JOINT EUROPEAN TORUS

JET–P(93)80

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A Review of Progress Towards a Next Step Divertor

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Preprint of a paper to be submitted for publication in
Plasma Physics and Controlled Fusion, based on a Review Lecture at the
20th EPS Meeting, Lisbon, August 1993
October 1993

ABSTRACT. Solution of the ITER divertor problem will require techniques which redistribute the SOL power onto a much larger surface than conventional target plate design permits, while maintaining good control of impurities. Progress made in developing such techniques is reviewed. These include gas target divertors, impurity-seeded radiating divertors, and glancing incidence targets.

Keywords: Edge physics, power exhaust, impurity control, tokamak.

I. INTRODUCTION

It is generally recognised that the coupled problems of power and particle exhaust, and impurity control, are among the most difficult facing the design of a next step large fusion device such as ITER. A review of the physics of power exhaust, with particular regard to tokamaks and stellarators, was presented by Neuhauser (1992). In this paper we first examine the solution to divertor problems in present day tokamaks, as embodied in the conventional "high recycling divertor" concept. We then show that this approach will not suffice for an ITER sized tokamak, principally because the heat deposition is too localised, resulting in severe erosion or melting of the target plates. The various solutions which have been proposed, each of which involves methods for distributing the exhaust power over a large divertor wall area, are then discussed. Only steady-state scenarios are considered. The very important area of instabilities (ELMs and others) is beyond the scope of this review.

II. THE "CONVENTIONAL" HIGH RECYCLING DIVERTOR

In a divertor tokamak, the power which crosses the last closed flux surface (separatrix) via perpendicular transport then flows primarily in the direction parallel to B along the open flux surfaces into the divertor chamber and onto targets. Because of the great disparity between perpendicular and parallel transport rates, the flow is confined to a thin region, the scrape-off layer (SOL), which is typically only about 1 cm thick at the midplane. Energetic ions incident upon the targets cause an influx of target material (impurities) into the divertor plasma via sputtering. The steady state distribution of impurities along the open field lines is set by a balance of friction force towards the target, thermal gradient forces away (Neuhauser 1984, Keilhacker et. al 1990), and perpendicular diffusion. In a well designed divertor most of the impurities will be retained near the targets.

We define a "conventional" high recycling divertor as one in which the plasma remains in contact with the targets ("attached") and most of the neutrals recycling from the target are reionized in the divertor, rather than escaping. The parallel heat flux is predominantly by conduction, except in the reionization zone near the targets. We further extend the definition, in the present context, by technical considerations: the targets should not receive a total heat load of more than 5 MW/m^2 to satisfy steady state cooling requirements, and the angle of incidence between the field lines and the target should not be less than about 1 degree in order to avoid the problem of tile misalignment, field errors, thermal distortions, etc. (Tomabechi et. al. 1991). (We discuss the consequences of relaxing this last restriction later in the paper.)

Present day thinking favours "closed" divertors, i.e. those for which the escape fraction for recycled neutrals is small. This leads to low temperature, high density divertor plasma for a given SOL power (P_{SOL}) and midplane separatrix density (n_s). Target sputtering is reduced and retention of impurities is enhanced (Vlases and Simonini, 1991). In addition, hydrogenic radiation losses increase due to the increased particle flux to the targets, reducing the heat load on the plates, and the divertor neutral pressure increases, leading to better pumping.

Finally, reducing flow of hydrogen neutrals to the main chamber reduces CX sputtering of wall material, which was shown to be a primary source of impurities in JET divertor discharges (Matthews et al. 1992). The divertor may be closed either mechanically, by proper arrangement of target plates and baffles (divertor walls), or at high densities by the plasma itself ("plasma plugging"). If the baffle is as shown in figure 1a, neutrals can recirculate freely within the divertor volume, at the expense of maximum density and minimum temperature near the plates. For a slot-like divertor (figure 1b), where neutrals are retained close to the target, the coldest densest plasma is obtained, but the radiation from recycling hydrogen and target-produced impurities is very localised near the target.

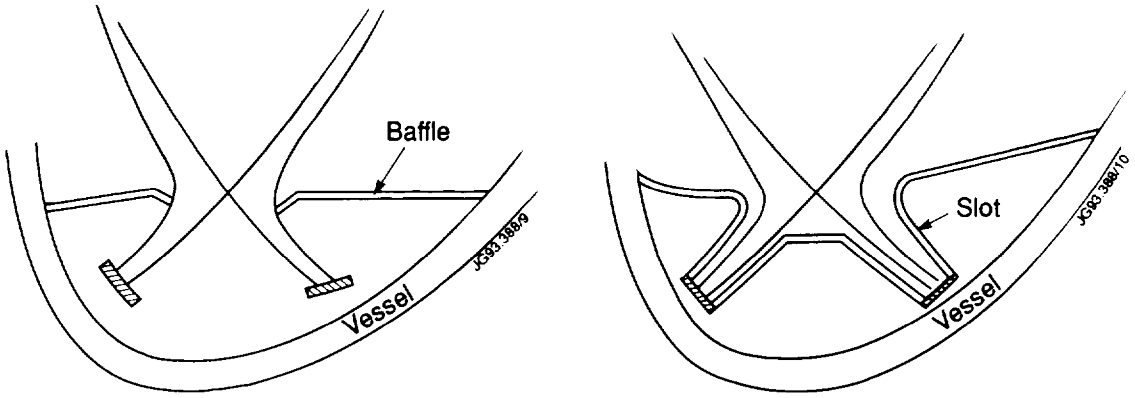

Fig. 1. Sketch of two types of closed divertors.

