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AN IMPROVED BUNDLE DIVERTOR DESIGN FOR ISX-B

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SUMMARY

The application of Westinghouse's improved bundle divertor design for the ISX-B tokamak at ORNL has been evaluated in detail. The divertor consists of distributed coils with radii increasing outwardly from the plasma plus two auxiliary coils in the vertical plane passing through the center of the divertor and null point of the separatrix. The DITE design that employs nondistributed divertor coils has also been evaluated and compared with the Westinghouse design. There are three major advantages for the Westinghouse design. First, the diverted fluxes are led further away from the plasma and expanded to a larger area; the expansion has been found to be dependent on the divertor coil orientation. Second, the current carried by the divertor coils is reduced and distributed over a larger area; the current density can be reduced by more than a factor of 2. Third, the null points of the separatrices lie approximately on a vertical line instead of on a curve which is convex with respect to the divertor coil. Therefore, more flux can be diverted and uniform shielding could be provided to protect the divertor coil in future reactor applications.

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1.0 INTRODUCTION

The Oak Ridge National Laboratory, Fusion Energy Division, is considering a number of improvements to the existing ISX device in order to provide for additional or upgraded capabilities. The upgraded device has been called ISX-B¹ in initial proposals. One of the important new features under consideration is a bundle divertor. In addition to an examination of the applicability of the DITE² bundle divertor design, ORNL has asked Westinghouse to examine the applicability of the divertor design concept conceived as an optional impurity and particle control method for TNS³.

The purpose of this work is to carry out the divertor magnetic configuration design and force evaluation of the Westinghouse bundle divertor concept^{3,4} when applied to the experimental tokamak ISX-B at ORNL. Since this divertor is very promising for future reactor applications, there is considerable incentive for an examination of the feasibility of an early demonstration of the concept in a near-term device such as ISX-B.

The Westinghouse bundle divertor concept was conceived as an optional impurity control and particle removal method during the ORNL/Westinghouse TNS studies. The trimetric view of such a divertor implemented in TNS is shown in Figure 1. The turns of the divertor coils are distributed over a large area and their legs coincide with the major radii passing through the centers of the neighboring TF coils. Therefore, the radius of the coil turns increase in moving away from the plasma. In other words, each divertor coil is like a section of a conical solenoid. In addition, there are expansion coils to lead the flux to the outside of the TF coils, and two auxiliary coils to increase the distance between the null points and the center conductor within the loop of the separatrix. Thus, the diverted particles can be collected outside the TF coils, and there is sufficient shielding space of uniform thickness to protect the conductor. In addition, the perturbation of the toroidal field on axis is small. Such a design enhances the viability of a bundle divertor for reactor applications. However, for an

experimental device such as ISX-B with a pulse length of 300 ms, the demonstration of flux expansion, neutron shielding compatibility, and particle dumping are not key design objectives. The main concerns are the feasibility of the magnetic field design, structural feasibility, cost, and simplicity. The dominant cost factor is the current and current density carried by the divertor coils. The present design is optimized to achieve the lowest current and current density in the divertor coil and yet has sufficient flux expansion within the constraints of the available space.

2.0 MAGNETIC FLUX CONFIGURATION

The key physical parameters of ISX-B related to divertor characteristics are listed as below:

Plasma Major Radius:	R_0	=	0.92 m
Magnetic Field On Axis:	B_T	=	1.8 T
Plasma Minor Radius:	a	=	0.2 m
Scrape-Off Thickness:	δ_{SC}	=	0.07 m
Pulse Duration:	t	=	300 ms

and there are 18 TF coils. The plan view of the divertor coils and magnetic flux are shown in Figure 2. Figure 3 shows a cross-sectional view. It can be seen from Figure 2 that the divertor coils are distributed over a length of 20 cm. The width of the conductor was chosen as 4 cm for the convenience of field and force computation. The coils can be circular or D-shaped. Their radius or half-width increases in moving from the inner end toward the outer end of the divertor coil. For simplicity, the expansion coils shown in Figure 1 are not used. Some flux expansion can be achieved by choosing the proper divertor coil angle as is demonstrated by Figure 4. The divertor coil in the upper half has a larger angle ($\alpha = 25^\circ$) than that of the lower half (20°). The separatrix produced by the upper coil arrangement is diverted to a larger radius whereas the plasma radius is the same. Thus, the coil angle $\alpha = 25^\circ$ was used for this design. The important design parameters are listed below.

Divertor Coil Angle:	α	=	25°
Total Divertor Current:	I_D	=	2.2 MA
Divertor Current Density:	j_D	=	14 kA/cm ²
Auxiliary Coil Current:	I_A	=	0.5 MA
Divertor Coil Length:	ℓ	=	20 cm
Width of the Divertor Conductor:	w	=	4 cm

The width of the conductor can be increased to reduce the current density, if necessary.

3.0 FORCE ANALYSIS

For the purpose of comparison, the flux pattern for the simple DITE divertor was computed and is shown in Figure 5a. A similar flux pattern was also obtained when the auxiliary coils are included. Figures 5b and 5c are the flux patterns for the Westinghouse designs where the divertor coils are circular and D-shaped respectively.

The detailed magnetic forces are computed on the grid points illustrated by Figure 6. Since the forces on the divertor coils are symmetric with respect to the equatorial plane, the forces on either the top or bottom half of the coil are computed. Each half of the coil is divided into 10 segments at equal angular intervals. They are segments of equal length for circular coils. The torque T_q and the forces F_R and F_ϕ for the cases (a) and (b) with circular coils are compared below:

	CASE (a)		CASE (b)
	DITE TYPE	DITE TYPE WITH AUXILIARY COILS	Ⓜ-ISX-B-1
T_q (kN-m)	43	34	43
F_R (kN)	72	53	107
F_ϕ (kN)	153	202	69
I_D (MA)	3.2	2.7	2.2

The forces are given for each arc segment and are not normalized. The torque for the Westinghouse design (Case b) is not reduced because of the increased coil radius. The larger F_R is due to the same reason. The advantage of the Westinghouse design will become clear later.

