Plasma-Surface Interaction Issues in Ignitor

F. Bombarda[‡], B. Coppi*, C. Ferro[‡], C.S. Pitcher*

MIT (RLE) Report PTP 00/05

*Massachusetts Institute of Technology, Cambridge MA
[‡]ENEA-Unità Ignitor

Cambridge, MA

July 31, 2000

1. Introduction

Power is exhausted from magnetically confined plasmas either in the form of electromagnetic radiation or as energetic particles. An important concern is that of reducing the power load on the physical walls exposed to the plasma, where impurities can be produced by sputtering and/or evaporation. Plasma-surface interactions need to be controlled to maintain a clean plasma core, i.e. by reducing the production of intrinsic impurities and improving their screening from the plasma core (Fig. 1), and to ensure a wide dispersion of power over the walls. Thus far, two solutions have been envisaged to deal with these issues:

i. The divertor concept, where the magnetic field lines at the periphery of the plasma are "diverted" to a location separate from the main plasma. The remote location from the plasma heat source allows the plasma temperature adjacent to material surfaces to be reduced, hence reducing the sputtering yield of the incident plasma ions. Although impurities that are generated in the region are potentially screened from the main plasma, it is not presently clear whether the divertor has indeed led to cleaner core plasmas over those in limiter devices [1]. One of the negative features of the divertor is that it tends to "focus" power over relatively small areas, i.e. the divertor plates, besides posing serious problems for its inclusion in an effective confinement configuration with a high magnetic field.

ii. The series of experiments on record high density plasmas carried out by the Alcator machines, with appropriate limiters, that produced unexpected high degree of purity have opened the way to another concept, where most of the plasma energy is lost by impurity radiation at the edge of the plasma column. In this case the conversion takes place in a rather narrow layer and is generally consistent with good confinement properties of the plasma column. As shown in Fig. 1 the impurities are, in effect, hindered from entering the plasma column in the regimes with the highest densities. We note that the related "cold radiating plasma mantle" concept was introduced in the context of the reactor exhaust problem [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 [3,4].

2. The limiter choice

After weighing different alternatives, Ignitor has adopted the solution with a limiter, on the basis of the second concept, with molybdenum tiles as the first wall material. This solution is in fact suitable to the requirements of plasma-wall interaction control in high density plasmas. The main relevant considerations are:

1) Plasma purity: minimal contamination and excellent confinement properties in high-density plasma regimes have been observed consistently, since the first Alcator and FT experiments, in a large variety of experiments that lately have included the reversed field pinch RFX. A scaling law relating plasma purity, radiated power, and machine dimensions has been derived from a significant database of toroidal confinement experiments [5]. The result from this scaling law is given in Fig. 2, using the reference Ignitor parameters. According to this, Ignitor is expected to radiate most of the input power from the edge, while $Z_{eff} \lesssim 1.2$. The relevant fraction of molybdenum ions relative to the electrons ($Z_{Mo} = 42$, average charge state $\langle Z \rangle_{Mo} = 38$) that is estimated does not compromise the possibility to reach ignition.
2) Thermal loads: these have been calculated assuming an ideal continuous first wall, under the conservative hypothesis that only 70% of the input power is radiated. Under ignition conditions, a maximum thermal load of 1.8 MW/m^2 is found (see Fig. 3) when plasma movements of ± 1 cm around the equilibrium configuration are considered (the expected average heat flux is $\lesssim 0.7$ MW/m^2).
3) Power loss distribution: radial profiles for the radiated power have been calculated by means of a self-consistent model [6], that couples the core of the plasma column with a single impurity species and the scrape off layer (SOL). The resulting radiating profiles show that 40% of the radiative losses are localized in the outer region of the main plasma and 40% in the SOL. These radiative regions

are close to the first wall surface, and do not affect the confinement conditions of the core of the plasma column.

3. Characteristics of the Scrape Off Layer

Outside the Last Closed Magnetic Surface (LCMS) the plasma, unimpeded by the magnetic field, is in direct contact with solid surfaces that act as particle and energy sinks. As a consequence plasma characteristics fall down radially in short scale lengths which can be determined by the balance between the cross field transport into the SOL and parallel exhaust rate to the surface. The characteristic power decay length, λ_p, determines, for a given power leaving the plasma, the heat flux incident on the first wall structures. Its value was estimated, assuming that the power flows into the SOL primarily due to cross-field diffusion, in the case of a SOL with or without poloidal gradients, to be approximately 8 mm. This value has been recently confirmed applying to Ignitor multi-machines scaling laws derived from recent experimental results [7].

