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# Lightly- or non-seeded, partially detached ITER divertor operation

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**Abstract**

The ITER divertor scenario calls for the reduction of direct target loading to $< 50$ MW by the use of edge/divertor radiation, enhanced by a seeded recycling impurity, to 'detach' the divertor plasma from the target plates. At this radiated power fraction core plasma confinement quality is degraded, the radiation comes mainly from the X-point region and impurity control becomes difficult. In this paper we examine the possibility of using either no impurity seeding, or very light impurity seeding, in an attached mode of operation to alleviate these problems. It is concluded that such scenarios should be possible if an edge separatrix density of $5 \times 10^{19}$ m$^{-3}$, which corresponds approximately to the ITER design value, can be achieved.

*Keywords:* ITER; Divertor plasma; 2D model

## 1. Introduction

The problem of designing a divertor which will exhaust the power and He ash while maintaining plasma purity and ensuring adequate target lifetime is one of the most difficult tasks facing ITER. In the CDA phase, a double null, high recycling divertor was proposed [1]. Early in the EDA phase, when it was believed that the ITER output power might be as high as 3.5 GW thermal, it was recognized that the conventional high recycling solution would not work because the target plates would be severely overloaded, even when tilted to the maximum amount allowed by technical constraints governing the angle between field and target plate surface. Rebut then proposed a 'gas box' divertor, with full removal of exhaust energy via hydrogenic radiation and charge exchange (the 'fully detached' solution in which the energy reaching the target plates is negligible) [2]. Calculations from several groups showed, however, that this was not feasible with hydrogenic plasma alone and the concept of impurity seeding was introduced to increase radiative losses. Whilst this change helps to solve the power exhaust problem, it brings complications with respect to impurity content, dilution and confinement quality of the main plasma.

As the EDA design work proceeded, it was decided to limit the ITER output to 1.5 GW thermal, primarily for reasons having to do with first wall design. This reduces the divertor target loading to the range where it is worth re-examining the question as to whether a fully detached divertor solution is necessary, or even desirable. In this paper we suggest a return to the non-seeded, partly attached case, if possible, or the use of very light impurity seeding, if required to keep the target plate loading to the design value of 5 MW/m$^2$.

## 2. The present ITER divertor strategy

In order to meet its goals, ITER must achieve:

- High energy confinement quality: $H/q_{95} \sim 2/3$.
- Good particle control: density controlled within 10%, adequate He exhaust rate.
- Low dilution: $Z_{\text{eff}} < 1.6$, including He ash ($\Delta Z_{\text{eff,imp}} <$ 0.2).
- Adequate target lifetime: minimize erosion, avoid melting ($\leq 5$ Mw/m$^2$, ELM energy arriving at target to be minimized).

The ITER plasma will be heated by 300 MW of $\alpha$ particle power, of which 100 MW is expected to be directly exhausted by Bremmstrahlung. It is proposed by the ITER team to introduce a recycling impurity seed to

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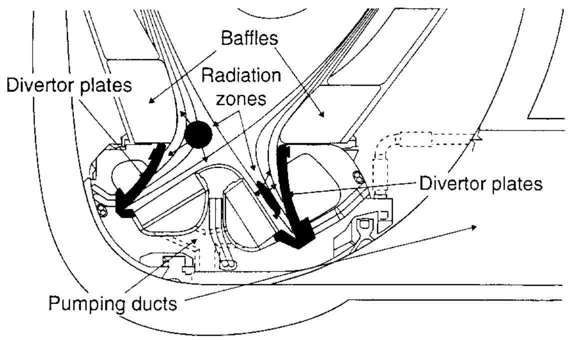


Fig. 1. The ITER vertical target gas box divertor.

radiate an additional 50 MW from the edge plasma and 100 MW from the divertor, in order to keep the total target loading below 50 MW [3]. This corresponds to a total radiated power fraction of over 80%. The geometry proposed is a 'vertical target gas box' (Fig. 1). Because the targets are highly inclined to the poloidal flux surfaces, the total available target area is quite large, approximately 60 $m^2$. The planned level of total core plus main plasma edge radiation implies operation near the $H \rightarrow L$ threshold as predicted from current scaling laws, so that type 1 ELMs may not be present.

This scheme has the advantages that (a), the peak power to the divertor plates is reduced well below 5 $MW/m^2$, minimizing erosion, and (b) because operation will be just above threshold, ELM impact on divertor should be minimal.