Codes have advanced to the point where multi-species simulations of divertors with realistic geometries, including inclined targets, are now possible. Simonini et al (1993) report a simulation for a proposed vertical target divertor in JET (figure 2a) where, with an upstream density of $n_s = 2 \times 10^{19}$ m^{-3} and $P_{SOL} = 20$ MW, only 3.7 MW of "conducted power" was transmitted through the sheath to the targets. Adding the heat load from surface recombination on the plates and from radiation, the total to the targets was estimated to be 11.2 MW, with a peak loading of 2.4 MW per m^3 (figure 2b). The value of Z_{eff} at the midplane remained below 1.2.. This calculation suggests that the conventional high recycling divertor approach should work well for the present generation tokamaks, where simulations indicate that heat loads can be kept well below 5 MW/m^2 and good impurity control is achieved.

We note that it seems advisable to restrict consideration of next step divertors to the single null configuration. As pointed out by Janeschitz et. al (1993), operation with unbalanced power into inner and outer divertors means that it is very unlikely that one can achieve similar behaviour in both divertor legs simultaneously (i.e. high recycling, or detached/gas target operation). With a single null, the power asymmetry normally found can be largely eliminated by operating with the ion grad B drift pointing away from the target; balancing the power between inner and outer divertor legs in a double null configuration appears difficult. Separate pumping/puffing capabilities in the inner and outer legs may help.

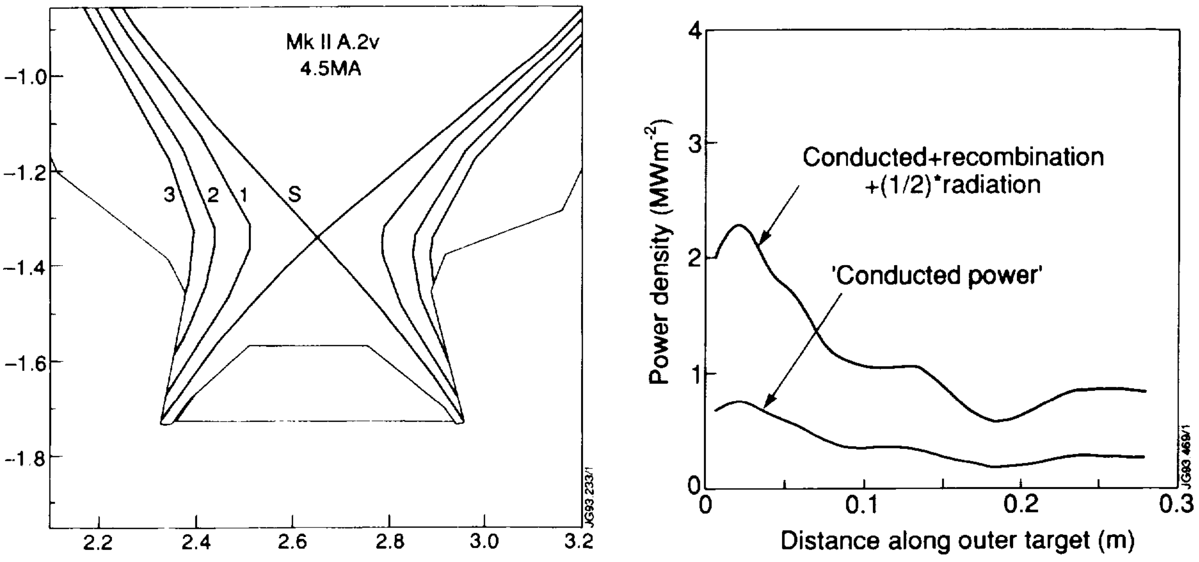

Fig. 2. (a) Geometry for a JET simulation with $P_{SOL} = 20\ MW$ *and* $n_s = 2x10^{19}\ m^{-3}$. *(b)Power to the outside target. (after Simonini et. al. 1993)*

III. THE ITER DIVERTOR PROBLEM

The poloidal wetted length on the target is given approximately by

$$\Delta_t \approx \lambda_s\ \alpha_s/\vartheta_i$$

where $\alpha_s \approx B_t/B_p$ at the midplane, which is typically 20° or less, λ_s is the midplane SOL thickness and ϑ_i is the angle of incidence between the (total) field line and the target. If we accept the technology - imposed limit that $\vartheta_i \geq 1°$, then

$$\Delta_t \leq 20\ \lambda_s \approx 0.2\ \text{m},$$

for $\lambda_s = 0.01$m, as illustrated in figure 3. For present-day devices, heat loadings are tolerable, but for ITER, because the 1° incidence angle limits the (non swept) target poloidal wetted length to 0.2 m, the loads exceed those which can be handled by cooling technology.

