## Lightly- or Non-Seeded, Partially Detached ITER Divertor Operation

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### 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 $MW/m^2$.

### THE PRESENT ITER DIVERTOR STRATEGY

In order 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: $Z_{eff} < 1.6$, including He ash ($\Delta Z_{eff,\,imp} < 0.2$)

- Adequate target lifetime: minimize erosion, avoid melting (≤5 $MW/m^2$, ELM avoidance)

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 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→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. 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 Figure 2 [4]. The main plasma transport appears to change from gyrobohm-like to bohm-like as H mode threshold is approached, as shown in Figure 3 [5] In addition, the hysteresis in the L→H → 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 ref. [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].

## 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.

## 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 $\chi_E = 1.0\ m^2s^{-1}$ and $D = 0.5\ m^2s^{-1}$ and no inward pinch. The midplane separatrix density was varied between 2.5 and 5.0 x $10^{19}\ m^{-3}$, with the upper value corresponding roughly to the ITER design operating point, and the lower to approximately the level expected for operation at 70% of the Greenwald limit. Figure 4 shows the computational grid used for the runs reported here.

### Target Plate Power Loading Density

Fig. 5 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. 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 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 should be 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 x $10^{19}$ $m^{-3}$, 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 MW of the 200 MW input to the SOL reduces the 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. In this simulation, some of the variables were still evolving on a very slow time scale, so the results should be taken as indicative only.

**Sensitivity of the power loading profile to perpendicular transport**

The target profile loading profiles, as exemplified in fig. 5, depend directly on the perpendicular transport model used. Fig. 6 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. 5. 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 peakpower 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 an inward pinch is also to raise the peak power slightly. The rather large variation in peak power loading seen in figure 6 emphasises the need for more precise knowledge of perpendicular transport in the SOL than is currently available.

**Distribution of Impurities and Impurity Radiation**

Figs. 7 and 8 show contour plots of the distribution of impurity particle density (summed over all ionization stages) and radiation density, respectively, for the case of lightly seeded nitrogen. The plasma is still "attached" to the plates, in the sense of pressure ratio from midplane to plates, except near the separatrix. 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. The contours represent linear, not logarithmic variations. There is very little radiation near the X-point. 98% of the nitrogen radiation is emitted from the divertor region. The impurity particle density is also 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 the high temperature there, but nevertheless contributes to $Z_{eff}$ in the SOL.

Figure 11 shows the poloidal distribution of nitrogen density and nitrogen concentration along the separatrix from the outer divertor to the inner divertor, and the corresponding value of $Z_{eff}$. Although the impurity density is highest in the outer divertor, the impurity 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, the maximum value of $Z_{eff}$ along the separatrix in this simulation satisfies the ITER requirement that

$$\Delta Z_{eff,\ imp} \leq 0.2.$$

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.

## DISCUSSION

### 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 confimenent, 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 T. 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.

### 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.

**Density Limit**

If a midplane separatrix density of 5 x $10^{19}$ $m^{-3}$ 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 about 30%, coupled with a Greenwald limit for ITER below $10^{20}$ $m^{-3}$, 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, resulting in unacceptably high values of $Z_{eff}$ in the plasma core. It does not appear to be possible, based on both simulations and experimental evidence, to increase the seed density only in the divertor and not in the core at achievable values of SOL flow, with a closed divertor.

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].

## 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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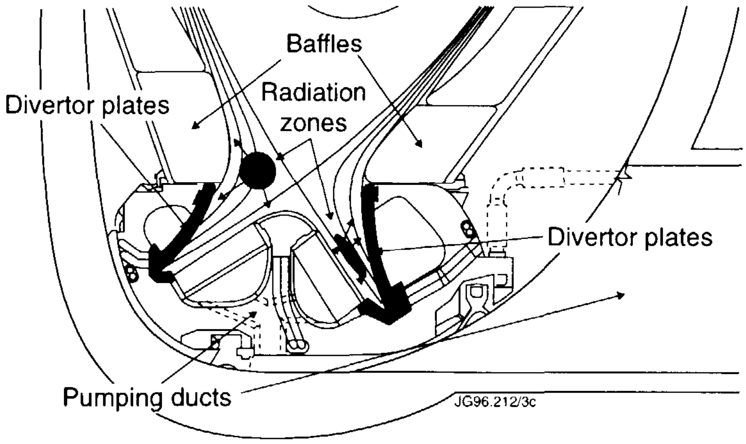