The actual power transported to the surfaces through energetic particles depends on the physical characteristics of the SOL which are determined by the plasma characteristics (density, temperature) at the edge. The value of the edge density in Ignitor, $n_a \simeq (2-3) \times 10^{20}$ m^{-3}, has been evaluated from a model that assumes edge fuelling (gas puffing) and a simple edge transport model [6], which gives a very good fit to a wide range of limiter experiments. Figure 4 shows the values of n_a from these experiments and the estimated value for Ignitor. The edge temperature has been derived by an energy balance between the total power, the radiated power and the power transported to the limiter, with the assumption of no poloidal temperature gradient in the SOL. Temperatures $T_a \simeq 35-60$ eV at the last closed flux surface are expected for core radiated powers between 10 and 25 MW. These values suggest that the SOL in Ignitor is not simply a region that conveys energetic particles to the material surfaces acting as the dominant power sink. On the contrary, in the SOL region [8] there are other different sinks, such as radiation, ionization, and charge exchange that are important in reducing particle energy and spreading out the power transported across the LCMS by energetic particles. Activities in this field are on-going.

A simple 1-D model can also be used to derive the SOL parameters as a function of the edge density [9]. Preliminary results have shown that for the range of the edge density estimated in Ignitor high fractions of power can be radiated in the SOL. Significant temperature differences in the poloidal direction can develop, with relatively low values close to the surface. At the higher densities, the plasma detaches from the surface and the temperature at the tiles falls to a few eV, while the fraction of power radiated in the SOL approaches unity. This model applies to the case where ionization is primarily in the SOL, and thus is appropriate for plasmas with an X-point as well as limiter configurations at high density with relatively "opaque" SOL's. From these results it is clear that operation at the highest possible edge density is desirable from the point of view of both power handling at the surface and reduction of impurity sputtering. The low temperatures adjacent to the surface can virtually eliminate the physical sputtering of molybdenum.

4. Impurity dilution and radiation

Impurity contamination in Ignitor can originate from low-Z elements (e.g. carbon, oxygen and, possibly, boron) and from the high-Z molybdenum. In the case of low-Z contamination, experience on Alcator C-Mod indicates that fuel dilution and edge radiation due to carbon and oxygen can be virtually eliminated by means of wall boronization and replaced to a lesser degree by boron. This procedure can very well be applied in Ignitor as well. Base Z_{eff} values in Alcator C-Mod at moderate and high density range between 1.1 and 1.5. Typically, half of the conducted power reaching the boundary is radiated by these low-Z elements in a thin radial region straddling the separatrix.

In the case of molybdenum, the effect of fuel dilution is relatively minor in comparison to the low-Z contamination (although Z_{eff} can still be affected). The primary effect of Mo in the core is on core radiation. A critical fraction of impurity concentration where plasma radiation losses are balanced by the α-heating was defined in [10] taking into account both radiation and dilution. Similar calculations have been done considering the Ignitor scenario and a boron concentration of 1% constant with radius [9]. As expected, the critical molybdenum level decreases towards values ranging between 5×10^{-4} and 1×10^{-4}. Experiments by the Alcator C-Mod machine have shown that typical levels of molybdenum concentrations, nearly uniformly distributed over the minor radius in ohmic or L-mode plasmas, are of the order of 10^{-5} and in the worst cases (with high levels of poorly executed ICRF heating) approach 10^{-4}, but never exceed this value. These fractions are acceptable for Ignitor, but clearly more research correlating the experiments with appropriate models needs to be carried out. The molybdenum source is mainly due to physical sputtering at first-wall components. In this respect the temperature at the wall plays the main role in reducing molybdenum source and the transport inside the main plasma plays a secondary role. It is worth noting that since 1982 quite a strong decrease in the central molybdenum density with increasing line averaged density was measured on Alcator-C [11]. Molybdenum behavior has been analyzed in Alcator C-Mod [12], where the various molybdenum sources have been measured by spectroscopic means, and their corresponding core penetration factors estimated. In Alcator C-Mod, molybdenum is produced at the inner wall, the divertor plates and the ICRF antennas. In the case of the inner wall and the divertor plates, relatively high sputtering rates are observed, more or less consistent with expected physical sputtering yields, allowing for both sputtering by deuterons as well as by low-Z ions. Little of this molybdenum appears in the plasma core, however, due to a high degree of impurity screening at these two locations.