Simulations of high recycling divertors such as the one described above show that up to about 50% of the energy can be radiated away by hydrogen and target sputtered impurities. However, this radiation comes from a small volume adjacent to the target plate, whose thickness is of the order of the mean free path for ionisation and is 1 cm or less. Hence, approximately half of the radiation goes directly onto the targets. Although the radiating target layer helps, it does not eliminate the heat load problem. It is thus clear from figure 3 that simply making a high recycling divertor "deep" does not effectively utilise its volume.

Four types of solutions have been suggested to reduce the power loading on divertor surfaces to tolerable levels, and they fall into two major categories:

- **Increase the wetted area**
  - Make the SOL thicker
  - Reduce ϑ_i below 1 ° ("Glancing incidence" targets)
- **Distribute energy losses throughout the divertor volume**
  - Inject radiating impurities into the divertor away from the target plates
  - "Gas Target" divertor: extinguish the plasma before it reaches the target plates by interaction with hydrogen neutrals along the length of the divertor plasma

We next discuss these approaches individually, although it is clear that a successful next step divertor will probably employ a combination of them.

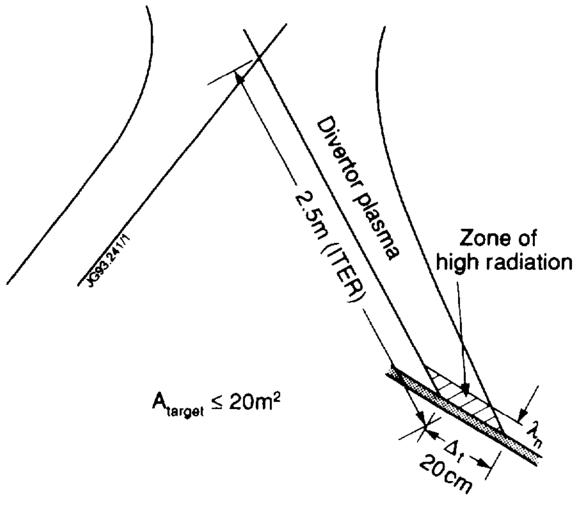

Fig. 3. Sketch illustrating problem of a conventional high recycling divertor of ITER dimensions.

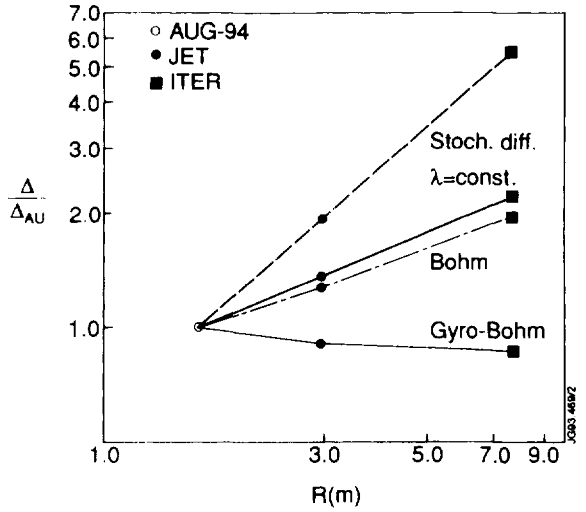

Fig. 4. Scaling of power SOL thickness, normalized to that for ASDEX Upgrade, based on a 2-point model using various transport models. (after Borrass 1993).

IV. EXAMINATION OF SOLUTIONS

Increasing Wetted Area via a Thicker SOL

Biasing of the SOL/Divertor plasma to make it thicker has been proposed as part of the ongoing DIII-D Advanced divertor programme, as reviewed recently by Shaffer et al. (1993). Similar studies have been pursued at the Tokamak de Varennes (Terrault et al. 1992). A second method to increase the SOL thickness, which has been studied at TORE Supra (A. Grosman et al. 1992) in a limiter configuration, is to ergodize the edge layer. Experiments on edge layer ergodization in a divertor tokamak have been proposed at JET, using the newly installed saddle coils. A third method for SOL control is via RF-induced ponderomotive forces (A. Grossman et al. 1992), studied at UCLA and PPPL. While each of these methods is interesting and potentially fruitful, they lie outside the scope of the present review.

On the other hand, the thickness of the "naturally occurring" SOL is not well enough characterised at present to permit confident extrapolation to an ITER-sized device. For a conduction-dominated SOL, the basic scaling of the temperature decay length, and hence of the power decay length ($\lambda_p=2/7\lambda_T$), is given by

$$\lambda_p \sim \sqrt{\frac{K_\perp}{K_\parallel}L} \qquad (1)$$

where $K_\perp$ and $K_\parallel$ are thermal conductivities, and L the connection length.

It is usually assumed that $K_\parallel$ is classical ($K_0T^{5/2}$), but the parallel heat flow may in some situations become flux-limited (Luciani et al. 1983), reducing it below the classical value. If the classical expression for $K_\parallel$ is used, the above formula becomes

$$\lambda_p \sim \frac{\chi_\perp^{7/9} n_s^{7/9} R^{14/9} q^{4/9} \varepsilon^{5/9}}{P_{SOL}^{5/9}}, \qquad (2)$$

where R,q, and ε are the major radius, safety factor, and inverse aspect ratio.