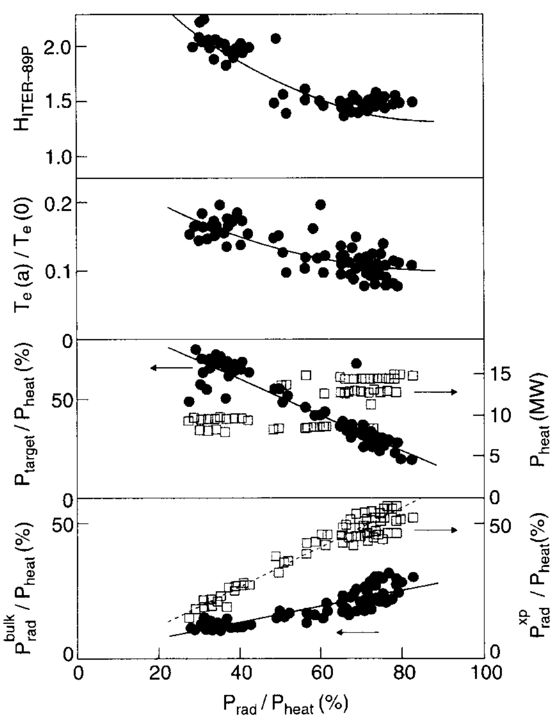


Fig. 2. Degradation of confinement with radiated power fraction, JET $N_2$ seeded shots (from Ref. [4]).

On the other hand, it has been observed experimentally at JET and on other devices that there are a several disadvantages of using such a high radiated power fraction. First, core confinement quality is reduced. An example of the decrease in the H-factor with increasing radiated power fraction for nitrogen-seeded discharges in JET is shown in Fig. 2 [4]. The main plasma transport appears to change from gyrobohm-like to bohm-like as H-mode threshold is approached, as described in [5]. In addition, the hysteresis in the $L \rightarrow H \rightarrow L$ transitions disappears [6]. These three effects make it difficult for ITER to ignite, given present understanding of the scaling laws.

Secondly, the use of a high radiated power fraction exacerbates the impurity control problem. Above a certain value of $f_{rad}$, the radiation zone moves from the proximity of the target plates to the X-point region, as shown in [7]. In this case, the impurities are not concentrated in the divertor region, the divertor volume is not used effectively, wasting valuable space within the first wall and it is difficult to achieve acceptably low values of $Z_{eff}$, especially at edge densities commensurate with the Greenwald density limit [8].

## 3. An alternate divertor strategy for ITER

We suggest that, in view of the difficulties listed above with the present ITER strategy, which results primarily from limiting the total direct target loading to 50 MW, that two other operating scenarios should be examined.

The first is to consider operating without impurity seeding, relying on the highly tilted targets and the naturally occurring volumetric loss processes (hydrogen radiation and charge exchange and radiation from intrinsic impurities to reduce the target loading to an acceptable value. If successful, this would provide good impurity control and improved main chamber confinement. However, it would raise new problems with respect to target peak heat load, erosion and the probable re-introduction of type 1 ELMs. These problems are discussed later in the paper.

As a back-up strategy, we suggest that if operating with no impurity seeding proves to be not feasible, then seeding should be used in the minimum amount necessary to bring the target loads to an acceptable level. In contrast to the present ITER strategy, this implies using low radiated power fractions and only partial detachment, to keep the radiation zone within the divertor volume and make use of the available power exhaust surface area. The primary question then becomes whether or not the stringent $Z_{eff}$ requirements can be met.

## 4. ITER divertor simulations

Simulations were performed for both pure plasmas and plasmas lightly seeded with a recycling impurity using the EDGE2D/NIMBUS code system [9]. The input power crossing the separatrix was kept fixed at 200 MW, with 150 MW and 50 MW in the ion and electron channels, respectively. The base case transport assumed $\chi_E = 1.0$ m$^2$ s$^{-1}$ and $D = 0\ 5$ m$^2$ s$^{-1}$ and no inward pinch. Two midplane separatrix densities were modelled, $5 \times 10^{19}$ m$^{-3}$ and $2.5 \times 10^{19}$ m$^{-3}$. The higher value corresponds to about 35% of the ITER design volume averaged density operating point [3] and the lower to 35% of 85% of the ITER Greenwald limit ($8.5 \times 10^{19}$ m$^{-3}$), typical of the normalized density reached in JET radiative divertor H-mode discharges.