In the case when the ICRF antennas have been introduced, on the other hand, although comparable rates of impurity production are observed, the screening is poor and the molybdenum readily penetrates to the core plasma. It is thought that this production is due to a sheath rectification effect near the antennas, resulting in elevated sheath voltages and therefore enhanced sputtering rates. Alcator C-Mod is presently investigating this effect, and in an attempt to reduce the molybdenum contamination during ICRF, molybdenum protection tiles have in part been replaced with boron nitride (BN) tiles. The BN tiles, being insulators, will prevent the rectification phenomenon and also eliminate the molybdenum source. It is not clear why molybdenum released at the outside mid-plane is particularly efficient at contaminating the core, but it may be related to poloidal variations in the cross-field diffusion rate (e.g. high at the outside mid-plane, low at the inside mid-plane). This result has been observed with other intentionally added impurities. Experiments are presently on-going.

Finally, referring to the limiter configuration of Ignitor, we note that sufficient space between the first wall and the chamber at the outboard side has been left for the possible introduction of pumped or vented limiters, noting that such structures may be desirable to improve plasma density control.

5. X-point configurations

The Poloidal Field Coils system of Ignitor can be adapted to introduce X-points of the magnetic configuration outside, in the proximity of the first wall, or within the first wall in order to access the H-mode regimes in a conventional way. The former configuration is clearly preferred as there are several disadvantages associated with an inside X-point configuration, a major one being that of a significant reduction in the plasma cross sectional area. Consequently, the plasma current that can be produced would be significantly decreased. Most important, the flat density profiles that characterize the conventional H-mode regimes are less desirable, taking all factors into account, than the peaked density profiles in view of obtaining ignition conditions. Thus, producing an inside X-point configuration is not considered a priority in the Ignitor design, but rather an interesting possibility to expand the range of regimes that can be studied on this device. The introduction of divertor strikepoints, as mentioned above, tends to focus the plasma power onto a relatively small area on the first wall, and power handling becomes an issue.

The inside X-point configuration would be produced at reduced power levels relative to those considered for ignition. Nevertheless, even with these power levels we estimate that the parallel power density in the SOL flowing upstream of the surface, $q_u = (q_\psi P_{SOL})/(4\pi a\kappa^{1/2}\lambda_p)$, would be of the same order as presently obtained in the Alcator C-Mod experiment. Taking into account the magnetic topology in the vicinity of the X-point, the power incident on the tiles is expected to be reduced from this parallel value by a factor of about 25. As indicated before, at medium or high plasma density, SOL impurity radiation can reduce this power flux significantly. Typical results in present experiments have incident heat fluxes reduced by factors of ~ 10, thus bringing q_t to less than 10 MW/m^2, which is acceptable for inertially-cooled molybdenum tiles.

Finally, we must consider localized concentrations of incident power. In particular, past experience on many machines indicates that localized heating results primarily from tile misalignment with respect to its nearest neighbors. Thus, alignments to within ± 0.2 mm are specified in the first wall design. Such tolerances, while demanding, have in fact been achieved in the past.

