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The Ripple Bundle Divertor for Tokamaks

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ABSTRACT

The bundle divertor, designed for density and impurity control, has been successfully applied on the DITE tokamak. In this application it is subject to high stresses and is restricted to short pulses and low toroidal fields. A new version is made possible by fitting the vacuum vessel close to the toroidal coils. This allows the plasma to exist in the outer regions of higher toroidal field ripple. This ripple bundle divertor should operate at lower stresses and for longer pulses at higher magnetic fields.

1. INTRODUCTION

Tokamaks will require a technique for removing particles from the plasma edge in order to maintain a constant mean density when operating for extended pulses with either particle refueling or with constant neutral injection heating at high current levels. Simple pumping around the edge of the plasma is unlikely to be an adequate solution to this problem because the coils and structure limit the gas pumping conductance to a level at which equilibrium can be achieved only at high neutral pressures at the plasma edge.

The only viable solution appears to be a divertor which pulls plasma from the edge region (scrape-off layer) into a second chamber in which there is a large pump and from which there is a low conductance for gas returning to the main plasma region. In addition to giving particle control and removing unwanted fusion products, a divertor also acts to shield impurities from the plasma and as a sink for the thermal power conducted to the plasma edge. Handling of the thermal power is now of particular significance because the massive heating proposed and being applied to tokamaks will lead to reactor level thermal wall loadings (excluding the neutron component). Thus, the divertor is also relevant to the shorter pulse devices which are not refueled. There are two main types of divertors considered for tokamaks. One is the poloidal divertor which is in use on the PDX,¹ the ASDEX,² and the DIVA³ tokamaks. Another type is the partial toroidal or bundle divertor which is applied on the DITE⁴ tokamak.

In its present form the poloidal divertor requires coils which carry large currents and link the toroidal coils. While it is hoped

that this device will be developed into a viable divertor for a reactor, it presents some severe technological problems, and its application places strong constraints on the entire tokamak design.

The bundle divertor has been successfully applied on DITE.⁴ It has an advantage over the poloidal divertor in that the coils do not link with other coils. In principle this divertor may be introduced between the toroidal coils and thus it imposes less constraint on the tokamak design. However, the present design operates with high current densities, $\sim 20 \text{ kA cm}^{-2}$, and consequently with mechanical and thermal stresses which limit the divertor to short pulses ($\ll 1 \text{ sec}$) and restrict the tokamak to low field ($B_{\text{tor}} \sim 10 \text{ kG}$).

2. RIPPLE BUNDLE DIVERTOR

The ripple bundle divertor is a new version which will improve accessibility and operate at significantly lower stresses. It should have the capability of operating for long pulses ($\gg 1 \text{ sec}$) and at high toroidal fields ($B_{\text{tor}} \gtrsim 30 \text{ kG}$). The ripple divertor is made possible by constructing the torus vacuum vessel as close to the toroidal coils as mechanical constraints permit (see Fig. 1). This vessel configuration offers other advantages in the areas of general access and ease of mechanical support. The vacuum vessel layout allows the plasma to extend out of the region of "low" toroidal field ripple, $\left[(B_{\text{max}} - B_{\text{min}}) / (B_{\text{max}} + B_{\text{min}}) < 5\% \right]$, that has commonly been used as a restriction on plasma radius into the "high" ripple region. This is illustrated in Figs. 1, 2, and 3 with a field line plot for a reference 16-coil tokamak design of major radius 205 cm.

Because the vacuum vessel does not place a severe restriction on the bundle position in the ripple bundle divertor, it is possible to site the central divertor limbs in a region where the field of the toroidal coils and outer divertor limbs is low (see Figs. 1 and 3). In fact, the field goes through zero in the center limb, the average field is reduced to $\sim 20\%$ of that at the plasma center, and with careful positioning of the central conductor, there will be no net torque. Because the field is low, the diverted field lines are spread out. With $B_{\text{tor}} \sim 30$ kG, the total divertor coil current is 6 MA turns, and the coil current densities are ~ 10 kA/cm², which is a level at which water-cooled copper coils may run steady state. In addition, the diverted bundle of field lines is wider, and if we make the divertor with "elliptic" coils, this bundle may be extended vertically which gives a much larger target area.

3. DISCUSSION

Obvious questions related to the use of the "high" ripple region for the plasma edge now arise. In the first tokamaks there was the concern that the magnetic fields should have as small a ripple as possible so as not to confuse the comparison of experiment and theory. In subsequent tokamaks there was the added motivation of avoiding ripple diffusion and the depletion of high energy ions from the plasma center observed in the T-3 tokamak.⁵ The avoidance of "large" ripple in the central region of the plasma remains an important issue. The ripple losses in the edge region are, however, not obviously damaging and may occur only if temperatures are high.⁶ The divertor action of the

ripple at the edge may be viewed as a desirable feature.⁷ In fact a high loss rate at the edge is needed to maintain the thick, cold-edge region required to minimize neutral penetration and sputtering. The ripple will certainly increase the loss of injected ions. Provided the high, ripple-edge region has a thickness of $\overline{n\ell} \lesssim 10^{15} \text{ cm}^2$, not many injected ions will be trapped there since the target thickness for typical injection energies is $\overline{n\ell} \sim 10^{16} \text{ cm}^2$. Thus ripple losses from the center remain an undesirable feature. In the edge region if the heat loss is high but not localized, the edge will cool, which is desirable; if losses are low because the edge is cold, then there is little reason to be concerned about them.

Other problems relating to enhancement of ballooning modes or other instabilities require attention. As a general rule it seems sensible to require that the ripple field variation should be less than the field variation from outside to inside in order to maintain the toroidal nature of these surfaces. It should be recalled that the divertor introduces 100% ripple in the scrape-off layer (i.e., magnetic mirrors), and it also connects the plasma to a metal plate. It is not obvious that introducing an additional 15% ripple is significant in comparison to this. Finally we note again that the DITE divertor has worked successfully and we believe that an extension to operation in tokamaks with reactor relevant toroidal fields should be possible with the use of the ripple bundle divertor.

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We have appreciated valuable discussions with J. K. Ballou and J. D. Callen of ORNL. We have benefited from the excellent work on divertors done by the DITE group and in particular by A. Gibson, B. Sanders, P. Stott, and C. Wilson.

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Fig. 1. Plot of field lines in the median plane with a central toroidal field of 30 kG and a total bundle divertor current of 6 MA turns. The toroidal field with and without divertor is also shown.

Fig. 2. Plot of toroidal field and toroidal field ripple as a function of major radius midway between two toroidal coils.

Fig. 3. Plot of the toroidal field due to the toroidal coils plus the outer limbs of the divertor coil in the position of the central limbs of the divertor coil.

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