### 4.1. Target plate power loading density

Fig. 3 shows the power loading profile for the outer target plate, which usually is the more highly loaded of the two. The curves include power transmitted through the sheath in the electron and ion channels and the surface recombination load. They do not, however, include the radiated power load. For the pure plasma base case at $n_s = 5 \times 10^{19}$ m$^{-3}$, the total power integrated across the two target plates is 180 MW, 3.5 times the amount allowed in the current ITER design specifications but nonetheless the peak power density (excluding radiation) is only 7 MW/m$^2$. This low peak value results from the relatively broad power profiles which were found with the assumed transport model. The ITER design requirement of 5 MW/m$^2$ is exceeded over only 12 cm of target height, or about 17% of the total available target area. It might be

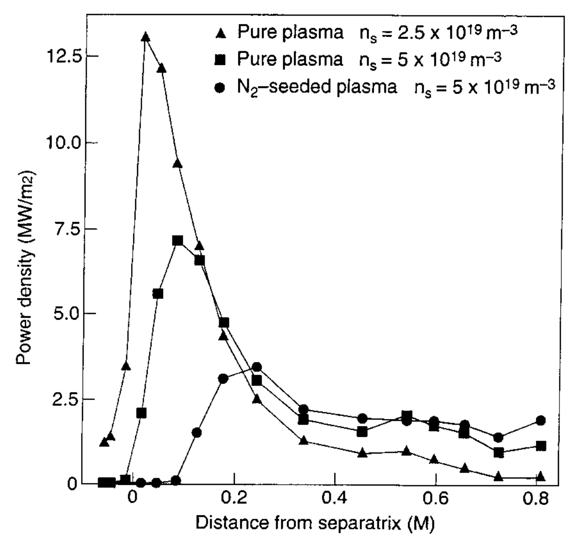


Fig. 3. Outer target power loading for the pure plasma and $N_2$ seeded base cases.

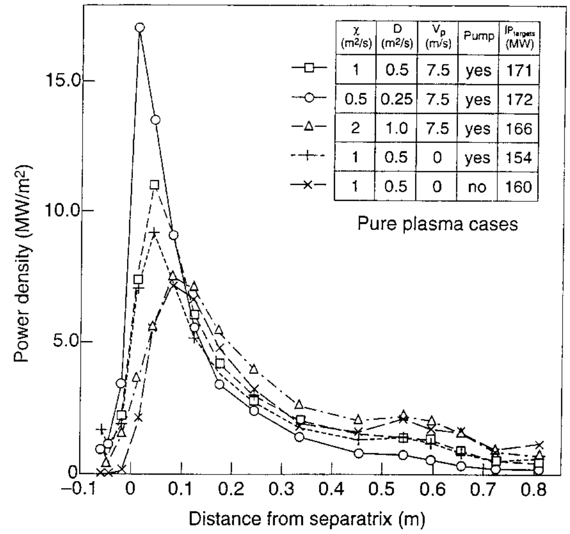


Fig. 4. Sensitivity of the power loading profiles to the assumed perpendicular transport.

possible to reduce the target loading to below 5 MW/m$^2$, in the non-seeded case, by reducing the poloidal plate angle from 15° to 10° near the separatrix (total field line inclination from about 2° to 1.3°) if technical considerations permit, or to accept a somewhat shorter target lifetime. When the midplane separatrix density is reduced to $2.5 \times 10^{19}$ m$^{-3}$, the loading rises to a peak value of 13 MW/m$^2$, due to a reduction in the volumetric loss processes, particularly near the separatrix. The addition of a sufficient amount of nitrogen (treated in these simulations as a fully recycling impurity) to radiate 80 of the 200 MW input to the SOL reduces the direct peak plate loading to below 4 MW/m$^2$ In this case the divertor plasma is detached near the separatrix, removing the high peak power normally found there, but attached further out.

### 4.2. Sensitivity of the power loading profile to perpendicular transport

The target profile loading profiles, as exemplified in Fig. 3, depend directly on the perpendicular transport model used. Fig. 4 shows the variation, for the pure plasma case at $n_s = 5 \times 10^{19}$ m$^{-3}$, when the transport coefficients are increased or decreased by a factor of 2 from the base case of Fig. 3. It also shows variations arising from assuming an inward SOL pinch, which has been found to be useful in reproducing some (but not all) of the features seen in JET experiments and finally from turning on pumping at the level of approximately $1.2 \times 10^{23}$ s$^{-1}$ (about 1% of the target flux). Reducing $\chi_E$ peaks the profiles towards the separatrix, increasing the peak power loading, while increasing $\chi_E$ has the opposite effect, as expected. The effect of pumping is to raise the peak power by raising $T_e$ near the separatrix. The effect of

