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ASSESSMENT ON F/W ELECTRICAL CUTTING FOR REDUCTION OF ELECTROMAGNETIC FORCE ON THE BLANKET MODULE

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Kazunori KITAMURA, Manabu KOMATSUZAKI*, Satoshi NISHIO
Kouichi KOIZUMI and Hideyuki TAKATSU

日本原子力研究所
Japan Atomic Energy Research Institute

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Assessment on F/W Electrical Cutting for Reduction of Electromagnetic Force on the Blanket Module

Kazunori KITAMURA, Manabu KOMATSUZAKI *, Satoshi NISHIO +
Kouichi KOIZUMI and Hideyuki TAKATSU +

Department of ITER Project
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

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For mitigating the electromagnetic (EM) force acting on the first wall (F/W) during plasma disruption, effects of toroidally electrical cutting slits on copper heat sink of F/W have been investigated by EM analysis of the blanket module designed for the International Thermonuclear Experimental Reactor (ITER). The analytical studies include 1) effects of F/W material and its thickness on eddy current reduction, and 2) effects of number of toroidal cutting slits on copper heat sink and of gap length of the slit on the eddy current reduction in the copper heat sink.

The following conclusions were obtained and the effectiveness of toroidal cutting of copper heat sink was clarified by a series of analyses;

a)A change of F/W material from copper alloy (DSCu) to SS316 decreases the eddy current and electromagnetic force on the F/W at plasma disruption. In the case of SS316, reduction effect is remarkable in the range of the thickness less than 50mm.

b)Toroidal cutting on F/W DSCu region can reduce total eddy current acting on the F/W. By increasing number of toroidal slits with 1mm gap length up to 17(corresponding to maximum limit), about 60% of the eddy current

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This work was conducted as an ITER Design Task and this report corresponds to the 1995 ITER Comprehensive Task Agreement for Design Task(Task No.D202).

\+ Department of Fusion Engineering Research.

* Kanazawa Computer Service.

in the F/W runs away through the SS316 support plate located at the behind of copper alloy heat sink.

Keywords : Modular Blanket, First Wall, Electrical Cutting, Eddy Current, Plasma Disruption

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第一壁のトロイダルカット構造の電磁力低減効果

日本原子力研究所那珂研究所ITER開発室
喜多村和憲・小松崎　学*・西尾　　敏+
小泉　興一・高津　英幸+

（1996年6月5日受理）

核融合実験炉（ITER）ブランケットの第一壁に作用するプラズマ崩壊時の電磁力低減対策として，第一壁表面の銅合金熱シンク材にスリットを施して熱シンク材をトロイダル方向に電気的にカットする構造概念の有効性について検討した。

検討は以下2つの評価によって行った。

1)第一壁表面材料を銅合金からSUS材への変更およびSUS材の板厚を変えることによる第一壁のトロイダル電気抵抗の増加によって渦電流，電磁力の低減効果の検討。

2)第一壁表面のトロイダルスリットのモジュール当たりの分割数，ギャップ長をパラメータにして，その渦電流低減効果を検討。

その結果，以下の結論が得られ，第一壁銅合金へのトロイダルスリット構造は，プラズマ崩壊時の第一壁の渦電流および電磁力低減に効果的であることが分かった。

a)第一壁表面材料を銅合金からSUS材に変更することによって，プラズマ崩壊時の第一壁への渦電流および電磁力は低減する。さらに，SUS材板厚50mm以下の領域でその効果は大きい。

b)第一壁表面銅合金のトロイダルスリット構造によって，プラズマ崩壊時の第一壁への渦電流および電磁力は低減される。インボードモジュールでは実機寸法に相当する1mmギャップ長のトロイダルスリット数を17（上限値）まで増加することにより，第一壁内渦電流の約60％がSUS構造材に流れる。

本作業は，国際熱核融合実験炉（International Thermonuclear Experimental Reactor）の工学設計活動として，1995年設計作業計画（Task No.D202）に基づいて実施した。

那珂研究所：〒311－01　茨城県那珂郡那珂町向山801-1

+　核融合工学部

*　㈱カナザワコンピュータサービス

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1. Introduction

A modular-type blanket structure has been proposed as a reference design concept of the ITER-EDA (Engineering Design Activity of the International Thermonuclear Experimental Reactor) [1] for its easy maintenance scheme and structural reliability. The blanket structure is composed of box-type SS316 shield blocks and they are welded to a back plate made of SS316. The back plate forms a cylindrical and thick shell structure in the toroidal direction. Figure 1 shows mechanical configuration of modular blanket structure [2]. A first wall (F/W) is installed on its plasma side to protect the blanket module from plasma high heat and particle loads during normal operation and plasma disruption. The F/W structure is composed of Be tiles as an armor material for protection of the module, copper alloy (DSCu) as a heat sink for effective heat removal, and 316 stainless steel(SS316) base plate as a support structure. These components are bonded by brazing or Hot Isostatic Pressing (HIP), and arranged at the plasma side surface. A cross section of the blanket module is shown in Fig. 2 [1].

