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HOT SPOTS IN THE INBOARD SECTION OF THE TFCX TOROIDAL FIELD COILS*

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HOT SPOTS IN THE INBOARD SECTION OF THE TFCX TOROIDAL FIELD COILS

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ABSTRACT

The TFCX conceptual designs call for the construction of the reactor torus through the use of "pie-shaped" segments for mechanical and maintenance considerations. The use of this concept results in hot spots in the inboard section of the torodial field (TF) coils due to neutron and photon streaming through the slots between the segments. This work studies these effects on the nuclear responses in the TF coils and introduces design solutions to reduce the impact on the reactor design.

I. INTRODUCTION

In most of the fusion reactor studies,[1-5] the shield systems addressed only two types of shields. These are the bulk shield for the plasma chamber and the penetration shields for the large openings in the first wall. The importance of these two types of shields results from their direct impact on the reactor cost. The economic analyses show that their capital cost representa 8 to 16% of the total direct cost.[1,3] However, there is another class of shielding problems which received much less attention from the fusion design community. These shielding problems have a major impact on the reactor performance and require design modifications to moderate their impact. They result from neutrons and photons streaming through small penetrations or slots required for the design. For example, slots between reactor segments impact the performance of toroidal field coils and the radiation exposure levels inside and outside reactor halls. Also, small penetrations, of less than 100 cm^2 in the cross section area, are required for diagnostics and fueling.

Recently, an interesting study[6] was performed on neutron streaming through several types of circular diagnostic penetrations in a fusion reactor shield. In this study, the shield consisted of graded layers of steel and water with a total thickness of 130 cm producing a total neutron flux attenuation of 5×10^{-9}. These layers were stacked to form a cylinder where a plane source was located in the front of the first layer representing the first wall. A vacuum boundary condition was used on all outer surfaces. The use of a 5-cm radius straight-through circular penetration in the shield reduced the total neutron flux attenuation factor to 1×10^{-3} at the penetration exit. This change in the flux level at the outer shield surface will cause about six order of magnitude local increase in the nuclear heating, the radiation damage in the reactor components, and the radiation exposure.

Another study[7] was carried out to determine the neutron dose rate through straight and single bend slots with various thicknesses in a one-meter-thick shield (80% Type 316 steel and 20% water by volume). A uniform plane source with a cosine angular distribution and 14 MeV neutron energy were employed. The results of this study[7] showed four order of magnitude increase in the neutron dose rate due to 5-cm straight slot relative to the unpenetrated shield. Adding a single bend of 60° to this slot reduced this increase in the dose rate to a factor of 300 instead of the four order of magnitude.

This paper studies, for the first time in any fusion reactor study, the neutron and photon streaming in the inboard section of tokamak reactor using the TFCX as a vehicle for the study. The TFCX conceptual designs call for the construction of the reactor torus through the use of "pie-shaped" segments for fabrication and maintenance considerations. The use of this concept results in slots between the reactor segments causing hot spots in the inboard section of the toroidal field coils from radiation streaming. This work quantifies the change in the nuclear responses, nuclear heating, fluence, insulator dose, and atomic displacement in the copper stabilizer, as a function of the slot width and introduce possible design solutions to reduce the impact on the reactor designs.

II. GEOMETRICAL MODEL AND SOLUTION PROCEDURE

As mentioned before, two types of slots, straight and single bend with widths of 3, 5, and 7 cm were considered for each. The radial build up of the TFCX geometry with a 60 cm inboard shield thickness at the midplane is shown in Table 1. The shield composition given in Table 1 is based on the optimization study of the TFCX bulk shield. The inboard shield consists of 80% type 316 steel and 20% water by volume with 2 cm boron carbide, with 0.7 density factor, at the back of the shield. The boron carbide acts as a sink for the low energy neutrons which reduces the neutron absorption in the toroidal field coils and consequently the nuclear heating. The outboard shield is included in the geometrical model to insure the right boundary conditions for the inboard section of the shield. In order to carry out this study, each slot was implemented in the inboard section of the shield as shown in Figs. 1 and 2. For the straight slot, the geometrical model uses a 15° slice representing one half of a reactor segment which makes use of the reactor symmetry. The boundary conditions are vacuum at the outer surface of the outboard shield and specular reflection on both sides of the slice under consideration. In the vertical direction, the geometrical model has no spatial variation and specular reflection on the top and bottom of the geometrical model. Such a choice of the boundary conditions produces the maximum nuclear responses expected in toroidal field coils due to slot streaming at the midplane. The neutron source has a uniform distribution over the plasma volume and an isotropic angular distribution. The source is located between R = 294 and 506 cm and has the same height of the geometrical model. In the case of the single-bend slot, the slice has a 30° angle as shown in Fig. 2.