*Fig.1: The ITER Vertical Target Gas Box Divertor*

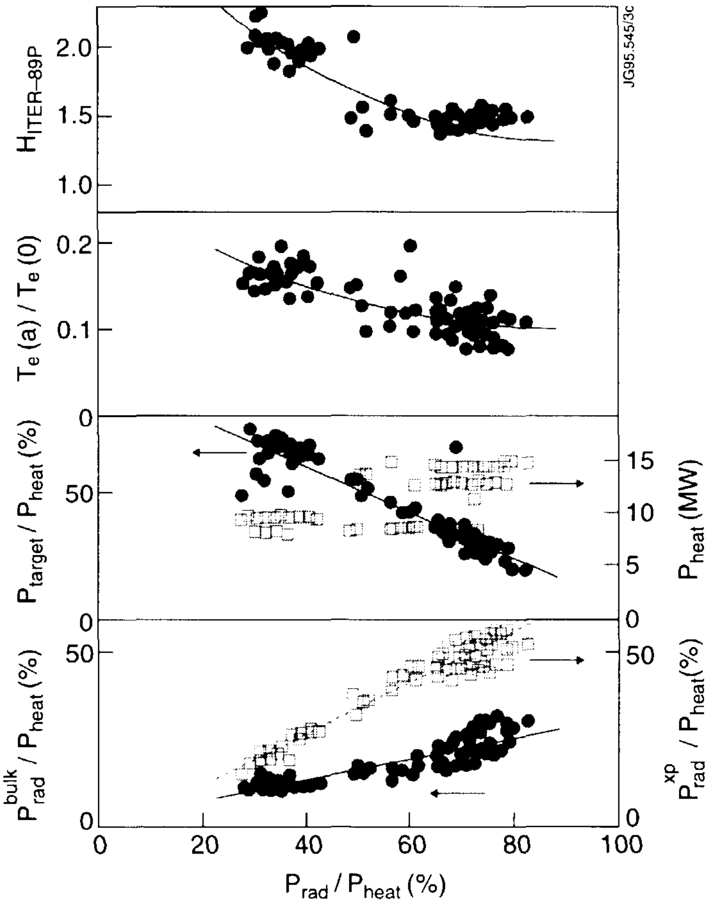



*Fig.2: Degradation of Confinement with Radiated Power Fraction, JET $N_2$ Seeded Shots (from Ref. 4)*

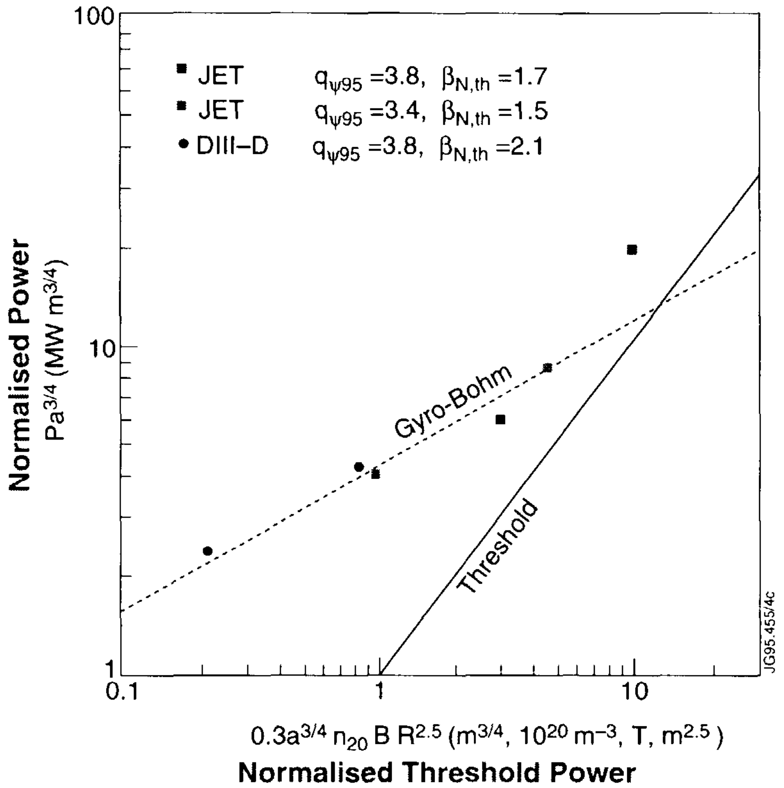



*Fig.3: Degradation of Transport near the H-mode Threshold (after Cordey et. al. [5])*