In addition to the large heat deposition, the large electromagnetic (EM) force acts on the F/W at the plasma disruption by the interaction effect between toroidal and poloidal magnetic fields and induced eddy current in the toroidal direction. The reduction of EM load acting on the F/W region, therefore, is one of the key design issues to ensure the reliability of the blanket structure. In the present F/W design, most of eddy current runs through the region of DSCu heat sink since the electrical resistance of SS316 is about 40 times larger than the value of DSCu, so that mitigation of the EM force on the F/W at plasma disruption may not be expected essentially.

The concept of toroidal cutting was proposed in order to reduce the EM force in the F/W region. This concept is to make a deep slit in the poloidal direction between F/W cooling channels with a depth from F/W surface to the DSCu/SS316 bonded interface for changing major current path from Cu alloy heat sink to SS316 support plate. Then, the effect of this concept has been investigated through a series of the electromagnetic analysis of the ITER blanket module to quantitatively evaluate its mitigating effects. The analysis includes the studies of 1) the effects of F/W material and thickness on eddy current reduction, and 2) effect of the number of toroidal slits and its gap length on the eddy current reduction in the copper heat sink.

2. Structural concept of toroidal cutting

Structural concept of toroidal cutting provides continuous slits in the poloidal direction between the F/W cooling channels, whose slit has a depth from plasma side surface to the bonded interface between DSCu and SS316. The gap width between slits is designed to be ~1 mm, which is as same order as that between Be armor tiles installed on plasma side surface of DSCu heat sink.

Figure 3 shows the structural concept of toroidal cutting on copper heat sink in the F/W.

1. Introduction

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Figure 3 shows the structural concept of toroidal cutting on copper heat sink in the F/W.

The number of the toroidal cutting slits are limited to be 34 for inboard module and to be 50 for outboard module, according to the number of cooling channels.

3. Effects of F/W material and thickness on eddy current reduction

If toroidal cutting slit can shut out most of the toroidal component of eddy current in the Cu alloy, an existence of the copper heat sink can be neglected from the viewpoint of the electromagnetic behavior. Therefore, as the first step of the analysis, the eddy current behavior of the inboard blanket module under centered disruption was investigated with a full ploidal blanket model as a function of F/W toroidal resistance by varying F/W material from the copper alloy to SS316 and by changing the thickness of SS316 support base plate.

Figure 4 shows an electromagnetic analysis model of a full poloidal blanket, which are represented with 3-dimensional shell elements of 9° toroidal sector, consisting of inboard/outboard blanket modules, back plate and double-walled vacuum vessel. Since centered disruption condition was considered in the analysis, detailed mesh was employed for 3 box modules around the inboard midplane, where relatively large eddy currents are predicted to be induced on the structural components. An electromagnetic analysis code, EDDYCAL [3] was used in the analyses. Materials and thickness of blanket structural components are listed in Table 1, and plasma disruption conditions in the analysis are also shown in Table 2.

Analyses were conducted for 4 cases with different materials and plate thickness for the F/W in the blanket modules. The Cu alloy of 10 mm thickness, SS316 plate of 50 mm thickness, SS316 plate of 22 mm thickness and SS316 plate of 10 mm thickness were considered for the analyses.

Schematic drawings of eddy current and electromagnetic force obtained for the inboard blanket module at the midplane are shown in Fig. 5, which has a 10 mm thick copper alloy first wall. The eddy currents and electromagnetic forces on the inboard midplane blanket module were obtained as a function of a change of F/W material and its thickness,, as shown in Tables 3 and 4, respectively. A change of material and thickness of the F/W is equivalent to the electrical resistance variation of the F/W in the analysis, so that analytical results of eddy currents and electromagnetic forces on the components are summarized as a function of the F/W electrical resistance, as shown in Fig.6.

A change of the F/W material from the copper alloy to SS316 and reduction of SS316 F/W thickness which corresponds to the increase of F/W electrical resistance, decrease the eddy current and electromagnetic force on the F/W at the plasma disruption. In case of SS316, the reduction effect is remarkable in the range of the thickness less than 50 mm.

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An equivalent electromagnetic thickness will be ~100 mm for SS316 support plate of shielding blanket from the standpoint of effective skin depth of SS316 for the electromagnetic phenomena with decay time of ~10 msec such as the centered plasma disruption, while actual SS316 thickness of the shielding blanket module is ~300 mm.

Here, above-mentioned SS316 skin depth, δs is obtained by following equation [4];

$$\delta s = (2\tau/(\sigma\mu))^{**}(1/2) \qquad (3\text{-}1)$$

where, τ : decay time constant (= 0.01 sec)
σ : electrical conductivity (= $1/\rho$)
ρ : electrical resistivity (= 8.02E-7 Ω/m)
μ : magnetic permeability (= 4 π E-7 H/m)

Therefore, the electromagnetic force on the module is estimated to be reduced by ~20 % for the shielding blanket, and by ~50 % for the breeding blanket which has 14-22 mm thick SS316 F/W.

4. Effect of toroidal cutting slits on eddy current reduction

The eddy current behavior has also been investigated for DSCu/SS316 bonded structure with the toroidal cutting slits on the Cu heat sink, as a function of number of toroidal cuts: N, thickness of SS316 support base plate behind the Cu heat sink: *ts* and gap length of toroidal slit: *ds*. Figure 7 shows the electromagnetic analysis model with 4.5° toroidal sector of partial inboard F/W with toroidal cutting slits on the copper heat sink, which corresponds to the configuration with N=5, *ts*=20 mm and *ds*=22 mm.