The transport calculations were performed using the Monte Carlo code MORSE[8] with P_3 legendre expansion for the scattering cross sections. A 67-multigroup cross section set based on ENDF/B-IV (46-neutrons and 21-photons) collapsed from the CTR library[9] was used. The MACKLIB[10] was employed to calculate the nuclear responses in the TF coils.

In all the calculations, the inboard shield and the TF coils were subdivided into small zones to facilitate the use of geometric splitting and Russian Roulette variance reduction schemes. Also, the subdivisions were utilized for tallying the nuclear responses. In the source sampling process, a biasing technique was employed to increase the number of neutrons generated near the slot area.

III. RESULTS AND DISCUSSIONS

Monte Carlo calculations were carried out in a parametric fashion for the two slot types considered in this study as well as another case without any slot. The 24° angle of the single bend slot was chosen based on fabrication and replacement considerations. The track length estimators were used to calculate the nuclear responses reported in this paper. Each zone used for tallying is divided into two sections. The first section is facing the slot exit, the hot spot, because it is expected to have the maximum nuclear responses for the cases under consideration. The second section is the rest of the zone away from the slot exit. The case without the slot gives a reference to compare the relative changes in the nuclear responses resulting from the existence of the slots in the inboard section of the reactor.

Table 2 gives the nuclear heating (and the fractional standard deviation) in the TF coil case and the front section of the winding material normalized to 1 MW/m^2 neutron wall loading at the first wall. The straight slots with 3, 5, and 7 cm increase the nuclear heating in the section of the TF coil which does not face the slot by factors of 5, 14, and 26 relative to the no slot case, respectively. Also, a similar increase has occurred in the TF coil winding material.

Such an increase in the nuclear heating has a significant impact on the design of the TF coils and the refrigeration power required for removing the heat load. Bending the slot as shown in Fig. 2 reduces this increase in the nuclear heating by a factor of two.

The section of the TF coil facing the slot exit gets a larger local increase in the nuclear heating as given in Table 2. This increase relative to the no slot case is given in Table 3 and it is defined as the nuclear heating factor. This local increase in the nuclear heating effects the cryogenic stability of the coils and it should be considered in the TF coil design.

The atomic displacement in the copper stabilizer and the radiation dose in the thermal insulator normalized to 1 $MW \cdot y/m^2$ are given in Table 4. These responses have changes similar to the nuclear heating discussed above. The increase in the copper atomic displacement at the slot exit will increase the copper resistivity which aggravates the local heating problems in this area. Again, this change in the copper resistivity can be accommodated by using a copper stabilizer which increases the coil thickness, or it can be partially annealed out by warming the coil, or the slot geometry can be redesigned to reduce the radiation streaming. The change in the insulator dose is more serious because the radiation damage caused by high doses is irreversible and limits the operating