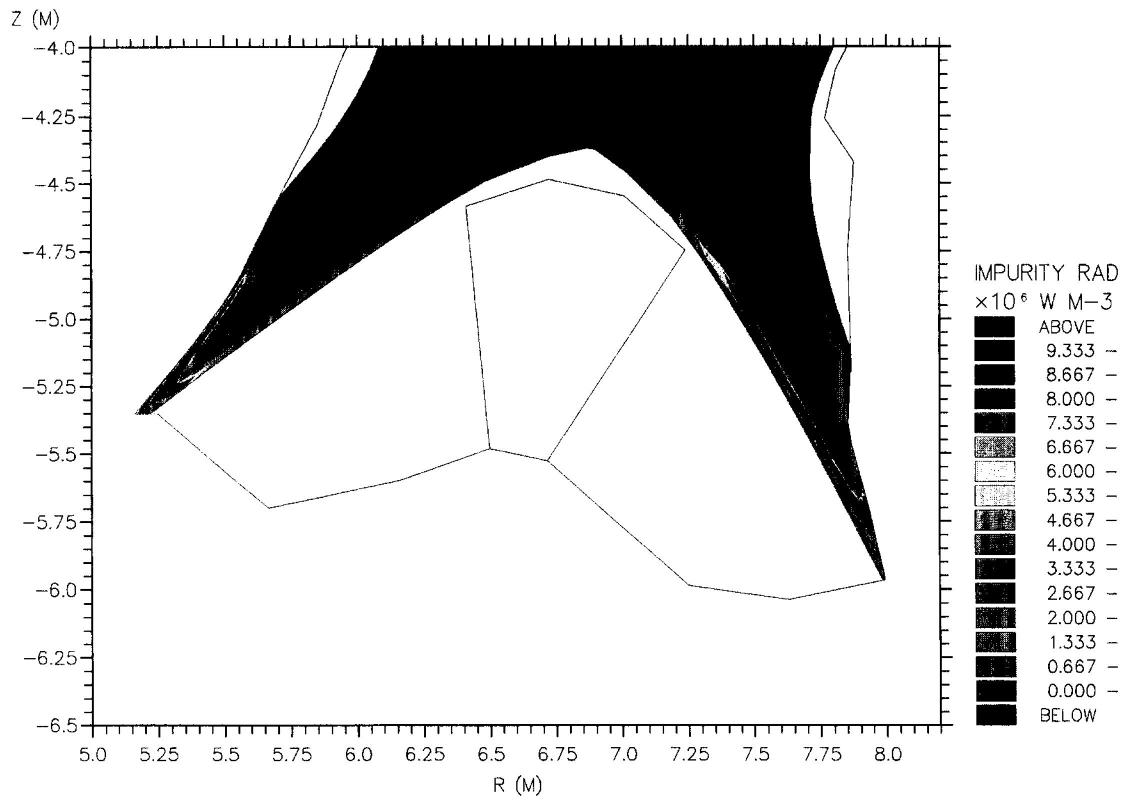


Fig. 5. Contours of impurity radiation density, 80 MW $N_2$ seeded case.

an inward pinch is also to raise the peak power slightly. The rather large variation in peak power loading seen in Fig. 4 emphasises the need for more precise knowledge of perpendicular transport in the SOL than is currently available.

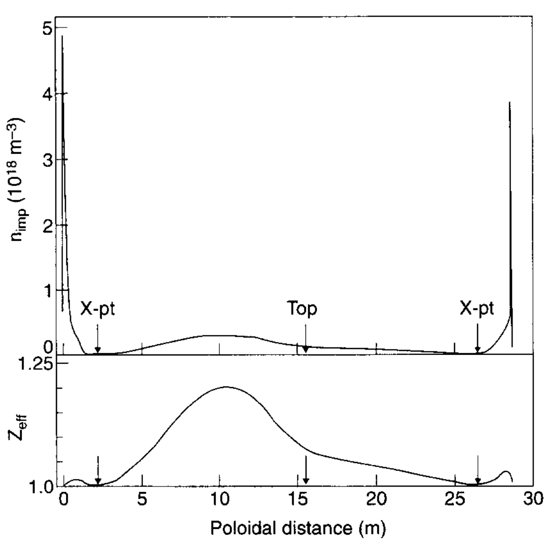


Fig. 6. Poloidal distribution along the separatrix of total impurity density and $Z_{eff}$, $N_2$ seeded case.

### 4.3. Distribution of impurities and impurity radiation

In this simulation the plasma is still 'attached' to the plates, in the sense of pressure ratio from midplane to plates, except near the separatrix. The detachment near the separatrix is caused by enhanced radiative power loss. Fig. 5 shows a contour plot of the distribution of impurity radiation density for the case of lightly seeded nitrogen. The band of radiation in the outer divertor leg extends from the plate, where it is most intense, along the separatrix towards the X-point. Such a distribution makes good use of the divertor volume by spreading the radiative load over a large surface area. The radiation on the inner leg is similarly dispersed, although to a slightly lesser degree. There is very little radiation near the X-point at this relatively low total radiated power fraction. 98% of the nitrogen radiation is emitted from the divertor region.