The major objective of this analysis is not to obtain the absolute value of eddy current on the copper heat sink and SS316 support plate at plasma disruption, but to get relative ratio of eddy current on the copper heat sink to that on the SS316 support plate.

Therefore, only inboard F/W component around the midplane was modeled in the FEM analysis, where relatively large eddy currents are predicted to be induced on the structural components.

4.1 Effect of number of toroidal cutting slits

As shown in Fig. 8, eddy currents on the DSCu heat sink and SS316 support plate were analyzed as a function of the number of toroidal cuts, N from 1 to 10 in the case with slit gap length of 22 mm and SS316 support plate thickness, *ts* of 20 mm. Table 5 shows the eddy currents on the DSCu heat sink and SS316 support plate as a function of the number of toroidal cuts, N and of SS316 phenomena with decay time of ~10 msec such as the centered plasma disruption, while actual SS316 thickness of the shielding blanket module is ~300 mm.

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Based on the above results, effect of number of toroidal cutting slits in the DSCu heat sink on eddy current reduction is indicated in Fig. 10, as a function of SS316 support thickness in case of 22 mm slit gap length. It was found from Fig. 10 that total toroidal current on the F/W, *It* decreased with the increase of the number of toroidal cutting slits, N and ratio of current on SS316 support to total toroidal current, (*Is*/*It*) increased with the increase of number of toroidal slits. Furthermore, *It* was reduced with the decrease of SS316 support thickness, *ts* and (*Is*/*It*) also decreased with the decrease of *ts*.

4.2 Effect of gap length of slit

Similarly, effects of number of toroidal cutting slits in the DSCu heat sink on eddy current reduction are indicated in Figs. 11and 12 in cases of 10 mm and 5 mm slit gap lengths, respectively. Their results shows almost as same tendency as those in Fig.10.

In ITER blanket design, inboard module has 34 cooling channels with 1 mm slit gap length for the F/W heat removal. This corresponds to maximum number of toroidal slits of 17 in this analysis model. Then, *It* and (*Is*/*It*) in case with N=17 and *ts*=100 mm were obtained from extrapolation of the results on the line with *ts*=100 mm to the point of N=17, in Fig. 10 to Fig. 12. Here, *It* and (*Is*/*It*) on the lines with *ts*=100 mm, were accepted because of its reasonable thickness for electromagnetic skin depth.

An effect of slit gap length on eddy current reduction in case with N=17 and *ts*=100 mm is shown in Fig.13, by summarizing the results in Fig. 10 to Fig.12. From the figure, about 60 % of eddy current on the F/W runs away on the SS316 support plate located behind the DSCu heat sink, by means of increasing number of toroidal cutting slits on the DSCu heat sink and of decreasing the slit gap length.

5. Concluding remarks

The analytical studies of electromagnetic behavior of the F/W were conducted to investigate the effect of toroidal cutting slits in the DSCu heat sink of the F/W for the reductions of eddy current and electromagnetic force on the F/W.
From the studies, following conclusions were obtained;

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From the studies, following conclusions were obtained;

1. (1) A change of the F/W material from DSCu to SS316 and of the thinner SS316 thickness decreases the eddy current and electromagnetic force on the F/W at plasma disruption, and the reduction effect is remarkable in the range of SS316 thickness less than 50 mm.
2. (2) Electromagnetic force on the inboard midplane blanket module is predicted to be reduced by ~20 % for the shielding blanket, and by ~50 % for the breeding blanket which has 14-22 mm thick SS316 F/W.
3. (3) A structural concept of toroidal cutting slit on the F/W DSCu heat sink region can decrease total eddy current and electromagnetic force acting on the F/W.
4. (4) About 60 % of eddy current on the F/W runs through the SS316 support plate located behind the DSCu heat sink, by means of increasing number of toroidal slits on the DSCu heat sink and of decreasing the slit gap length.

Therefore, toroidal cutting slits in the DSCu heat sink of the F/W is considered to be a effective concept for the reduction of eddy current and EM force on the F/W during the plasma disruption.

Acknowledgment

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Table 1 Materials and Thickness of Blanket Structural Components

Component	Material	Thickness
Blanket Module		
First Wall	DSCu/SS316	10-50 mm
Side Wall	SS316	30
End Wall	SS316	30
Top/Bott Plates	SS316	30
Support Leg	SS316	70
Back Plate	SS316	80/100
Vacuum Vessel		
Inner Skin	SS316	40
Outer Skin	SS316	40

Table 2 Plasma Disruption Conditions

Plasma Current	21	MA
Major Radius	7.90	m
Minor Radius	2.90	m
Decay Time	10	msec
Decay Mode	Centered Disruption	
Blanket Thickness	0.50	m

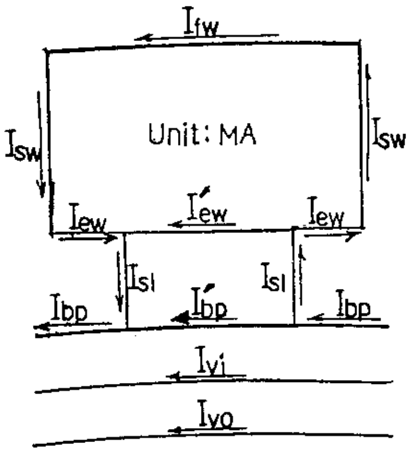
Table 3 Eddy Currents on Inboard Midplane Blanket Module