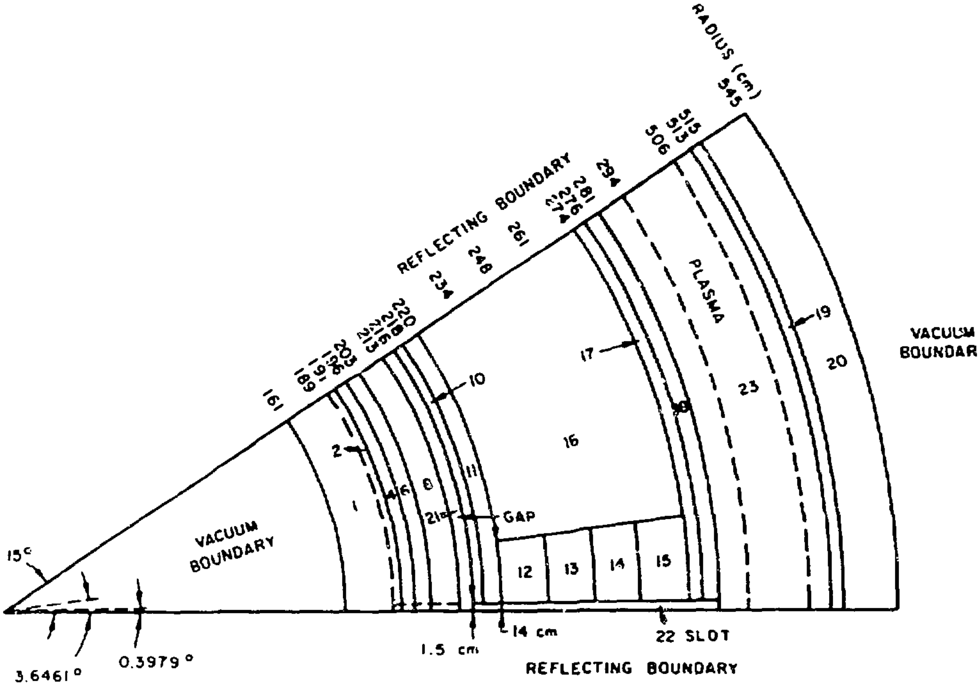

Fig. 1. Sketch of straight slot model.

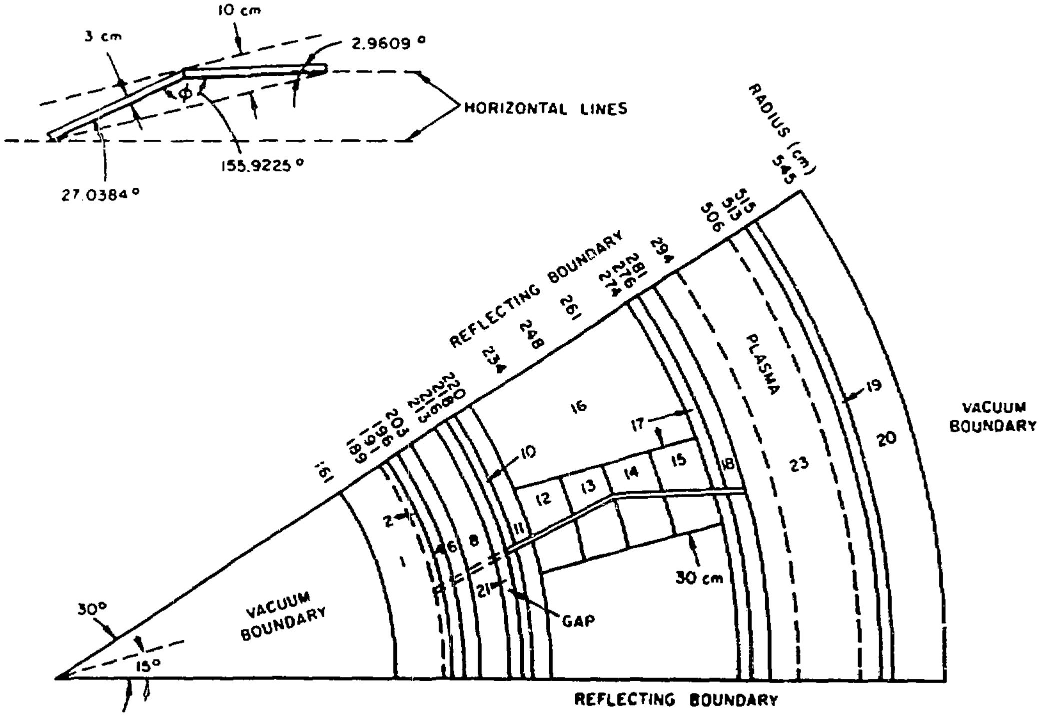

Fig. 2. Sketch of the single-bend slot model.

TABLE 1. RADIAL BUILDUP AND MATERIAL COMPOSITION FOR EACH ZONE

Zone Numbers	Zone Description	Radius (cm) From	Radius (cm) To	Width (cm)	Composition Volume percentage
1	TF magnet	161	189	28	5% NbTi, 23% Cu, 45% Type 316 steel, 8% epoxy
2,3		189	191	2	
4,5	Magnet case	191	196	5	100% Type 316 steel
6,7	Thermal insulator	196	203	7	1% epoxy
8,9	Vacuum vessel	203	213	10	100% Type 316 steel
21	Gap	213	216	3	Vacuum
10	Shield jacket	216	218	2	100% Type 316 steel
11	B_4C	218	220	2	100% B_4C (0.7 density factor)
12-16	Inboard shield	220	274	54	80% Type 316 steel, 20% H_2O
17	First wall	274	276	2	50% Type 316 steel, 50% H_2O
18	Graphite	276	281	5	100% graphite
	Scrape-off	281	294	13	Vacuum
23	Plasma	294	506	212	Vacuum
	Scrape-off	506	513	7	Vacuum
19	First wall	513	515	2	50% Type 316 steel, 50% H_2O
20	Outboard shield	515	545	30	80% Type 316 steel, 10% H_2O, 10% B_4C (0.7 density factor)