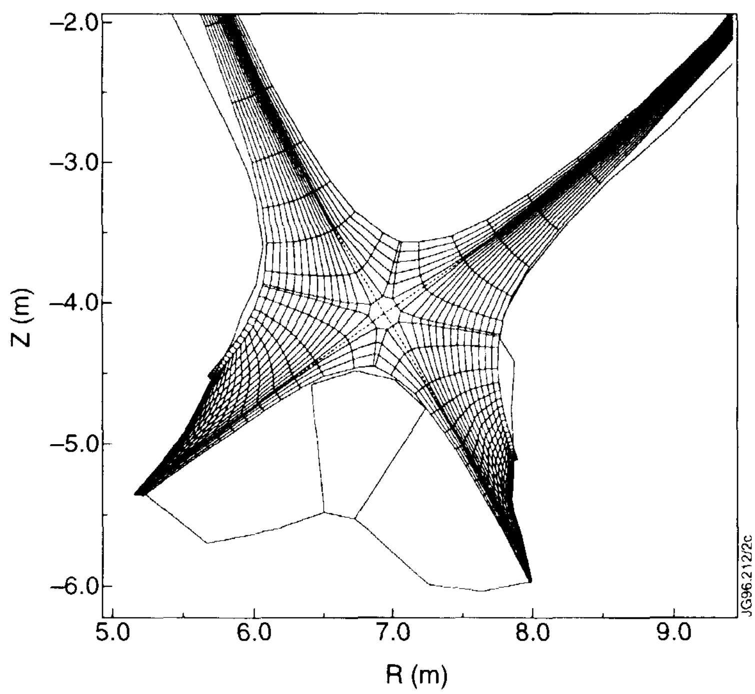



*Fig.4: The EDGE2D Computational Grid for ITER Simulations*

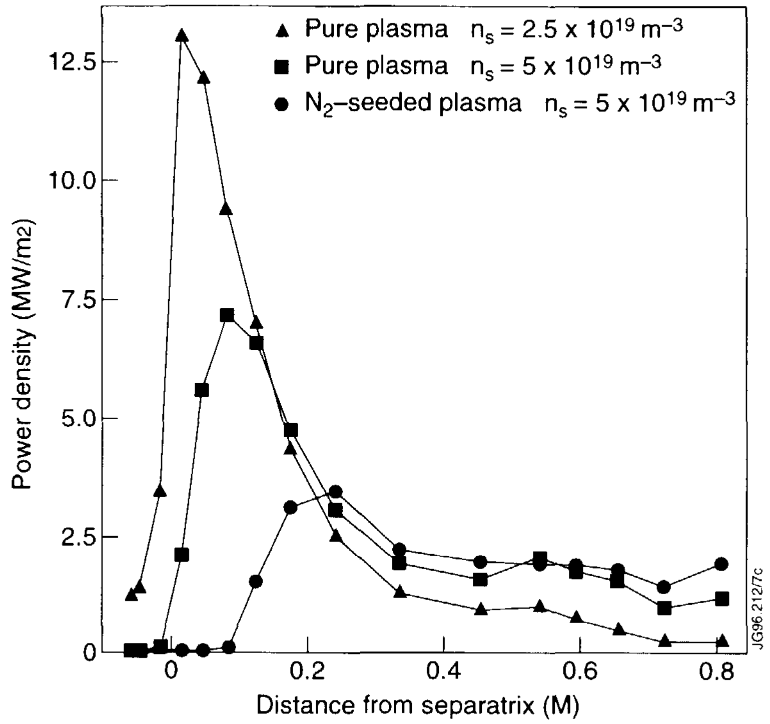



*Fig.5: Outer Target Power Loading for the Pure Plasma and $N_2$ Seeded Base Cases*

