Limiter and X-point Configurations

in Ignition Experiments

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Introduction

The introduction of a proper divertor in meaningful fusion burn experiments is at times advocated with the argument that it addresses the "reactor relevant" issue of ash and impurity control and it allows easier access to the H-mode regime. On the other hand, a divertor decreases the volume available for the plasma and introduces structures that have to withstand high thermal wall loadings and the effects of disruptions in a high magnetic field environment. Other related questions are whether the density profiles that characterize the H-regime are optimal for ignition, whether the divertor has indeed led to cleaner core plasmas than those produced in limiter devices, and whether other means to remove the α-particles produced by fusion reactions, e.g. during their slowing down, are more appropriate even in principle.

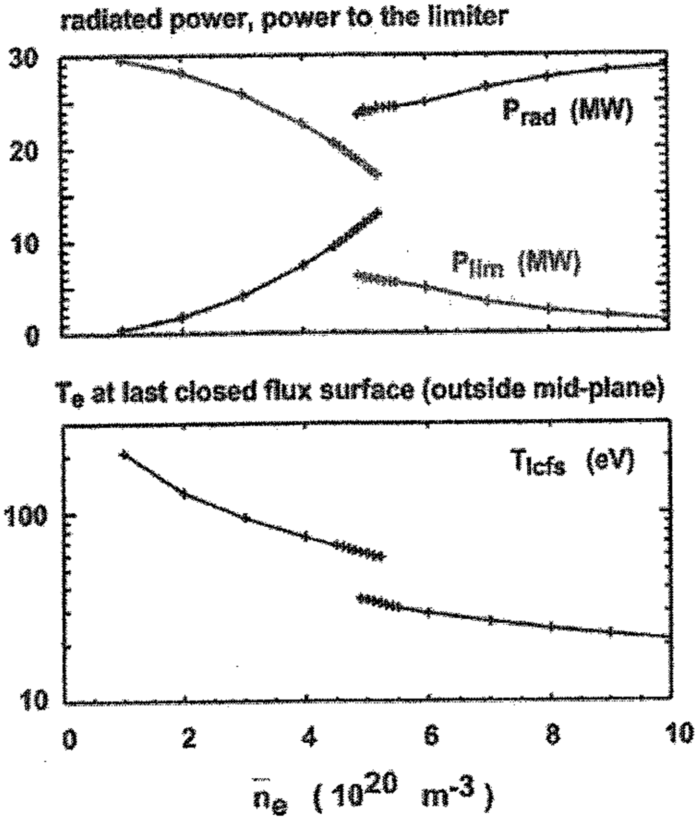
Divertors have been considered the reactor relevant solution to manage power and particle exhaust based on experimental experience acquired up to the early '90s on machines that, we point out, were operating for the most part in the low to medium density plasma regimes. In dealing with processes that involve sputtering and neutrals, it is necessary to refer to the absolute density, not to the value relative to the maximum value achievable on a specific device (e.g. the density limit).

In recent years, the upgrading of various machines and a general trend to operate at higher density have led to a re-assessment of the effective advantages of the divertor solution relative to the limiter one. A new view of the divertor and of the role played by particle recycling from the main chamber and cross-field diffusion have been pointed out by the Alcator C-Mod group [1], challenging the standard picture of the divertor as the sole power and particle sink, in plasma regimes that are similar to those expected in Ignitor. In reality, the closed divertor region receives only part of the total particle efflux from the main chamber and recycling on the main chamber surface is predominant, already at intermediate density; the cross-field particle transport increases strongly with distance from the separatrix. In practice, the divertor is effective to exhaust power only if a large fraction of it is lost by radiation before entering the divertor region. In low density plasmas this result has been achieved with the *ad hoc* introduction of impurities into the plasma, while it occurs naturally at high density. Both limiter and divertor machines have routinely obtained good energy confinement times with a highly radiating edge (up to 90% of the total power).

The limiter solution

In the traditional limiter operating regime, recycling fuel neutrals at the limiter penetrate across the last closed flux surface (LCFS) and ionize in the confined plasma, afterwards diffusing as plasma ions across the LCFS and traveling along field lines back to the limiter. The region of open field lines is called Scrape-Off Layer. Heat is carried in the boundary both radially and along field lines by convection. This has been the regime ("Simple SOL") in most previous limiter tokamaks, including PLT, TFTR, JET (limiter), TEXTOR, etc. Such devices usually have relatively hot and low density plasmas in direct contact with the limiter.

In high density regimes the radiation losses gain importance in dissipating the power leaving the main body of the plasma column and the whole scrape-off region contributes actively in dispersing power flow and reducing the energy of the particles impinging on the material walls (the "Complex SOL" regime [2]). The critical parameter turns out to be the edge density. In fact, in high density plasma experiments the level of impurity contamination has consistently been observed to be low, thanks to low plasma temperatures at the edge and improved screening properties of the adjacent plasma. The plasma density is a key parameter in achieving ignition. In Ignitor the optimal conditions for ignition at 13 T, 11 MA correspond to peak densities around 10^{21} m^{-3} [3], with typical peak-to-volume averaged density ratios around 2 [4]. According to various estimates, the edge densities range from 2 to 3 × 10^{20} m^{-3}. In these conditions, the average Z_{eff} is $\simeq$ 1.2. For this level of contamination, an estimated 80% to 90% of the α power can be radiated, according to a multi-machine scaling law [5]. Therefore the limiter-like solution appears as the most suitable for Ignitor, which is expected to operate with relatively cold edge plasmas and, consequently, reduced impurity emission from the plasma facing materials. The first wall, covered with molybdenum tiles, acts as an extended limiter. The resulting thermal wall loads are rather modest. These have been calculated assuming an ideal continuous wall under the conservative hypothesis that only 70% of the α-power is radiated. Under ignition conditions, a maximum thermal load of 1.8 MW/m^2 is found when


radiated power, power to the limiter

T_e at last closed flux surface (outside mid-plane)

Fig. 1. Edge temperature and radiated power estimated by the EDI code, assuming a total power loss of 30 MW.

