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ABSTRACT

An outline design for a bundle divertor matched to a conceptual tokamak reactor is presented. With water cooled copper coils the power consumption is less than 4% of the electrical output of the reactor. The current density and field strength in the coils are sufficiently low to make superconducting coils a possibility, and the addition of simple exhaust coils allows a large expansion of the plasma bundle leading to a low power density on the target plates. It is concluded that the bundle divertor concept has considerable potential for use in a reactor and would justify more detailed engineering studies.

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1. INTRODUCTION

Impurity contamination has long been recognised as a major barrier to the realization of thermonuclear fusion, and indeed tokamak reactor plasmas will have to be a good deal cleaner than those in existing devices since the presence of even small quantities of high Z impurities will prevent ignition [1]. The basic problem is to reduce the interaction between the plasma and the first wall, and at present the most effective and predictable way appears to be by means of a magnetic divertor. In such a device the magnetic field lines are arranged to exhaust the escaping plasma into a separate chamber where it can be neutralized and the resulting products can be pumped away and prevented from returning to contaminate the plasma. In a reactor this exhaust function will be particularly important to reduce the fluxes of power and particles reaching the first wall, and in a steady state situation to control the overall particle balance. The divertor further improves the plasma purity by surrounding the hot central core of the discharge with a screening layer, within which impurities released from the wall are ionised and swept into the divertor before they can penetrate the central hot plasma core.

We also point to a more specialised application of divertors during the start-up phase of a reactor when powerful auxiliary heating must be applied. If neutral injection heating is used, any decrease in the plasma purity will result in a serious decrease of the beam penetration which may already be marginal for a reactor sized plasma. In this case the capital and operating costs of a bundle divertor could well prove to be less than the substantial costs which would be incurred if the beam power and energy were increased in an attempt to maintain adequate penetration.

The Bundle Divertor [2,3] is a configuration which has been developed and demonstrated at Culham on DITE [4,5]. The divertor action is produced by a pair of relatively small, circular coils which produce a highly localised distortion of the toroidal field at the edge of the discharge. It has the attractive feature that the divertor coils and vacuum system can be completely external to the main torus. In a reactor, such coils can be more easily shielded from the neutron flux and removed for maintenance than the coils of a poloidal divertor. It has the disadvantage that in order to divert the large toroidal field the current in the divertor coils and the mechanical forces acting on them are large.

A previous feasibility study of a bundle divertor for a fusion reactor [6] indicated that if the divertor coils were protected by an adequate thickness of neutron shielding, copper conductors would dissipate up to 15% of the electrical power output of the reactor. The field strength and current density in the divertor coils appeared to be too high to permit the use of superconductors. It has been generally assumed therefore that a bundle divertor would not be an attractive proposition for a reactor.

A more recent study of the optimisation of the magnetic design of bundle divertors for experimental tokamaks [7] has led us to a more optimistic appraisal of the reactor potential of a bundle divertor. The power consumption of copper divertor coils is reduced to less than 4% of the reactor power output, whilst still providing space for an adequately thick neutron shield. In the new design, the field strength and current density are within the range of present-day superconducting technology. As with any divertor system, the extrapolation to a reactor will be extremely difficult and will involve formidable engineering and technological problems beyond the scope of this paper, which is intended simply to establish that bundle divertors merit further consideration for reactor systems.

2. MAGNETIC DESIGN OF THE BUNDLE DIVERTOR

The magnetic topology of a bundle divertor is complex but has been described in detail elsewhere [2]. For the present purpose a simplified description will suffice. The divertor coils (Fig. 1) carry a current in such a direction as to oppose the toroidal component of the magnetic field and produce a stagnation region a suitable distance inside the first wall. The multi-polarity of the bundle divertor field resulting from the relatively small size of the divertor coils ensures that there is only a small perturbation of the confining fields inside the hot central core of the discharge. The divertor action can be described approximately by saying that the confined region of plasma is surrounded by an annular zone which we will call the divertor scrape-off layer. The inner boundary of the *scrape-off layer*, which we will call the *separatrix radius*, a_s, is defined by field lines which pass through the stagnation point, and the outer boundary is defined by the innermost projection of the first wall, which we will call the *limiter radius*, a_L.