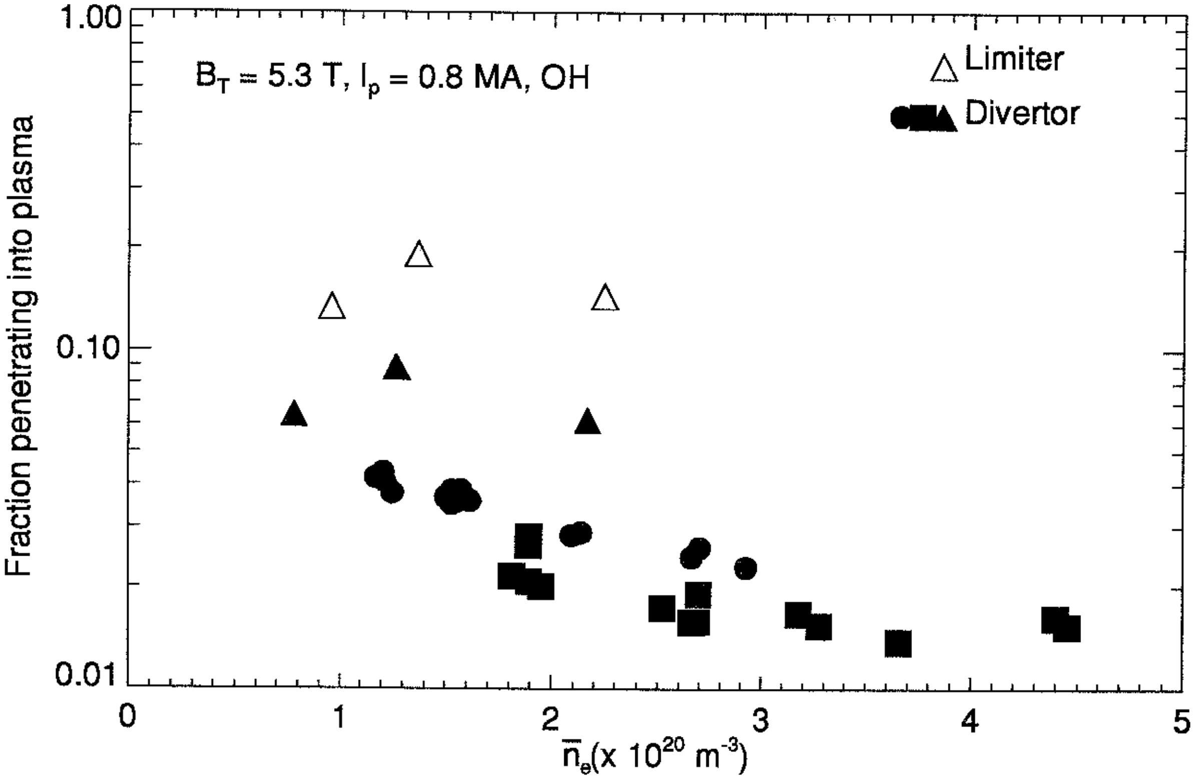

Fig 1. Effect of electron density on the plasma screening of Ar impurity ions in experiments by the Alcator C-Mod machine.

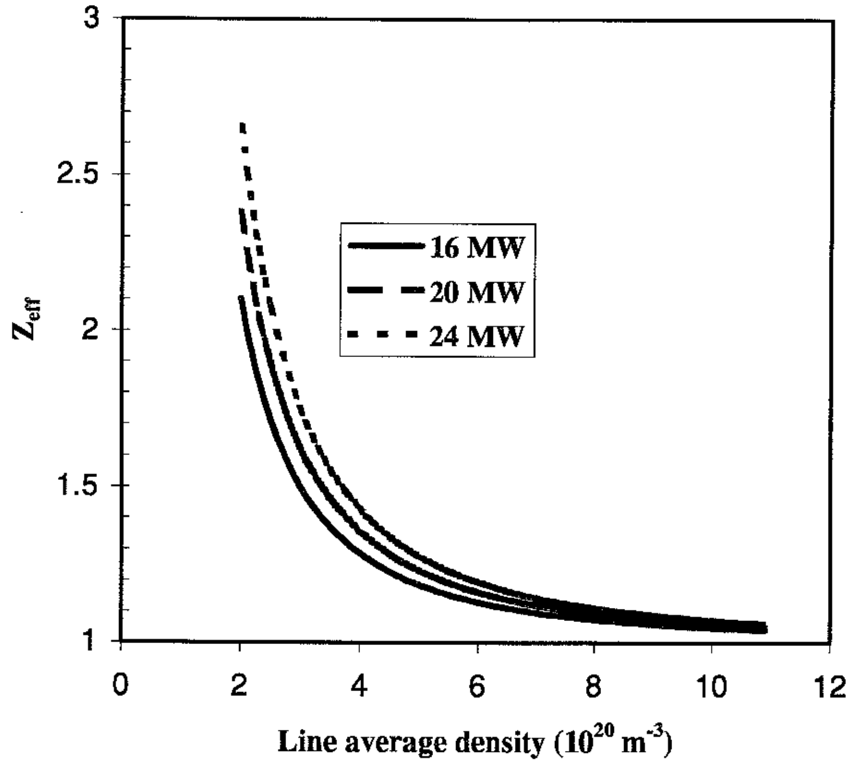

Fig 2. Degree of plasma contamination as a function of density according to the scaling of Ref.[5] applied to Ignitor, for different amounts of radiated power.