"physiological" plasma movements of ± 1 cm around the equilibrium configurations are considered (the expected average heat flux is $\lesssim$ 0.7 MW/m^2) [6].

The edge conditions for limiter-like geometry are being re-analyzed with the new, 2-D EDI (EDge of Ignitor) code, taking into account impurity radiation, parallel temperature gradients in the boundary plasma and the effects of neutrals on the scrape-off ionization. Cross-field conduction is also included, although not entirely self consistently. For specified values of the line averaged density, impurity contamination, and total power leaving the plasma core, the edge temperature is derived based on power balance. As a first test the code was run assuming a power loss from the main plasma, 30 MW, considerably higher than the expected one (18 MW). The radiated power and its complement, the power going to the limiter, are shown in Fig. 1 (top) as a function of the line average density, as well as the corresponding edge temperature (bottom). The EDI results show a bifurcation at about 5×10^{20} m^{-3} (an approximate value for the given power), corresponding to the so-called plasma "detachment" at higher densities, with the possible formation of a MARFE on the inner wall. The thermal loads on the wall scale with those calculated previously, when the difference in the total plasma power is taken into account. Nevertheless they are acceptable for the molybdenum tiles and a 5 s pulse length.

X-point Configurations

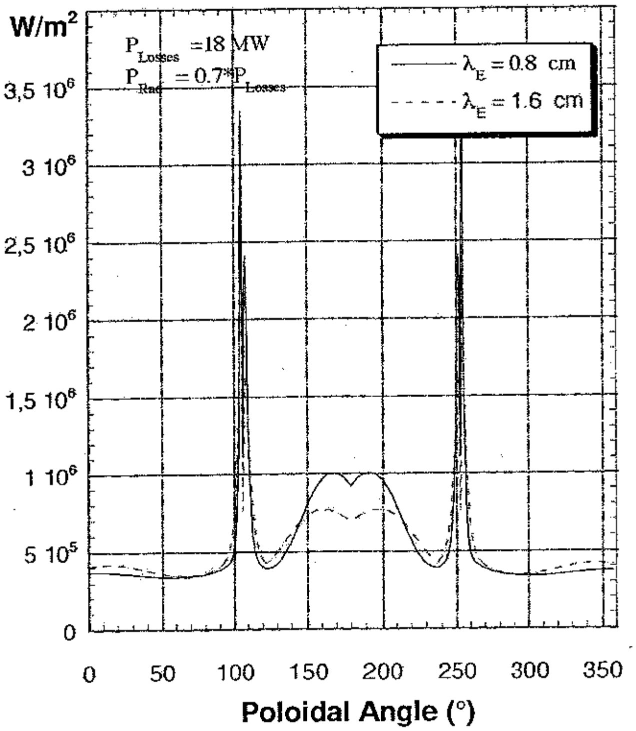


Fig. 2 Thermal load profiles in a double null configuration at 9 MA in Ignitor for two values of the energy decay length.

The Poloidal Field System of Ignitor can produce X-point configurations in addition to the optimized limiter ones, but at lower parameters, e.g., reduced current and smaller cross section. Both double-null and single null configurations have been analyzed [7]. A specific example is a configuration with the X-points just outside the first wall, which is a hybrid configuration, from the point of view of plasma-wall interactions, because the LCMS is determined by the tangency with a material surface. The separatrix solutions are constrained to have $q_{95} \approx 3$, resulting in reduced plasma currents: 10 MA for the double null configuration and about 9 MA for the single null. A common feature of these configurations is the requirements of significantly higher currents than the reference design values in the PF coils near the X-point, which may possibly require a modification of the design for few coils of the PFC system. It is possible to take advantage of the large, natural spread of the flux surfaces near the X-point, which induces an increase of the power decay length and consequently a reduction of power loads. These preliminary results indicate maximum peaks of 2.5 – 3.5 MW/m^2 (see Fig. 2), obviously higher than those found in the limiter configuration but similar to the values currently seen in Alcator C-Mod, for example.

Conclusions

The new analyses confirm the early results that suggested a "Complex SOL" in Ignitor where radiation, ionization and charge exchange are all important in reducing particle energy and spreading out the power transported across the LCFS by energetic particles. In Ignitor, a high fraction of the power leaving the core can be radiated. Therefore only a relatively small fraction will be deposited onto the wall. Low edge temperatures imply low sputtering yields of high Z material from the wall. Ionization of neutrals takes place in a narrow layer at the plasma edge and impurity penetration in the core is low. For these reasons a proper divertor has not been deemed necessary. On the other hand, it is also possible to produce X-point configurations at lower currents with tolerable loads on the first wall.

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