F/W Type	DSCu-10 mm	SS316-50 mm	SS316-22 mm	SS316-10 mm
Ifw	1.03	0.86	0.65	0.43
Isw	0.86	0.79	0.65	0.52
Iew	0.88	0.82	0.70	0.58
(Iew')	0.12	0.26	0.28	0.39
Isi	1.14	1.22	1.11	1.10
Ibp	1.09	1.20	1.15	1.26
(Ibp')	-0.02	-0.01	0.06	0.16
Ivi	0.19	0.05	0.14	0.06
Ivo	0.01	0.11	0.02	0.03

Unit : MA

Table 4 Electromagnetic Force on Inboard Midplane Blanket Module

F/W Type	DSCu-10 mm	SS316-50 mm	SS316-22 mm	SS316-10 mm
Ffw (MN)	0.75	0.49	0.34	0.15
(Pfw)(MPa)	0.96	0.64	0.44	0.19
Qsw (MN/m)	2.41	2.23	1.84	1.43
Qsi (MN/m)	2.07	2.23	2.02	2.00



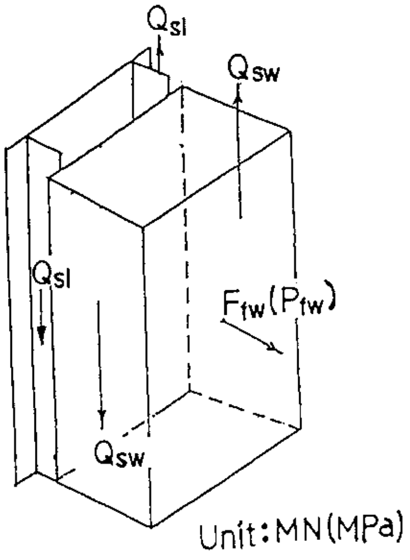
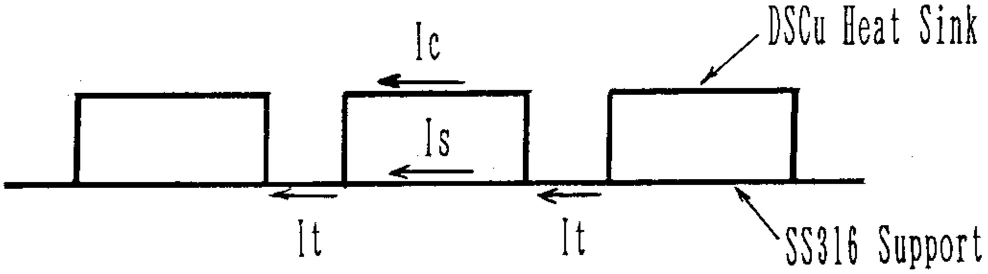


Table 5 Eddy Currents on DSCu Heat Sink and SS316 Support as a function of Number of Toroidal Cutting Slits and SS316 Support Plate Thickness in Case of Slit Gap Length of 22mm.

SS316 Thickness	ts = 20 mm			ts = 50 mm			ts = 100 mm		
Number of Cuts	N=1	N=5	N=10	N=1	N=5	N=10	N=1	N=5	N=10
Ic (MA)	3.69	2.86	2.08	3.38	2.88	2.14	2.93	2.48	1.83
Is (MA)	0.40	0.43	0.50	0.91	1.03	1.38	1.49	1.73	2.15
It (MA)	4.08	3.29	2.58	4.29	3.91	3.52	4.42	4.20	3.98
Ic/It	0.10	0.13	0.19	0.21	0.26	0.39	0.38	0.41	0.54
Is/It	0.90	0.87	0.81	0.79	0.74	0.61	0.62	0.59	0.46