The thickness of the scrape-off layer $a_L - a_s$ is a very important parameter in designing a bundle divertor. The layer must be made sufficiently thick to provide adequate exhaust and screening efficiencies for the divertor operation. However, if the layer is made too thick it reduces the volume of reacting plasma and produces a serious increase in the current required in the divertor coils. It is therefore important to make a realistic estimate of the scrape-off layer thickness which will be required in a fusion reactor but this is by no means easy. We will base our conceptual design of a reactor-sized bundle divertor on a scrape-off layer width of 20 cm which corresponds to about 10% of the minor radius and which occupies about 20% of the total plasma volume.

The density gradient in the scrape-off layer and hence its exhaust efficiency is determined essentially by the relative strengths of cross field diffusion and parallel flow into the divertor.

A simple model of the scrape-off layer [8] gives the density scale-length $\Delta = (D_{\perp s}\ 4\pi\ R\bar{q}_D\ M/v_s)^{\frac{1}{2}}$, where $D_{\perp s}$ is the cross field diffusion coefficient, R is the major radius of the torus, $\bar{q}_D$ is the average number of times a field line transits the torus before entering the divertor, M is the mirror ratio in the divertor throat and v_s is the ion speed in the divertor scrape-off layer.

The main difficulty is to choose a suitable model for the cross-field diffusion coefficient $D_{\perp s}$. The assumption of neoclassical diffusion rates results in very steep density gradients and consequently thin scrape-off layers. These are probably optimistic as steep density gradients would almost certainly lead to drift-wave-type instabilities which would produce anomalous diffusion. In the divertor experiments on DITE we have obtained better agreement with the measured density gradient in the scrape-off layer by assuming an empirical value equal to 100 times the Pfirsch-Schluter rate. Extrapolated to the reactor case and with the scrape-off layer density and temperature assumed to be 3.5×10^{13} cm^{-3} and 1 keV respectively gives a density scale length $\Delta = 1.7$ cm. The corresponding exhaust efficiency $\xi_x = 1 - \exp(-(a_L - a_s)/\Delta)$ would be close to 100%. Somewhat lower values of exhaust efficiency are obtained if we assume Bohm diffusion in the scrape-off layer. Clearly there is insufficient information available about diffusion in the reactor boundary plasma to be more precise about the exhaust efficiency but we note that the thickness of the scrape-off layer could be increased if necessary, or several divertors fitted if the exhaust efficiency of a single divertor was inadequate.

3. OPTIMISATION OF THE MAGNETIC DESIGN

Consideration of several factors influces the design of the divertor coils. These include the current, current density and power dissipation of the coils, the forces acting on them and the efficiency with which plasma is diverted. We have found [7] that the best results are obtained when the divertor coil angle α, as defined in Figure 1, is between 45^o and 55^o. The diameter of the divertor coils has an optimum value for minimum power consumption and has to be consistent with the constraints set by other engineering components and by the desirability of minimising the perturbation of the toroidal field in the non-diverted core of the plasma.

The divertor coils should be as close to the plasma boundary as possible. The minimum distance is set by the combined thickness of the scrape-off layer, the first wall and the neutron shield. An adequate thickness of neutron shield between the first wall and the divertor coils is required to attenuate the nuclear radiation to a sufficiently low level set by the acceptable nuclear heat load on the coils and by radiation damage to the coil and its structure. A recent study by Abdou [9] considers that the most critical factor is that of radiation damage to electrical insulators. Inorganic insulators are more resistant to radiation than organic materials, and Abdou estimates that to ensure an adequate lifetime (30 to 300 MW yr m^{-2}) for an inorganic insulator would require a minimum thickness of 0.5 to 0.8 m of a stainless-steel and B_4C shield. We have based our divertor design on a minimum shield thickness of 0.75 m on the assumption that suitable inorganic insulators will be developed. We note that there would be a considerable saving in the power consumption of the divertor if the shield could be made thinner, either by improving the shield design or accepting a more frequent replacement of the divertor coil. This latter possibility might be considered acceptable in view of the relatively good access to the bundle divertor compared to other types of divertor.