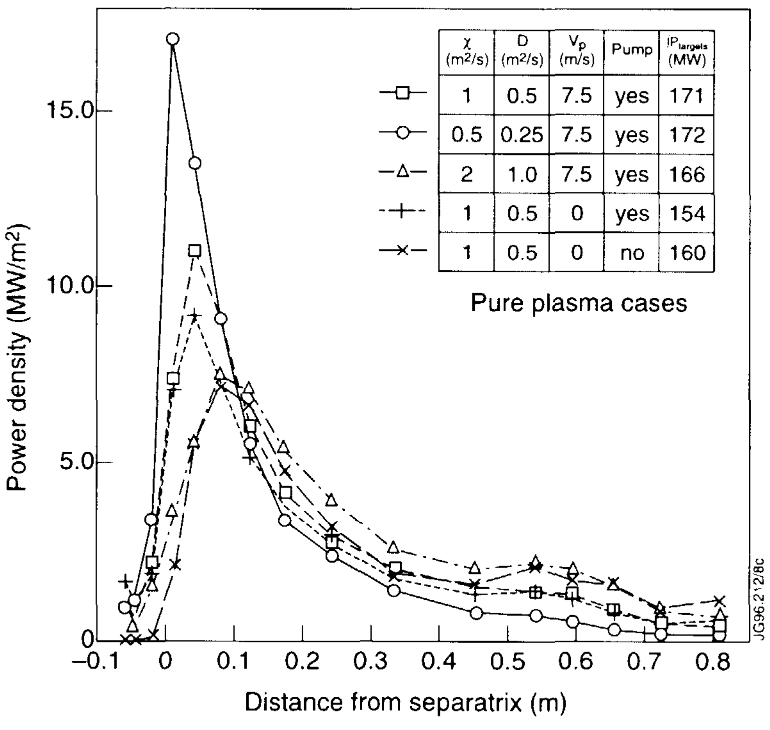



*Fig.6: Sensitivity of the Power Loading Profiles to the Assumed Perpendicular Transport*