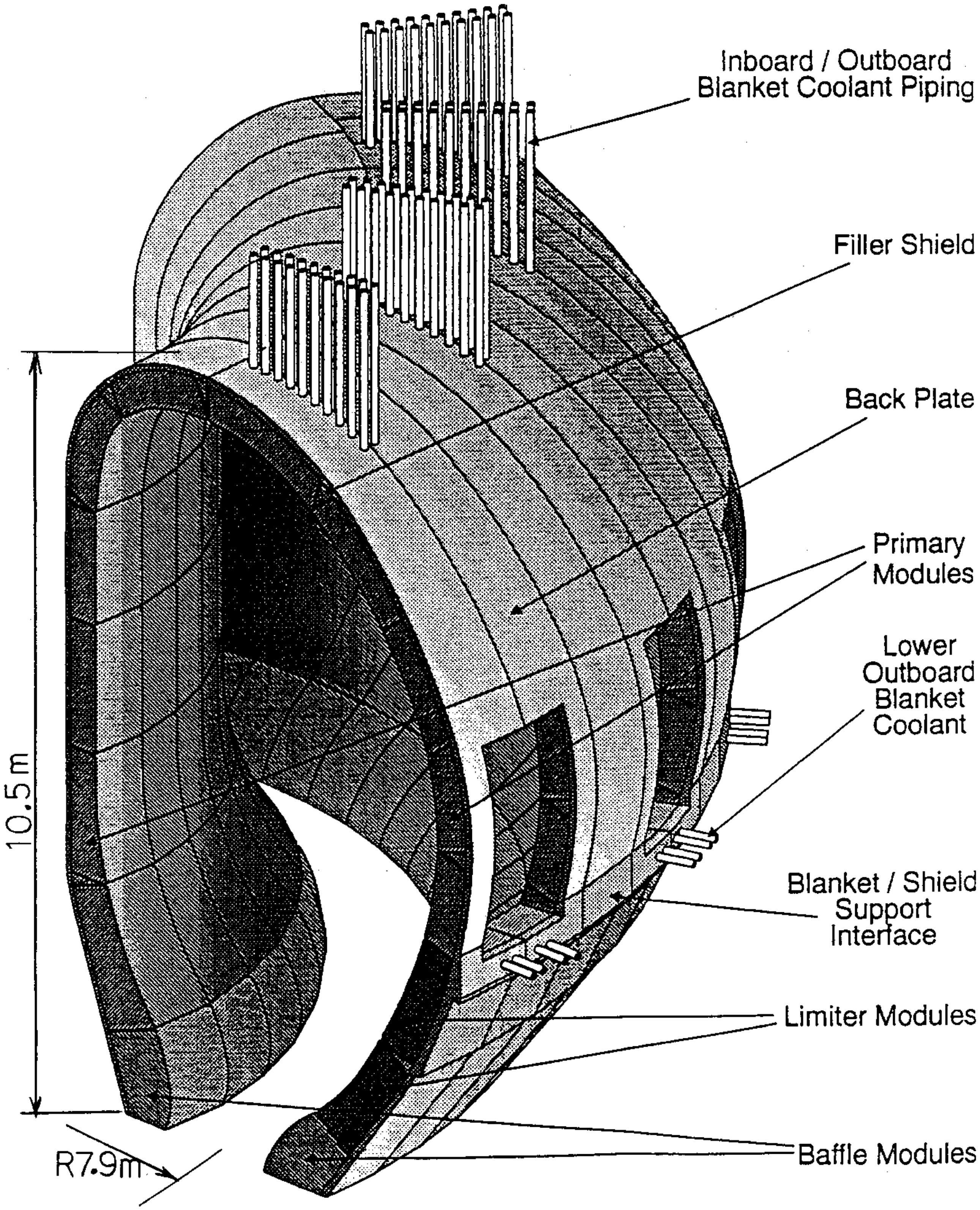


Fig. 1 Mechanical configuration of modular blanket structure

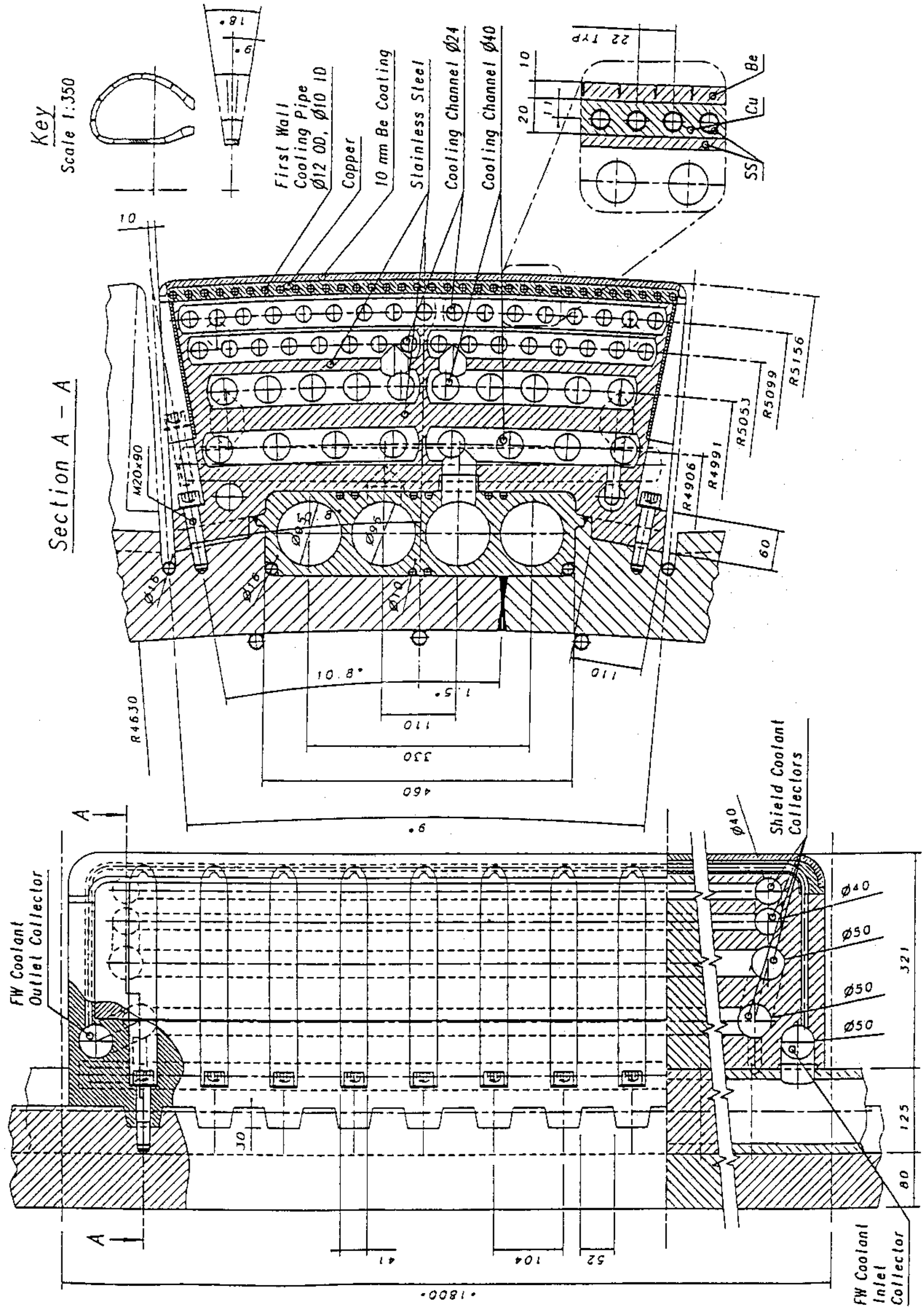


Fig. 2 Cross section of inboard blanket module