The major uncertainty lies in the scaling of $K_\perp$ (= $n_s\chi_\perp$). Most simulations of edge plasma have used either $\chi_\perp$ = constant or $\chi_\perp$~T/B ("Bohm-like"). However, it is quite possible that the edge diffusivity depends also on machine size through the dimensionless Larmor radius (ρ_i/a). Two popular alternatives to Bohm-scaling for the main plasma transport are the "gyrobohm" $\chi_\perp \sim \chi_B \cdot (\rho_i/a)$ and the "stochastic" $\chi_\perp \sim \chi_B(\rho_i/a)^{-1}$ models (Christiansen et. al 1992). These models for the perpendicular diffusivity can be used in a two-point semi-analytic model of the SOL (Borrass 1991) to produce a scaling of SOL thickness with machine size. Figure 4 shows the result of such a calculation for three different machines, ASDEX Upgrade, JET, and ITER, which cover a range of about 6 in dimensionless Larmor radius. In this figure, the SOL power was taken to be half the installed heating power or half the α power, and the divertor temperature was taken to be the same in each device. If the edge diffusivity follows gyrobohm scaling, the SOL thickness will be less in ITER than in present devices, which exacerbates the power exhaust problem. On the other hand, with the stochastic diffusion model for edge diffusivity, the SOL thickness would grow sufficiently that the conventional high recycling approach would in principle be satisfactory due to a very large wetted area on the targets. The Bohm scaling lies in between.

Itami et. al (1992) reported that the power decay length measured on the divertor plates in JT60 over a wide range of power and density scaled approximately as indicated by equation (2) for fixed R and ε, assuming χ = constant. They further reported that values of χ = 2-5 m^2/s were required, in L mode discharges, to match measured edge profiles of H_α, density, and electron temperature. McCormick et al. (1993) carried out a comparison of measured density fall-off lengths in ASDEX with results from the Braams code using three different transport models, and concluded that the best fit (although far from satisfactory) was obtained by assuming $D=\chi_\iota=(1/3)\chi_e$ = constant. Unfortunately there is not enough data from these two cited studies, or others in the literature, to make any definite statement about the dependence of SOL width on machine size. In view of the importance of this dependence, as indicated in figure 4, it is clear that many further experiments need to be done in machines of various sizes.

Glancing Incidence Targets

The divertor in the ITER EDA design is about 2.5 m deep poloidally. If the targets were inclined to the poloidal flux surfaces such as to occupy most of the 2.5 m, they would have a wetted area of about 200 m^2. If half or so of the power into the divertor were radiated away to opposite facing divertor walls, the resulting power load on the targets and walls would be reduced to acceptable values.

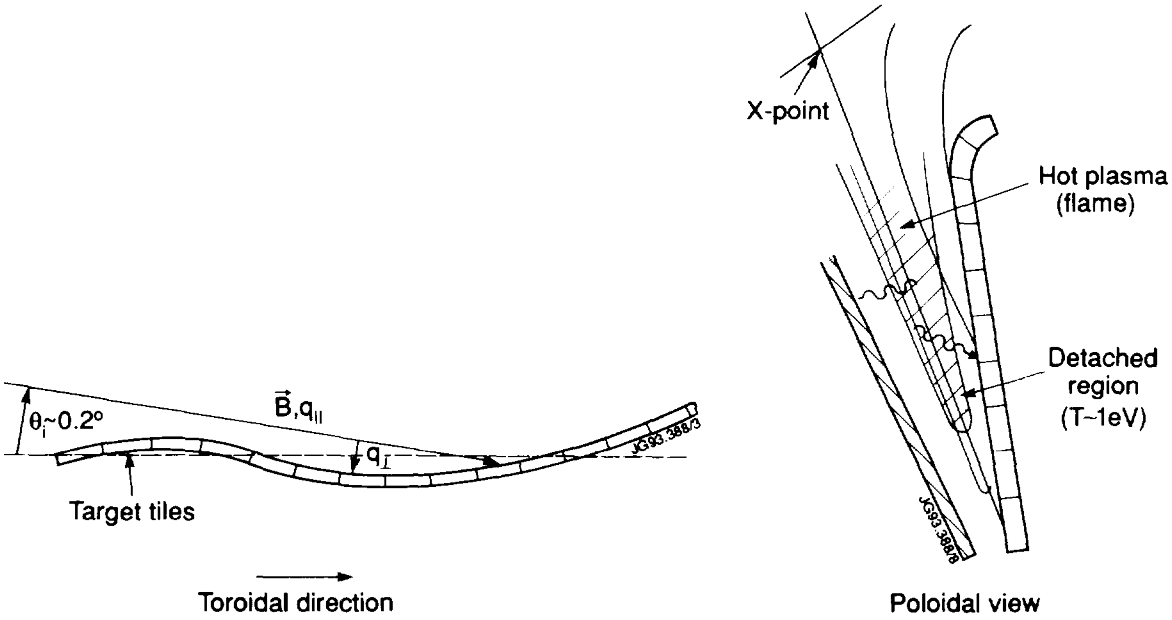

Fig 5. Sketches relating to glancing incidence targets. See text.

