complexities in machine and magnet design, as well as operational risks with the presence of current carrying conductors in regions of high magnetic field. In Ignitor, X-point configurations with double magnetic nulls outside the first wall can be produced for all or part of the discharge if necessary, with relatively little sacrifice in plasma and magnet parameters, i.e., somewhat smaller I_p, but more localized wall loading.

2. The Ignitor Pellet Injector

In order to control the density profile during the initial current rise phase of the discharge, which is critical for optimizing the Ohmic and fusion heating rates, a fast pellet injector, the Ignitor Pellet Injector (IPI) has been developed in collaboration between ENEA and ORNL [3]. The injector is designed to launch solid deuterium pellets in the 1.9 – 4.4 mm size range at speeds of 3 to 4 km/s, and features two innovative concepts: (i) the proper shaping of the propellant pressure

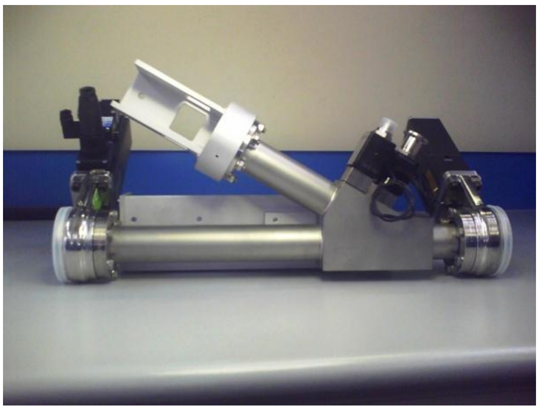

Fig. 1 – One of the new target chambers during preliminary tests at ENEA

pulse to improve pellet acceleration, and (ii) the use of fast closing (< 10 ms) valves to drastically reduce the expansion volumes of the propellant gas removal system. Two independent sub-systems have been built separately by the two teams and integrated at ORNL. New light gates, microwave cavity mass detector and control software have been developed specifically for this application. The propellant sub-system, including four independent two-stage guns (TSG) and pulse shaping valves, the (patent pending) gas removal system, and the associated controls and diagnostics, has been thoroughly tested by the CRIOTEC industrial group before shipping to ORNL. The pressure rise in the downstream expansion volume was shown to be completely cut-off by appropriately reducing the delay (relative to the pressure pulse time) with which the fast gate valve starts to close. Preliminary tests have demonstrated that the two systems match properly, while their respective control systems interface correctly and perform outstandingly. The cryostat is actively cooled by a pulse tube refrigerator, but it has also been equipped with supplemental cooling from a liquid helium dewar. The performances of barrels 3 and 4 of the IPI, compared with those of the Single Pellet Injector (SPIN) installed of the Frascati Tokamak Upgrade (FTU) in the early 90's, indicate that, for the same value of the pressure peak, the IPI has the potential of achieving higher speeds. The improved performance may be associated with the pulse shaping valve, or with the larger bore of the IPI barrels. However, it was more difficult than expected to preserve pellet integrity at velocities above 2 km/s. In-flight pictures showed that, as the speed increases, pellets tilt, while their trajectories drift out of the midplane, striking against the side wall of the narrow guide, causing them to break. For this reason, the sections of the guiding tubes have been increased and other design improvements have been implemented for the latest experimental campaign: the inner diameter of the conduit crossing the diagnostics has been increased from 9.5 to 19 mm; additional ports for accurate leak testing of the barrels and the diagnostics have been provided; tracing of the helium exhaust from the main heat exchanger to the thermal radiation

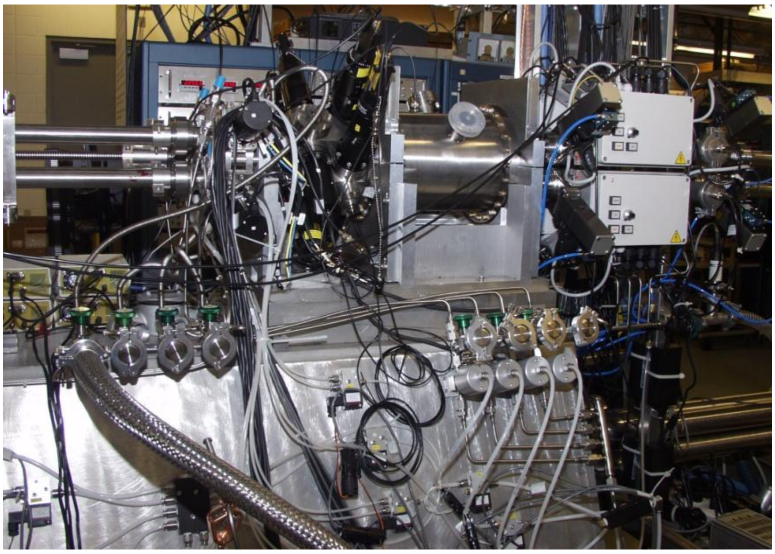

Fig. 2- The new arrangement of the IPI diagnostic area, showing the target chambers on the right.

shield has been implemented. A set of four target diagnostics (Fig. 1) have been implemented to monitor the dispersion of pellets trajectories just downstream of the microwave cavity mass probe, which has been temporarily removed (Fig. 2).

Real time monitoring is achieved by four CCD cameras (provided by ORNL), looking at the targets through optical windows. Short movies can be captured by means of a 4 channels video-recorder (Fig. 3). A new set of four adapting flanges, accommodating both the ORNL propellant valve and the ENEA TSG on each barrel (and including the rear deuterium feed), was also integrated in the system. All the mechanical improvements were verified to be leak tight to a leak rate of < 10^{-9} mbar l/s. Tests with liquid helium showed that the thermal radiation shield readily achieved a minimum temperature of about 50 K (to be compared with 128 K usually achieved after many hours of operation with the cryocooler), but the onset of a leak in the helium circuits prevented its further use during this campaign.

Important progress was achieved towards pellet formation at lower pressure. The considerable effort made to avoid some very small leakages, detected in previous tests, which seemed detrimental to pellet formation, allowed reducing the D_2 pressure during pellet formation. This “modus operandi” requires more time to form a pellet, but suggests a better quality of the solid, provided that high purity of the deuterium and cleanness of the system is ensured. Intact pellets were launched at speeds up to 1.9 km/s without the additional cooling from liquid helium (in previous tests, the maximum speed achieved was ≤ 2 km/s with liquid helium, and ≤ 1.7 km/s without liquid helium). Further improvement may be achieved by optimizing the power delivered to the upstream and downstream heaters.

Fig. 3 – The impact of a pellet on the thin Al target, showing a very limited dispersion.

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