4. A DIVERTOR WITH WATER COOLED COPPER COILS

We have based this design study on the Culham conceptual tokamak reactor Mark II [11] whose parameters are given in Table I. In order to simplify the computations we have represented the D-shaped toroidal field coils with rectangular coils and we have neglected the poloidal field due to the plasma current as we have shown elsewhere that the design of bundle divertors can be carried out successfully using only the toroidal field [7].

The parameters of the divertor coils are listed in Table II. The power consumption is approximately 46 MW per coil and the total consumption of the divertor is 92 MW. This is high but we note it is less than 4% of the electrical power output of the reactor (2500 MW). The current density in the conductor is 1.48 kA/cm^2. This is well within the range of conventional continuous water cooled copper coils. The electro-mechanical forces acting on the coils are large and are due mainly to the interactions between the divertor and toroidal fields and to the self fields of the divertor coils themselves. The largest force is the turning moment of 315 MN m on each coil and a net outward force of 33 MN per coil. These forces are large, but so is the space available for a support structure, and so we would not expect the stresses to be any worse than in present experimental bundle divertors.

Figure 2 shows a plan view of the coil design. Each divertor coil consists of four circular sub-coils. The support structure is not shown but would lie between the divertor coils and the B_ϕ coils. The hatched area represents 75 cm of neutron shielding. The dashed lines indicate the projection of the flux bundle entering the divertor.

5. A SUPERCONDUCTING BUNDLE DIVERTOR

The power consumption of a conventional set of divertor coils makes it desirable to consider using superconducting windings. The average magnetic field inside the divertor coils is about 5 T and the maximum value, at the inner edge of the coil, is close to 7 T. The average current density in the coil is 1.5 kA cm^{-2}. These values appear to be reasonable even in terms of present-day superconducting technology.

The rigidity of superconducting divertor coils imposes a stringent condition since even small deflections of the coils under electromechanical loading will produce significant local heating. However current densities of 4.5 kA cm^{-2} have been attained with present-day superconducting technology [10] and this will allow 2/3 of the available cross-section to be taken up by steel strengthening elements whilst still maintaining the overall current density of 1.5 kA cm^{-2}.

6. FLUXES OF POWER AND PARTICLES INTO THE DIVERTOR

If we assume that the reactor exhaust will be handled by a single bundle divertor, it must be capable of handling a particle flux equivalent to $4 \cdot 10^4$ A and an associated power flux of 910 MW assuming that the divertor must handle all the α-particle power. This presents a difficult dissipation problem whether gas or material targets are used and the cross-section of the diverted flux bundle must be sufficiently large to distribute this power over a large area.

Assuming an upper limit of 5 $\mathrm{MW/m}^2$ on the target, a total target area of 180 m^2 is needed. Using two divertors and with two flux bundles entering each divertor this implies a flux bundle cross-section of about 20 m^2 assuming this area can be at least doubled by arranging for the diverted flux to strike the target at an inclined angle as shown schematically in Fig. 3. With only one divertor a flux bundle cross-section of 40 m^2 is needed. It may be preferable to have two divertors to provide greater flexibility of operation and greater exhaust efficiency, especially if superconducting coils are used, as there would be little extra power consumption. Correctly positioned, even a single pair of exhaust coils, will channel the plasma flux bundle behind the toroidal field coils, where the field lines naturally expand so that a large cross-section exhaust region is easily formed. In this region behind the toroidal field coils there is plenty of space for all necessary target and pumping systems. Figure 3 illustrates this with the addition of two exhaust coils to the design and their parameters are also listed in Table II.

7. CONCLUSIONS

With careful positioning of the divertor coils and optimisation of the geometry of the diverted magnetic flux bundle, it appears possible to design a bundle divertor for a conceptual tokamak reactor. The neutron shield must be sufficiently thick to extend the life of insulators for both copper or superconducting coils. The use of superconducting windings is particularly attractive because of their minimal power consumption, but we note that even the power consumption of copper conductors does not exceed 4% of the reactor electrical output. This may be considered acceptable if a divertor results in a substantial improvement in plasma purity and in an effective means of exhausting the plasma power and particle fluxes. We emphasise that there may be scope for further optimisation of the magnetic design, especially if a bundle divertor is included at the outset of a reactor design study before the dimensions of the toroidal field coils are frozen.