Such targets would have field line angles of incidence of only about 1/4°. We believe that the problem of protruding edges can be overcome by careful design such as mounting adjacent tile corners on common pads; such an approach has been adopted for the JET Mark II divertor where it is expected to be able to accommodate field line angles of 1/2° (Lowry, 1993). However, even with perfect edge alignment, there will remain unavoidable longer wavelength undulations in the toroidal direction between the field lines and the target surface due to thermal distortions of the machine and field errors, as illustrated in figure 5a. In the conventional view of target loading, it would be concluded that the "back sides" of the undulating surface would receive no power, and the illuminated sides would be overloaded. It has been pointed out by Stangeby (1992) that at these small angles of incidence, perpendicular diffusion of heat is no longer negligible relative to $q_{\parallel}\sin\vartheta_i$, and the shadowed areas would be "filled in". Support for this has come from inner wall limiter experiments at glancing angles on TFTR (Pitcher et al. 1992) and TORE Supra (Seigneur et al, 1993). The sheath changes character at these very small angles (Chodura 1992), and no thorough analysis of a glancing incidence divertor has yet been carried out. A problem with this approach is that the strike points would be extremely sensitive to motion of the X-point. A somewhat related idea has been put forward by Lackner (1993). If the divertor plasma "detaches" from the plates, such that a dense neutral layer with very small plasma pressure exists between the divertor (fully ionised) plasma and the plates, the surface irregularities may become unimportant; see fig. 5b. In this case the wall might be thought of as a stabilising "flame holder" for a gas target/detached plasma divertor, which is discussed further later in this paper.

Impurity Seeded Radiating Divertor

If impurities can be introduced into the divertor throughout its volume rather than just in the target area, large amounts of energy can be radiated, relatively uniformly, to the sidewalls. Objections have been raised in the past on the basis that light impurities will radiate only in a very small temperature range and thus in a small portion of the divertor volume, making it impossible to distribute the heat to the walls sufficiently evenly. This appears to be incorrect due to two effects which effectively extend the radiation cooling curve for light elements to high temperatures. The first is the transient effect which produces large quantities of radiated energy from atoms in the process of being stripped, and the second is the enhancement of radiation, due to charge exchange effects, in the presence of even small amounts of neutral hydrogen. Calculations of these effects have been carried out by Allen (1992) for nitrogen and for carbon and beryllium by Horton and Summers (1992). Lackner and Schneider (1993) estimate analytically, using Allen's calculations, that powers as high as 240 MW could be radiated from the ITER divertor.

A more serious objection has to do with whether or not the injected impurities can be retained in the divertor. Studies made by Stangeby (1993) using the DIVIMP Monte Carlo impurity tracing code (Stangeby 1992) run on a plasma background generated by EDGE2D (Simonini et. al 1992) indicate that, in the trace impurity approximation, injected carbon atoms will be satisfactorily retained if they are injected into regions where the hydrogen flow towards the targets is sufficiently strong and the ion temperature is low, and that several kev per injected atom will be radiated before the atom returns to the target or diffuses out of the system. Taroni et al (1993) report a fully self-consistent multi-species 2D studies of the radiation from C atoms injected into a divertor with inclined plates. Figure 6 shows contours of impurity density, n_Z, summed over all C ionisation stages, resulting from uniform injection through the vertical targets of the same JET Mk II divertor geometry discussed in Section I. In this simulation, the C radiation increased to 6.0 MW, and the total radiation and CX losses, including those from hydrogen, amounted to 12.6 MW out of the 20 MW injected power. The impurities remained fairly well confined within the divertor volume, with Z_{eff} reaching 1.65 in the SOL at the midplane.

The stability of highly radiating divertors is of concern. Simulations by Schneider et al. (1992) using the B2 code (Braams 1984) with an approximate model representing uniformly mixed impurity with a cooling curve equivalent to 2% C-O mixture indicated that a "divertor MARFE" which formed near the targets would migrate out of the divertor and settle in a position near the X-point, inside the separatrix, and that the divertor would simultaneously become quite leaky with respect to H neutrals. However, experiments at JET (Janeschitz et al. 1992) suggest that a stable, highly radiating zone can exist in the divertor region for several seconds without the main plasma becoming contaminated.

In order to radiate, for example, 100 MW with a non-recycling impurity, it would be necessary to inject on the order of 100 kg per day, which is not feasible. One must therefore consider recycling impurities. For conventional "attached" plasmas, this will probably not help much because the impurity will collect near the plates, resulting in localised radiation. However, for a "detached" divertor with free recirculation of neutrals within the closed divertor chamber, as described in the next section, injection of recycling impurities may be effective. It seems preferable to use light elements rather than heavier ones such as Argon because they cause fewer problems if they get into the main plasma.