TABLE 2. AVERAGE ZONE HEATING IN THE TF COIL CASE AND WINDING MATERIAL NORMALIZED TO 1 MW/m^2 NEUTRON WALL LOADING AT THE FIRST WALL

Slot		Average Zone Heating (mW/cm^3)			
Type	Width (cm)	TF Coil Case Section Relative to the Slot Exit		Front 2 cm of TF Coil Winding Material Relative to the Slot Exit	
		Away	Facing	Away	Facing
No slot	-	7.44-1[a](0.20)[b]	-	6.74-1(0.20)	-
Straight	3.0	3.66+0(0.19)	1.23+1(0.27)	2.80+0(0.20)	6.71+0(0.23)
Straight	5.0	1.02+1(0.18)	2.81+1(0.32)	8.61+0(0.19)	2.02+1(0.23)
Straight	7.0	1.95+1(0.20)	5.80+1(0.22)	1.57+1(0.19)	4.04+1(0.22)
24° Single bend	3.0	1.84+0(0.22)	3.33+0(0.31)	1.64+0(0.25)	2.80+0(0.36)
24° Single bend	5.0	5.62+0(0.20)	1.33+1(0.28)	4.48+0(0.22)	1.34+1(0.45)
24° Single bend	7.0	9.69+0(0.14)	1.99+1(0.16)	7.42+0(0.15)	1.41+1(0.16)

[a] 7.44-1 reads 7.44 x 10^{-1}.

[b] The number in parentheses is the fractional standard deviation.

TABLE 3. NUCLEAR HEATING FACTORS[a] IN THE TOROIDAL FIELD COIL

Slot		Nucl. Htg. Factor	
Type	Width (cm)	TF Coil Case	TF Coil Winding Material
Straight	3	16.5	10.0
Straight	5	37.8	30.0
Straight	7	78.0	59.9
24° Single bend	3	4.5	4.2
24° Single bend	5	17.9	19.9
24° Single bend	7	26.7	20.9

[a] Nuclear heating factor is defined as the ratio between the maximum nuclear heating due to the slot divided by the nominal nuclear heating without slot in the same reactor component.

TABLE 5. ATOMIC DISPLACEMENT AND THERMAL INSULATOR DOSE FACTORS

Slot		Atomic Dis. Factor	Thermal Ins. Dose Factor
Type	Width (cm)		
Straight	3	11.8	13.7
Straight	5	41.8	44.4
Straight	7	78.3	91.1
24° Single bend	3	3.3	4.7
24° Single bend	5	20.6	20.3
24° Single bend	7	22.5	25.3

TABLE 4. ATOMIC DISPLACEMENT IN THE COPPER STABILIZER AND RADIATION DOSE IN THE THERMAL INSULATOR NORMALIZED TO 1 MW·y/m^2

Slot		Atomic Displacement in the Front 2 cm Section of the Copper Stabilizer Relative to the Slot Exit, dpa		Thermal Insulator Dose Relative to the Slot Exit, rads	
Type	Width (cm)	Away	Facing	Away	Facing
No slot	-	5.77-4(0.20)	-	2.25+9(0.19)	-
Straight	3	2.23-3(0.21)	6.81-3(0.33)	9.44+9(0.21)	3.08+10(0.24)
Straight	5	7.53-3(0.25)	2.41-2(0.27)	2.82+10(0.21)	1.00+11(0.31)
Straight	7	1.39-2(0.26)	4.52-2(0.26)	5.59+10(0.24)	2.05+11(0.30)
24° Single bend	3	1.36-3(0.25)	1.88-3(0.29)	5.96+9(0.25)	1.06+10(0.32)
24° Single bend	5	4.04-3(0.20)	1.19-2(0.41)	1.55+10(0.21)	4.56+10(0.25)
24° Single bend	7	5.97-3(0.20)	1.30-2(0.18)	2.57+10(0.18)	5.69+10(0.17)

life of the coil. Table 5 shows that the TF coil has to be designed one to two orders of magnitude below the radiation damage limits to accommodate the slots in the inboard shield.

IV. CONCLUSIONS

This study demonstrates the strong impact on the TF coils of narrow slots between the reactor segments.

The impact was quantified for the straight and the 24° single bend slots as a function of the slot width. The results show one to two order of magnitude increase in the nuclear responses of the TF coils relative to the no slot case typically used in the design studies. The single bend has half the impact compared to the straight slot. The use of more than one bend in the slot and a different angle for the bend requires more investigation to improve the shield performance.

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