Additional exhaust coils can be used to guide the diverted flux bundle outside the toroidal coil structure and to expand the bundle so that in principle the exhausted power flux can be dissipated over a large target area.

We have not attempted to give a full discussion of the many engineering and technological problems, but we conclude that the bundle divertor concept has sufficient reactor potential to justify more detailed study.

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REFERENCES

[1] Meade, D.N., Nuclear Fusion, 14 (1974) 289.

[2] Colven, C., Gibson, A. and Stott, P.E., Proc. of 5th European Conf. on Controlled Fusion and Plasma Physics, Grenoble (1972) I, 6.

[3] Stott, P.E., Gibson, A. and Wilson, C., Nuclear Fusion, 17 (1977) 481.

[4] Paul, J.W.M., et al, Proc. of 6th Conf. on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden (1976) 2, IAEA Vienna (1977) 269.

[5] Fielding, S.J., et al, Proc. of 8th European Conf. on Controlled Fusion and Plasma Physics, Prague (1977) I 36.
Paul, J.W.M., et al, Proc. of 8th European Conf. on Controlled Fusion and Plasma Physics, Prague (1977) II 49.

[6] Crawley, H.J., Proc. of 9th SOFT Conf. Garmisch (1976) 381.

[7] Sanderson, A.D. and Stott, P.E., to be published.

[8] Stott, P.E., Gibson, A. and Wilson, C., to be published in Nuclear Fusion and Culham Report CLM-P478, (1977).

[9] Abdou, M.A., Argonne National Lab. Report (1977) ANL/FPP/TM-81.

[10] Cornish, D.N. and Khalafallah, K., Proc. of 8th SOFT Conf. Jutphaas (1974) 973.

[11] Hancox, R. and Mitchell, J.T.D., Plasma Physics and Controlled Nuclear Fusion Reseach, Berchtesgaden (1976) III, IAEA Vienna, (1977) 193.

TABLE I

BASIC PARAMETERS OF THE CULHAM CONCEPTUAL TOKAMAK REACTOR MK II

Electric power output	2500 MWe
α-particle power	910 MW
Major radius	7.4 m
Plasma semi-axis (horiz)	2.1 m
Plasma semi-axis (vert)	3.7 m
Toroidal field at $R = 7.4$ m	4.1 T
Discharge current	11.7 MA
Plasma temperature	12 keV
Plasma density	3.5×10^{14} cm^{-3}
Safety factor q (surface)	2.5
Safety factor q (axis)	1.0

TABLE II

PARAMETERS OF THE BUNDLE DIVERTOR

Coil inclination angle	α	45°
Mean coil radius	R_c	1.8 m
Mean major radius of outer leg	R_2	10.75 m
Current in each divertor coil		14.14 MA/coil
Total current		28.28 MA
Current density		1.5 kA cm^{-2}
Total power consumption for water cooled copper coil		92 MW
Maximum field in divertor coil		7 T
Divertor magnetic mirror ratio	M	2
Mean no of transits of field line between diversion	$\bar{q}_D$	20

PARAMETERS OF EXHAUST COIL

Coil inclination angle	α	50°
Mean coil radius	R_c	1.0 m
Coil current		6.0 MA/coil