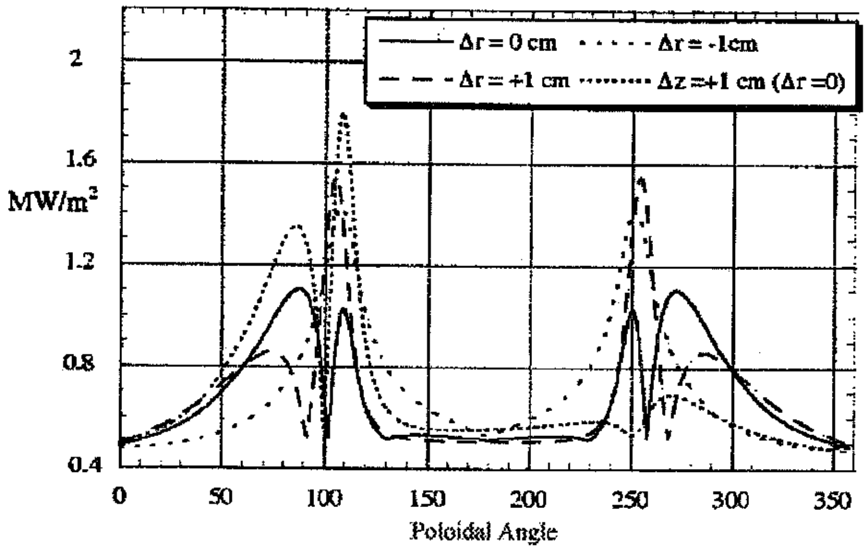

Fig. 3. Thermal load distribution under ignition condition for different radial shifts.

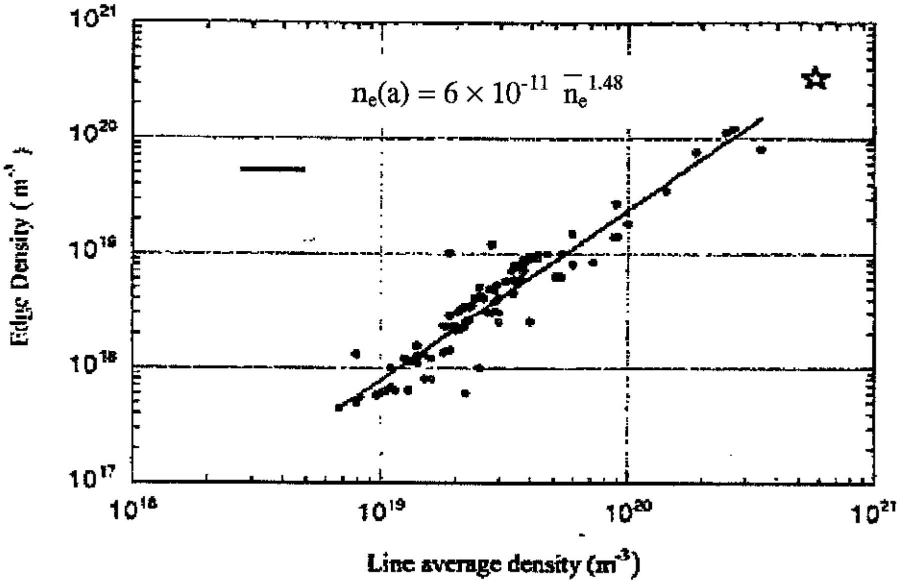

Fig. 4. Experimental values of the edge density vs the line average density. The star represents the extrapolated value for the reference Ignitor discharge.

References

[1] C. S. Pitcher and P.C. Stangeby, *Plasma Phys. and Control. Fusion* **39**, 779 (1997).

[2] A. Gibson and M.L. Watkins, *Controll. Fusion and Plasma Phys.*, Proceed. 9th EPS Conf., Vol. **1**, 31 (1977).

[3] Minutes of the "Workshop on Research Programme on Radiative Mode in Existing European Facilities", Jülich (Germany), January 13-14, 1999.

[4] R.R. Weynants, A.M. Messiaen, J. Ongena, *et al.*, *Fusion Energy* 1998,Yokohama, Japan, paper IAEA-F1-CN-69-EX1/3.

[5] G.F. Matthews, *et al.*, *Journal of Nuclear Materials* **241 & 243**, 450 (1997).

[6] R. Zanino and C. Ferro, *Contrib. Plasma Phys.* **36,** 260 (1996).

[7] K. McCormick, *et al.*, *Journal of Nuclear Materials* **226 & 269**, 99 (1999).

[8] P.C. Stangeby, G.M. McCracken, *Nuclear Fusion* **30**, 1225 (1990).

[9] S. Pitcher, *Private Communication.*

[10]J. Bohdansky, J. Roth and H. Vernickel, *Fusion Technology*, 10th S.O.F.T., Pergamon Press, Oxford, p.801 (1979).

[11]B. Lipschultz, *et al.*, *Journal of Nuclear Materials* **128 & 129**, 555 (1984).

[12]B. Lipschultz, *et al.*, 13th PSI Conference, paper O-26, accepted for publication in *J. of Nuclear Materials.*