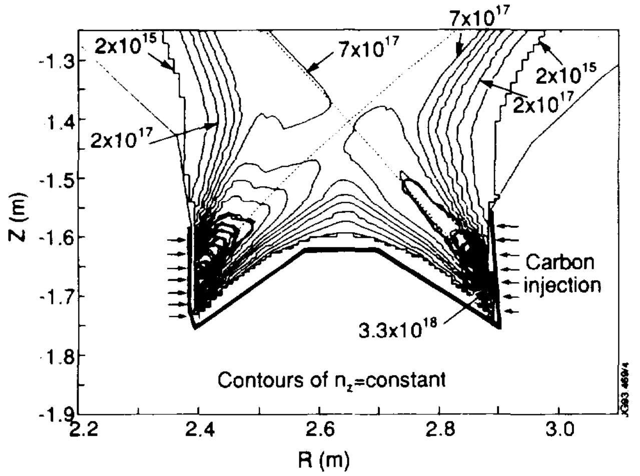

Fig. 6. *Contours of impurity density in an EDGE2D/U multi-species simulation of an impurity-injected (Carbon) JET divertor (after Taroni et. al. 1993).*

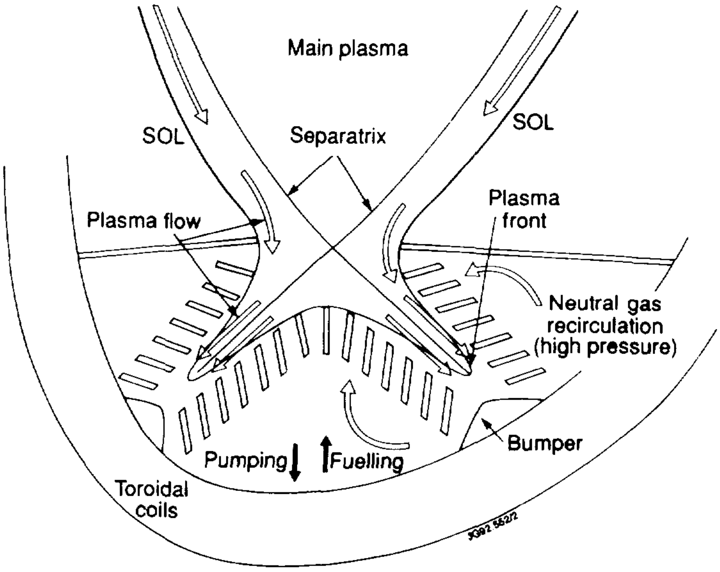

Fig. 7. *ITER EDA gas target divertor concept (after Rebut 1993). Louvres shown in poloidal plane for clarity, but would be placed in toroidal direction.*

Gas Target Divertor

Figure 7 shows a schematic view of the ITER EDA conceptual divertor design (Rebut et al 1993) wherein hydrogenic neutrals entering the hot part of the divertor plasma laterally remove energy and momentum by CX and radiation processes. The plasma should be "extinguished" or detached from the end plates, and all the power absorbed by the sidewall structures, which are louvered to permit the free passage of neutrals in and out of the divertor plasma region.

We shall distinguish between "energy detachment", where nearly all of the energy is removed but a cold ($\leq$ 1 ev) plasma remains in contact with the end plates, and full detachment, where there is no flow of plasma to the end; the latter requires either substantial volume recombination or strong perpendicular diffusion of plasma to the side structures.

The idea of a gas target divertor seems to have originated with Tenney and Lewin (1974), and been further developed by Nedospasov and Tokar (1986), Barr and Logan (1990), and Watkins and Rebut (1992). During the past year there have been simulations by several groups, some of which will be discussed below. Experiments have been carried out at low power fluxes and fields in at least three linear simulator experiments (Hsu et al. 1982, Fiksel et al. 1990, and Schmitz et al. 1990) and such work is continuing actively. Related experiments in Tokamaks have also been reported. Both DIII-D (Petrie et al. 1991) and JET (Janeschitz et al. 1992) have reported detached divertor plasmas where the power measured on the targets was reduced to a small fraction (10 to 20%) of that entering the divertor. In the JET experiments, detachment was achieved on both sides of the divertor, by balancing the power by operating with the ion ∇B drift away from the divertor. The majority of the radiation is believed to be from hydrogen. Borrass and Stangeby (1993) have produced an analytic detached divertor plasma model which reproduces certain features of the JET experiments.

Several key questions come to mind in connection with the gas divertor:

- What value of the neutral density n_o is required adjacent to the divertor plasma to achieve an acceptable extinction length ($\leq$2m)?
- Is that value of n_o compatible with the midplane separatrix plasma density n_s for a given P_{sol}? (How closely coupled are n_o and n_s?)
- How can the required recirculation pattern for the neutrals be achieved; can it occur naturally or does it require massive pumping and puffing?

- If cold plasma remains in contact with the plates, how much energy from surface recombination do they receive?

In the year or so that has elapsed since it was announced that the gas target concept was the favoured one for the ITER EDA, a great deal of work has been done around the world in attempting to develop realistic simulations. Although no unambiguous answers to the above questions have been produced, certain trends are beginning to emerge.