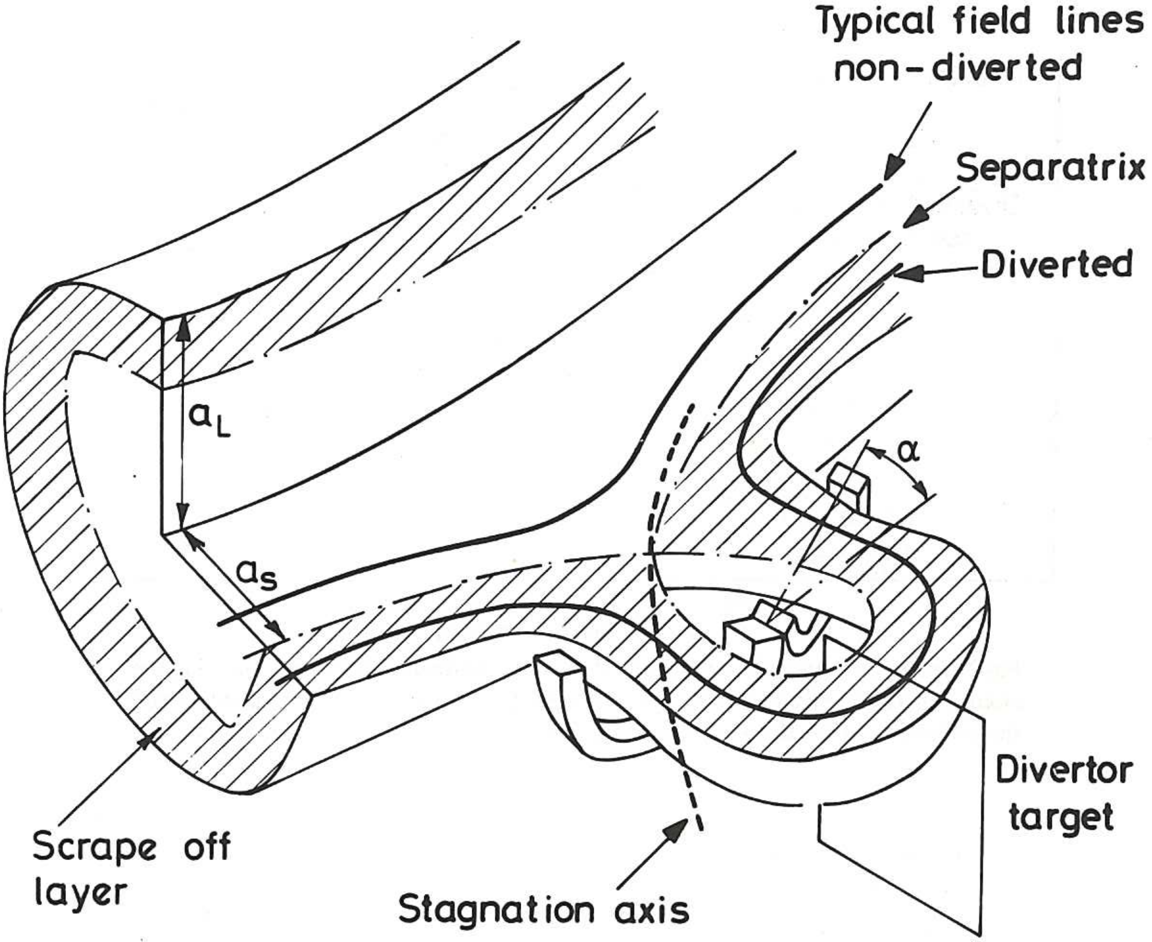

Fig.1 Schematic diagram of an idealised bundle divertor.