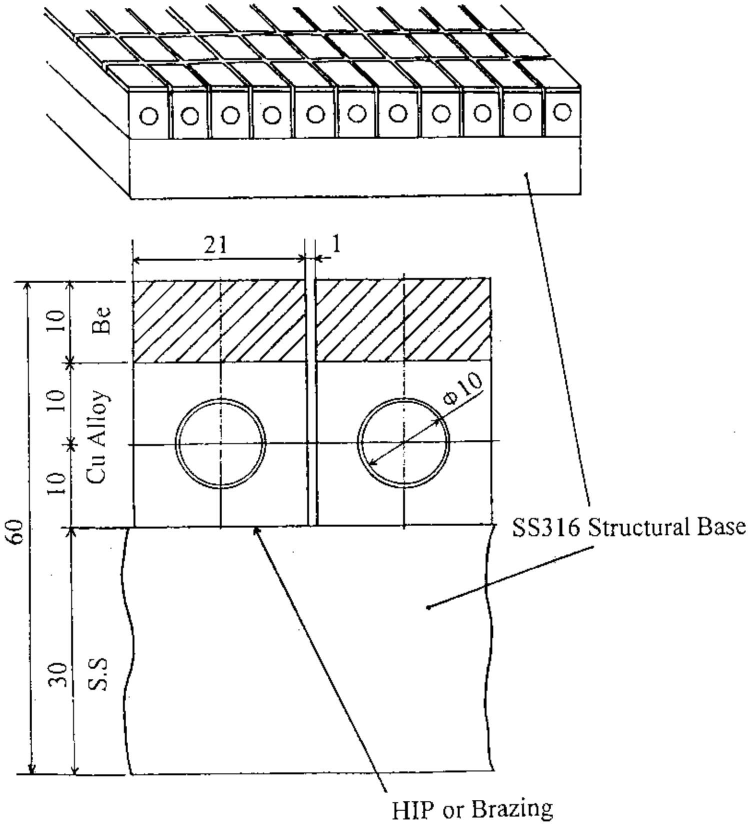


Fig. 3 Toroidal Cutting Structural Concept on Copper Heat Sink of F/W

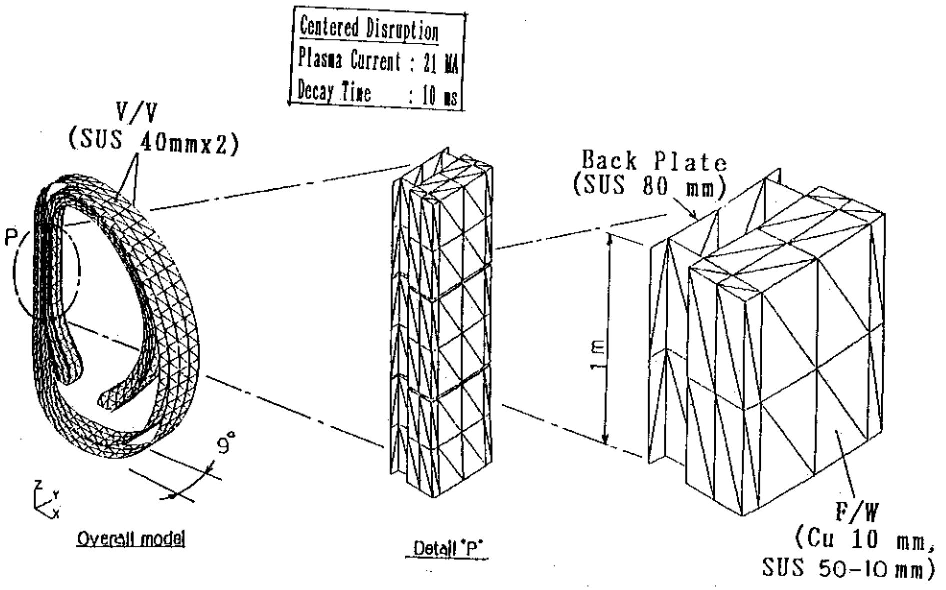


Fig. 4 Electromagnetic analysis model of blanket structure.