One can distinguish between high and low pressure solutions. In the former case the neutral pressure is approximately equal to the divertor plasma pressure, on the order of 1 Torr, which is roughly 1000 times higher than typically measured in the private flux region of today's divertors. By a low pressure solution we mean one where the neutral pressure is on the order of 10 mT, similar to that which has been observed in the pumping baffle of the DIII-D advanced divertor (Klepper et al. (1993)).

A simulation of a high pressure gas divertor has recently been reported by Petravic (1993), using a 2-d plasma model and a fluid neutral model, for an ITER geometry. The solution domain was bounded by the separatrix on one side (no private flux region) and a close-fitting perfectly reflecting wall conforming to a flux surface a few cm out from the separatrix, with an orthogonal target at the bottom. A power of 220 MW was assumed to flow into the outer divertor leg, and the divertor chamber was filled with various amounts of neutral gas. Profiles along the separatrix in the poloidal plane are shown in figure 8. There exists a relatively short zone of a few cm where the transition from plasma to neutral gas takes place via recombination. This zone is roughly in Saha equilibrium. The neutral density is of the order of a few times 10^{22} m^{-3} near the target, and its pressure is comparable to that of the plasma. The energy flux to the target is reduced to negligible levels, and the energy is radiated to the sides by ionisation and recombination radiation processes. Although the radiating zone is short, the "stand-off" distance to the target increases going outwards from the separatrix, thus helping to spread out the radiation over more of the sidewall areas. The midplane density for this case was $1.4 \, . \, 10^{20}$ m^{-3}.

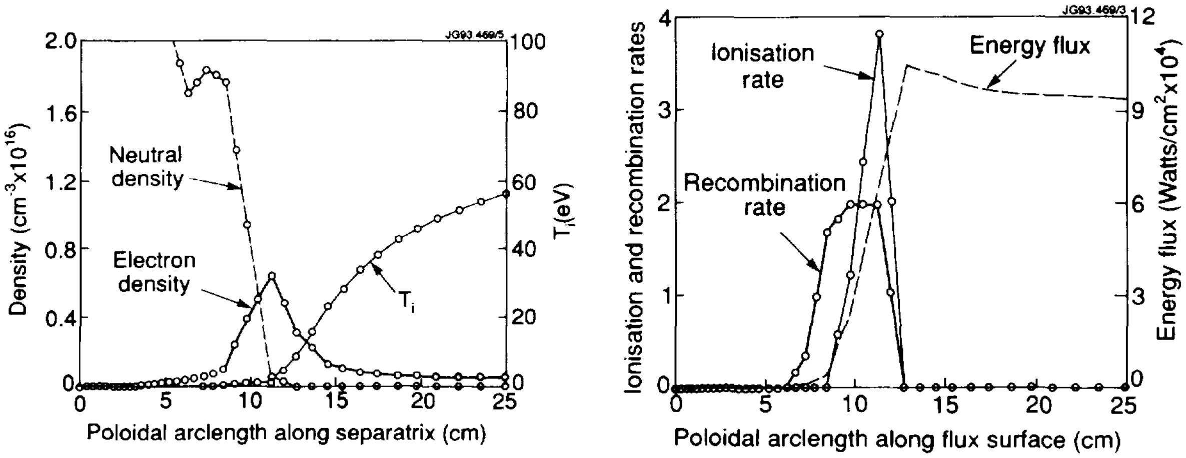

Fig. 8. Plots of various quantities along the separatrix for a high neutral pressure gas target simulation of Petravic (1993).

Petravic's solution is a very interesting one which demonstrates significant progress in modelling of gas target divertors. There are two major concerns about it. First, the choice of the location of the boundaries and how they are treated may hold the midplane density to lower values than would actually occur, i.e. plasma plugging of the neutrals will probably not be as efficient as indicated. Secondly, the opacity of such high pressure neutral gas to the recombination radiation may require simultaneous solution of the radiative transfer problems. Both issues are being addressed in further studies.

We turn now to the question of whether low pressure solutions exist. If one imagines an idealised case in which an entering neutral either CX's and carries the acquired energy of the hot ion directly to the wall, or ionises, removing about 20 ev by radiation and increasing the charged particle flow, a simple calculation suggests that the required energy extinction length of about 1m could be achieved with neutral pressures on the order of 10 mT. This estimate compares well with those given earlier by Nedospasov and Tokar (1986) and Barr and Logan (1990), and Watkins and Rebut (1992). However, at these pressures the recombination length is very long, and cold dense plasma contacts the plate. Estimates suggest the recombination heat load on the plate remains tolerable.

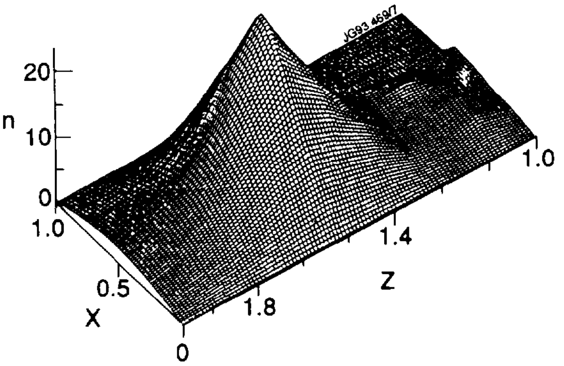

Fig. 9. 3-D plots of ion density (in units of 10^{19} m^{-3}) for a slab divertor model at low neutral pressure. with no electron-ion equilibration. (after Kukushkin 1993).