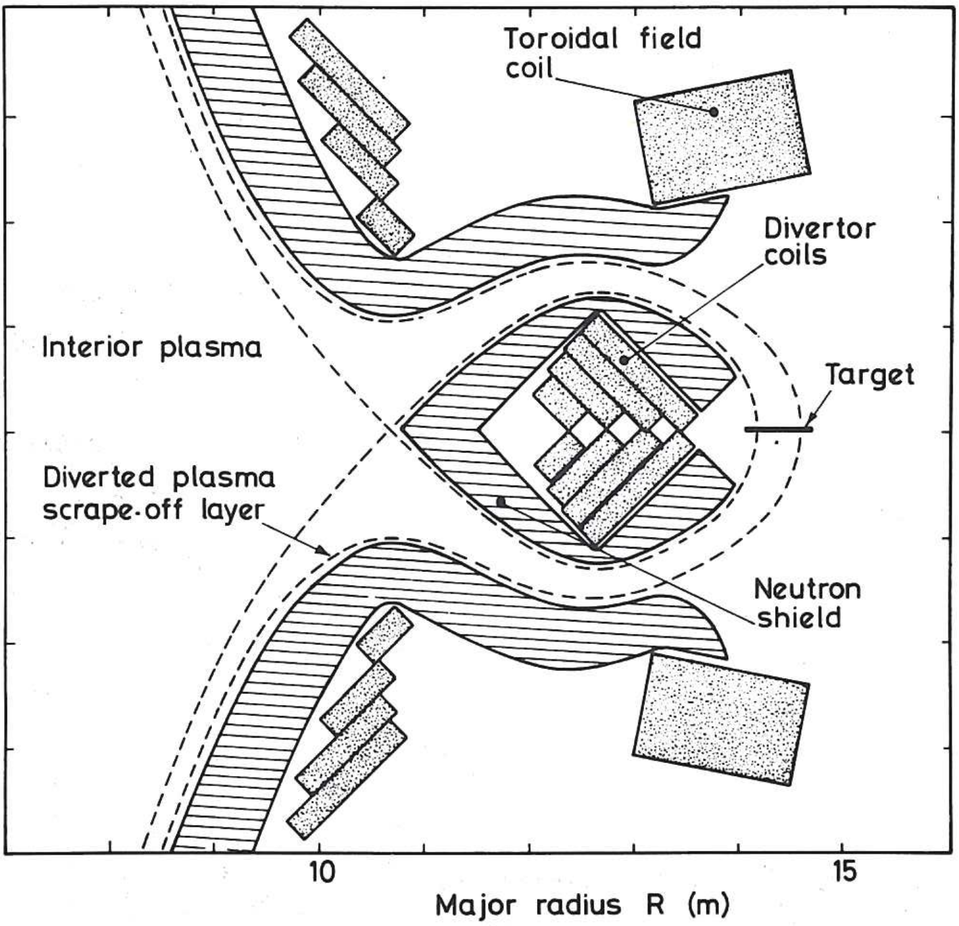

Fig.2 Section through the bundle divertor on the horizontal mid-plane showing the circular divertor coils, the nearest two toroidal field coils, the neutron shielding and the projection of the diverted plasma bundle.

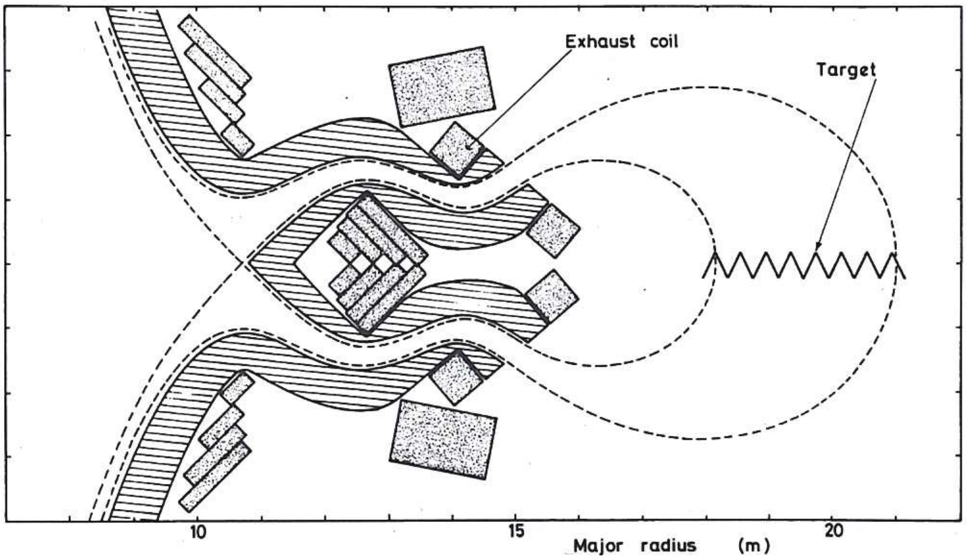

Fig.3 Section through the bundle divertor on the horizontal mid-plane showing the addition of two exhaust coils to expand the diverted flux bundle. The effective target area can be increased by arranging for the diverted plasma to be incident on the target at an inclined angle, as indicated schematically.