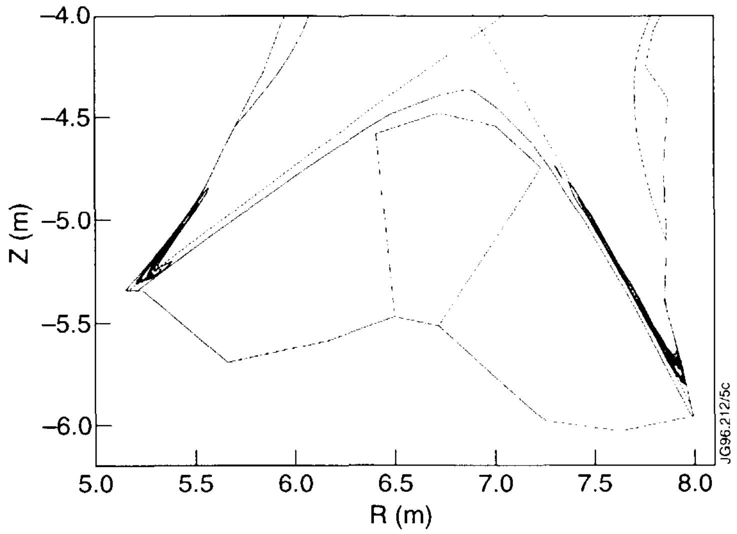



*Fig.7: Contours of Impurity Radiation Density, 80 MW $N_2$ Seeded Case*

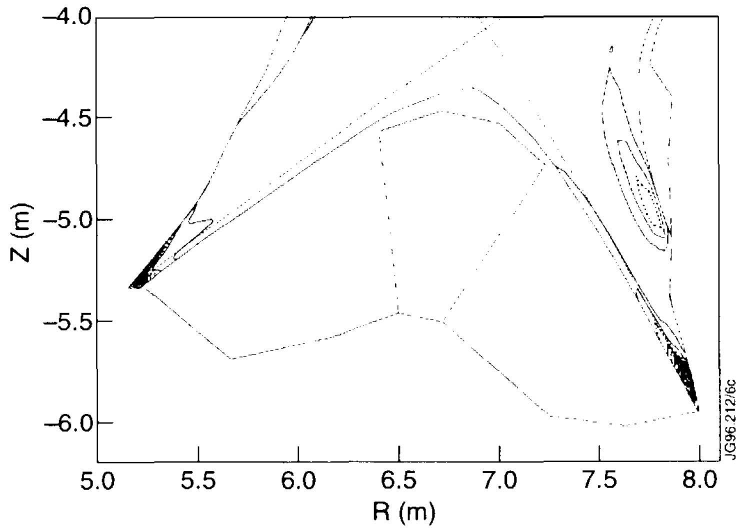
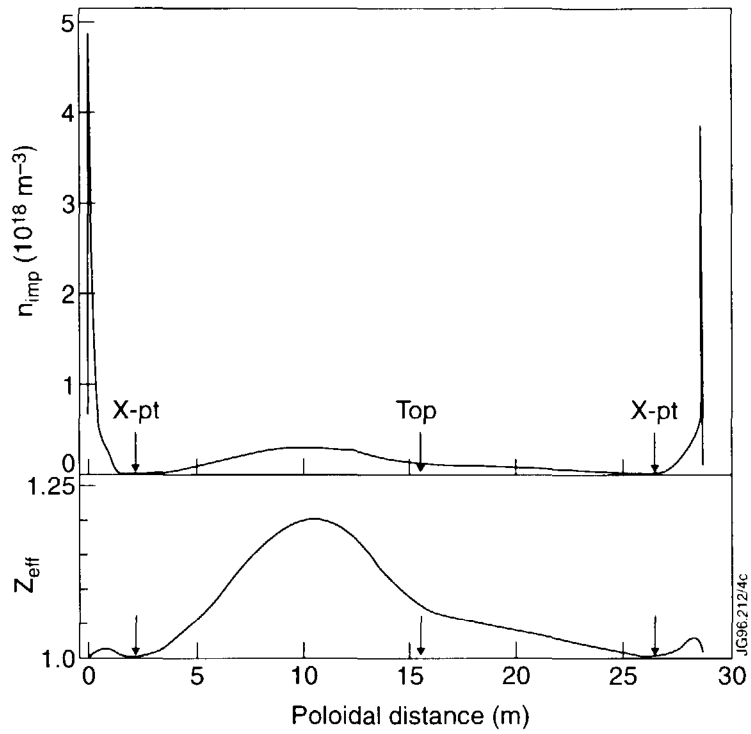



*Fig.8: Countours of Impurity Density, 80 MW $N_2$ Seeded Case*



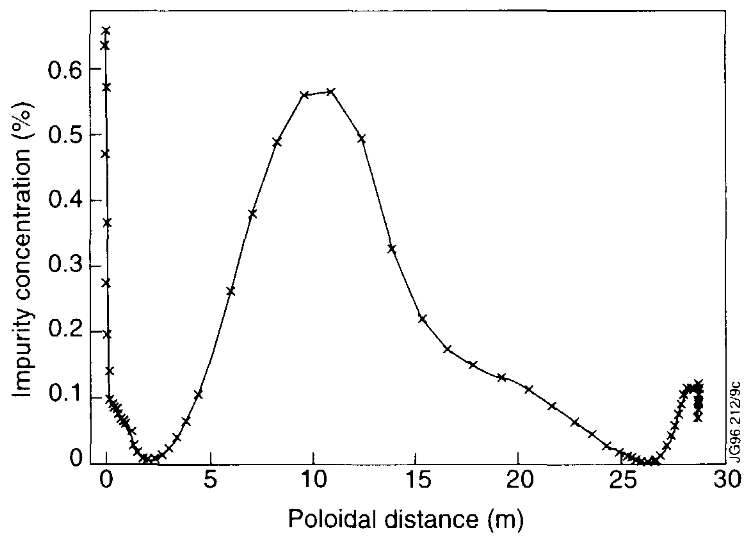




*Fig.9: Poloidal Distribution along the Separatrix of Total Impurity Density, Impurity Concentration, and $Z_{eff}$, $N_2$ Seeded Case*