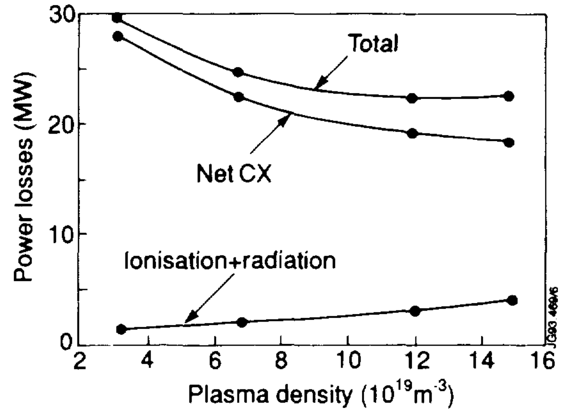

Fig. 10. Power losses in a 4 m deep divertor channel. The input power was 100 MW. Particles were extracted from the target and re-fed uniformly along the separatrix. (after Weber et. al. 1993).

An interesting study of the low pressure case has been presented by Kukushkin (1993), who used a slab geometry, with a 2-D fluid plasma Monte Carlo neutral code. In his solution, the target and walls were perfectly absorbing to plasma and hot neutrals, and cold neutrals were fed back in uniformly through the walls to maintain particle balance. 99% of the energy entering the divertor was carried by the ions. For the case shown (figure 9), which was carried out to show the relative importance of various physical processes, equipartition between ions and electrons was turned off, and an extinction length of less than a meter was found, for a neutral density of only 1 x 10^{20} m^{-3}, corresponding to an upstream plasma density of 2 x 10^{19} m^{-3}. The energy was removed almost entirely by CX.

A similar "slab" calculation has been reported by Weber et al. (1993) using a 2D fluid code with a 2-group diffusion approximation for neutrals. The same "artificial" recycling pattern used by Kukushkin was assumed, but power was supplied equally to electrons and ions, and equipartition was included. The energy which could be extracted from a 4m deep divertor by CX and ionisation was limited to about 30% of the 100 MW input over a range of upstream densities (figure 10). The corresponding neutral density, which was tightly coupled to the upstream density, was very low ($<1 \times 10^{19}$m^{-3}). for acceptable upstream plasma densities. This tight coupling seems to result from imposition of the standard sonic condition at the targets. This condition may be overly restrictive, and may adversely impact the attempt to find low pressure gas target solutions. Work on relaxing this condition is in progress.

Other simulation groups have also been active in this area. We note in particular the work on high-pressure gas target divertors (similar conditions to Petravic's) presented by Schmitz (1993) and on detached plasmas by Schneider et al. (1993).

The divertor geometry clearly plays a role in its performance. In order to distribute the CX and radiation processes uniformly, the recycling neutrals must have paths by which they can return from the cold, downstream volume to the more energetic region near the divertor entrance. Thus, the plasma at the end plates must either be completely detached or cold enough (≤4eV) that the neutrals escape reionization at the targets. Moreover, the walls must be "loose fitting" or louvred, as in the ITER EDA proposal; a tight slot will not be effective. Free recirculation of neutrals within the divertor volume should also help the impurity-seeded radiating divertor by inducing flow further from the ends.

IV. CONCLUSIONS

To solve the ITER divertor problem it will be necessary either to increase the wetted area of a conventional high recycling divertor dramatically, either through achieving a thicker SOL or tilting the plates to extreme angles, or to remove the energy before it reaches the target by radiation and CX losses distributed fairly evenly throughout the divertor chamber.

Significant progress has been made in the modelling of both impurity seeded divertors and gas target divertors in the past year. Although no completely satisfactory simulation of an ITER divertor has yet been produced for either high or low neutral pressures, trends are becoming discernible and there is some basis for optimism. It appears that a low to moderate neutral pressure, large volume gas target divertor, possibly assisted by some radiation from injected recycling impurities, has a reasonable chance of being successful. Further support for these concepts comes from the rather successful experiments carried out at DIII-D and JET on highly radiating, detached divertor plasmas.

It is clear that experiments on radiative and gas target divertors and on scrape-off layer thickness scaling are needed in a variety of configurations and machines to provide the basis for model refinement and a convincing extrapolation to ITER.

VI. ACKNOWLEDGMENTS

The author wishes to thank his colleagues at JET, K. Borrass, G. Janeschitz, M. Keilhacker, A. Loarte, G. Matthews, R. Simonini, P. Stangeby, A. Taroni, P. Thomas, and M Watkins, as well as those at other institutions, K. Lackner, A Kukushkin, K. McCormick, J. Neuhauser,. R. Schneider, and M. Petravic, for stimulating discussions on various aspects of the material reviewed here.

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