Fig. 6 shows the poloidal distribution of nitrogen density along the separatrix from the outer divertor to the inner divertor and the corresponding value of $Z_{eff}$. The impurity particle density is peaked in the divertor, but only 32% of the total inventory of nitrogen atoms is found there. The 68% found in the main SOL/core edge does not radiate appreciably because of its high temperature there, but nevertheless contributes to $Z_{eff}$ in the SOL. Although the nitrogen density is highest in the outer divertor, its concentration there is similar to that in the midplane, where the highest $Z_{eff}$ occurs. This is characteristic of our simulations, from which we conclude that ITER has too low a pumping speed to create a SOL flow sufficient to effectively retain recycling impurities in the divertor. Because of the low total $N_2$ radiation, coupled with the high edge plasma density, $Z_{eff,max}$ along the separatrix in this simulation satisfies the ITER requirement that $\Delta Z_{eff,seed} \leq 0.2$.

The computed values of radiation depend directly, of course, on the accuracy of the atomic physics data used in the code and in particular on the radiation cooling curves. There is some indirect evidence from JET experiments that the nitrogen cooling curve may overestimate the amount of radiation per injected nitrogen particle. Likewise, our attempts to simulate radiation from intrinsically produced carbon suffer both from lack of accurate knowledge of the cooling curve, as well as from poor characterization of the chemical sputtering yield. Thus, precise prediction of radiation in ITER will not be possible until improved, validated atomic physics data is available.

## 5. Discussion

### 5.1. ELMs

The scenarios we are suggesting, where edge impurity radiation is minimized and consequently about 200 MW flows into the SOL, means that the operation may be well above the H → L threshold, which should improve main chamber confinement, but re-introduce type 1 ELMs. These pose a serious problem for the divertor unless the energy loss per ELM which is actually transmitted to the divertor plates is less than about 1% of the stored energy and the SOL is substantially broadened during the ELM event. The scaling of ELM energy loss with machine size is not yet firmly established, but recent estimates by Osborne [10] suggest that the total energy loss per ELM for type 1 ELMs in ITER may be around 3%. Lingertat et al., however, report that of the total energy loss in an ELM measured in JET, most is radiated and only a small fraction is transmitted to the target plates. Furthermore, they report a broadening of the SOL by a factor of 3 or 4 [11]. There is thus room for optimism that type 1 ELMs of the size expected in ITER may pose less of a divertor problem than has been anticipated.

### 5.2. Erosion

Operating portions of the target at power densities above 5 $MW/m^2$ reduces their lifetime. At a power density of 7 $MW/m^2$, obtained in the high density pure plasma case, the reduction may be acceptable. At 10 $MW/m^2$, the estimated reduction is a factor of 2.8 [12], which is excessive.

### 5.3. Density limit

If a midplane separatrix density of $5 \times 10^{19}$ $m^{-3}$ can be achieved in ITER, then both the pure plasma and lightly seeded plasma scenarios discussed above might satisfy ITER's divertor design criteria. However, if the edge density is limited to an appreciably lower value, as would be suggested by the ratio of edge to line average density commonly accepted for ELMy H-modes of 30–40%, coupled with a Greenwald limit for ITER of $8.5 \times 10^{19}$ $m^{-3}$, then the divertor problem becomes much more difficult. In the case of pure plasma operation, the plate loading rises to values resulting in relatively short lifetimes. In the seeded case, the amount of seed required to produce a given radiated power goes up rapidly (see Ref. [8]), resulting in unacceptably high values of $Z_{eff}$ in the plasma core. It does not appear to be possible, based on these simulations, to increase the seed density only in the ITER divertor and not in the core at achievable values of SOL flow. Although there is a large database suggesting that the Greenwald limit cannot readily be exceeded in gas-puffed H-mode discharges, recent experiments at ASDEX Upgrade using repetitive pellet fuelling have demonstrated H-mode operation well above the Greenwald limit, albeit at the expense of reduced energy confinement [13].

## 6. Conclusions

Adopting a low radiated power fraction, partly attached divertor operating scenario for ITER may make it possible to maintain the required confinement quality and purity in the main plasma while providing satisfactory divertor target plate lifetimes against erosion. The viability of this approach requires more information on the scaling of ELMs and the H-mode threshold, as well as better characterization of the perpendicular SOL transport and sputtering and radiation data. This approach (and all ITER divertor scenarios) depend rather critically on the upstream SOL density which can be achieved.

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