Figures 7 and 8 show the force per unit area per arc segment over the cross sections near 0° and 180° for case (a) and (b). Even though the arc lengths are longer in case (c), the forces are significantly smaller.

The vector sums of f_ρ , f_z , on the first layer ($N=1$) of the coil, i.e.,

$$\vec{f}_\rho = \sum_{M=1}^4 \vec{f}_\rho^{1,M}$$

$$\vec{f}_z = \sum_{M=1}^4 \vec{f}_z^{1,M}$$

acting on each arc segment along the coil perimeter are graphed and shown in Figures 9 and 10. Figure 11 is a plot of the tension T along the perimeter. As one can see, the maximum f_ρ , f_z and T are reduced by a factor greater than 3 even though the length of the segment of case (c) is longer. The tension is approaching a constant value. The net force

$$\vec{f}_z = \sum_M \sum_N \vec{f}_z^{N,M}$$

is plotted in Figure 12. There is not much difference between these two curves because the length of the segment in case (c) is longer and the distributed current and auxiliary coil do not reduce f_z appreciably, as one would expect.

4.0 MECHANICAL DESIGN CONSIDERATIONS

In Case a (DITE) of Figure 5 the divertor current is concentrated in a small area so that the required current density is as high as 37 kA/cm^2 at $B_T = 1.8 \text{ T}$. It is not possible to provide internal structure to restrain the local forces so as to protect the electrical insulation between turns. The design of Case (a) therefore must rely on the strength of the copper conductor itself to resist the magnetic forces. However, in Case b (W-design) of Figure 5 there is twice as much area available with less current required. Sufficient structure can be provided to restrain the local forces as shown in Figures 7 and 8. A possible design would use stainless steel bobbins as illustrated by Figure 13. The dimensions of the structure shown in Figure 13 are estimated by using the maximum f_ρ and f_z from Figures 7 and 8.

5.0 SUMMARY DISCUSSION

From the analysis that has been made, we can summarize the significant improvements offered by the Westinghouse design utilizing D-shaped coils (Case c) by comparing it with the DITE design (Case a).

	$B_T = 1.8 \text{ T}$		$B_T = 1.2 \text{ T}$	
	DITE Case a	Ⓜ Case c	DITE Case a	Ⓜ Case c
Max. f_p per Segment (kN/cm^2)	8.7	2.5	5.8	1.7
Max. f_z per Segment (kN/cm^2)	6.0	1.9	4.0	1.3
I_D (MA)	3	2.2	2	1.5
J_D (kA/cm^2)	37.5	14	25	9.3

Since the coil cross section is doubled in Case c the current density is only $\sim 17 \text{ kA/cm}^2$ for $B_T = 1.8 \text{ T}$ or 11.5 kA/cm for $B_T = 1.2 \text{ T}$ even though structure is provided. Therefore, the ohmic heating is greatly reduced and the temperature increase during the pulse is much less, so that cooling the system is much easier and is inherently safer to operate.

The expansion of the divertor flux is also larger for the Westinghouse designs. It is largest for Case (c) where the divertor coil is D-shaped. However, it is not necessary to complicate the fabrication by using a D-shaped coil at this stage.

Besides the advantages mentioned above, the Westinghouse design concept offers significant improvements for reactor applications because of the relatively low current density requirements and small local forces.

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Figure 1. Trimetric View of a Bundle Divertor Design

Figure 2. Plan View of the Westinghouse Designed Bundle Divertor for ISX-B Where the Divertor Coils Are Circular.

Figure 3. Cross-Sectional View of the Westinghouse Designed Bundle Divertor for ISX-B.

Figure 4. Effect of the Coil Angle α on the Divertor Flux.

Figure 5. Flux Patterns for (a) DITE-Type Divertor; (b) ⊗-ISX-B Divertor With Circular Coils; (c) ⊗-ISX-B Divertor With D-Shaped Coils.

Figure 6. Angular and Cross-Sectional Grids for Force Computation.

FIGURE 7. DISTRIBUTION OF f_ρ , f_z (IN KN/CM^2 PER ARC SEGMENT) FOR DITE DESIGN (CASE A).
ONE CM IS ALSO EQUIVALENT TO $10 \text{ KN}/\text{CM}^2$.

FIGURE 8A. DISTRIBUTION OF f_ρ , f_z (IN KN/CM^2 PER ARC SEGMENT) FOR THE WESTINGHOUSE DESIGN WITH CIRCULAR COIL (CASE b) ON THE FIRST HALF OF THE COIL CROSS SECTION (1-10).

FIGURE 8B. DISTRIBUTION OF f_ρ , f_z (IN kN/cm^2 PER ARC SEGMENT) FOR THE WESTINGHOUSE DESIGN WITH CIRCULAR COIL (CASE 1b) ON THE SECOND HALF OF THE COIL CROSS SECTION (11-20).

Figure 9. Vector Sum of $\vec{f}_p$ (per arc segment) Over the First Layer of the Divertor Coil as a Function of Angular Position.

Figure 10. Vector Sum of $\vec{f}_z$ (per arc segment) Over the First Layer of the Divertor Coil as A Function of Angular Position.

Figure 11. Tensions vs Angular Position Along the Perimeter.

Figure 12. Vector Sum of $\vec{f}_z$ (per arc segment) Over The Coil Cross Section as a Function of Angular Position.

Figure 13. Conceptual Mechanical Structure for the Divertor Coils.

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