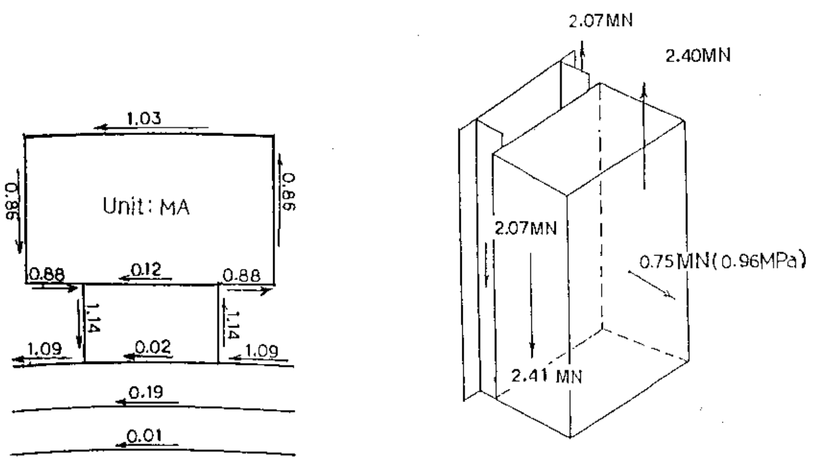


Fig. 5 Schematic drawings of eddy current and EM force on inboard midplane blanket module with a 10mm thick copper alloy first wall.

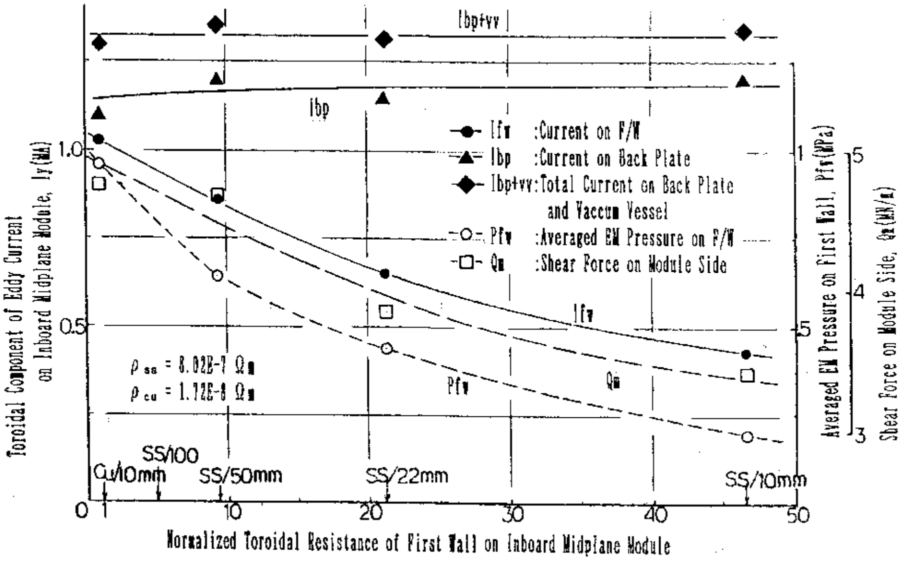


Fig. 6 Toroidal Eddy Current on Structural Components of Inboard Module as a Function of First Wall Toroidal Resistance.

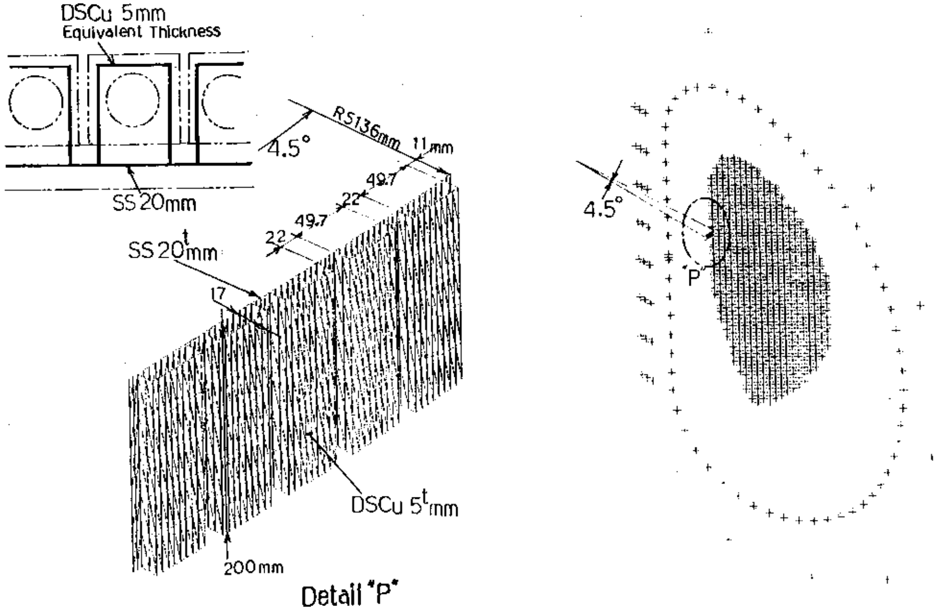


Fig. 7 Electromagnetic Analysis Model of Inboard First Wall.

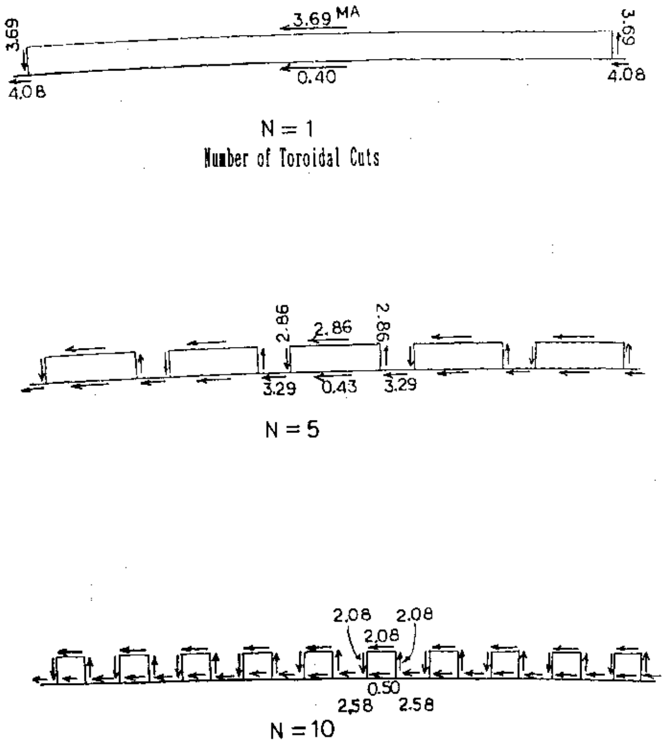


Fig. 8 Eddy Currents on DSCu Heat Sink and SS316 Support In case of F/W with Different Number of Toroidal Cuts.
(N=1, 5 and 10) ts=20mm

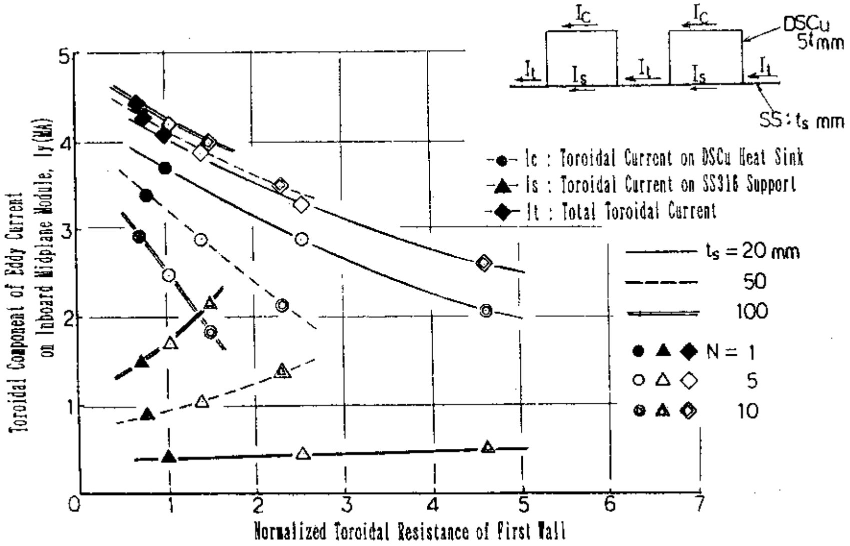


Fig. 9 Eddy Currents on DSCu Heat Sink and SS316 Support as a function of Number of Toroidal Cuts on F/W.

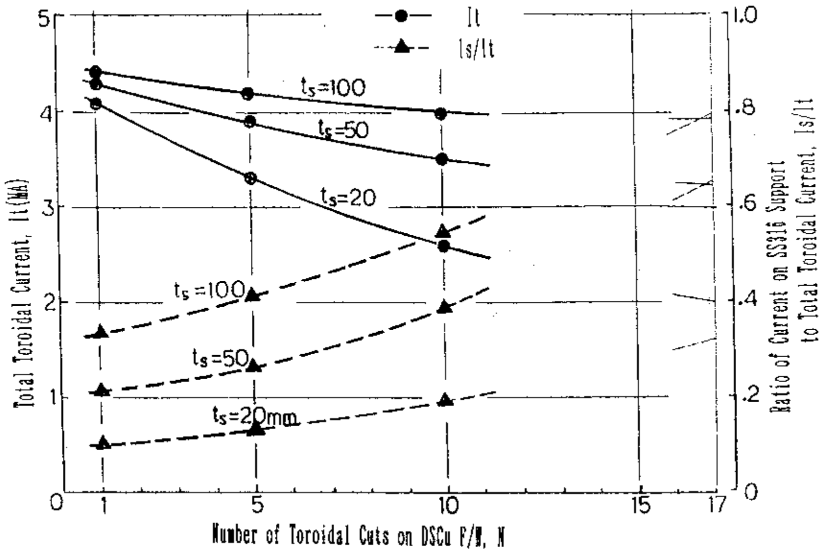


Fig. 10 Effect of Toroidal Cutting in DSCu Heat Sink on Eddy Current Reduction as a function of SS316 Support Thickness in case of 22mm Gap Length.

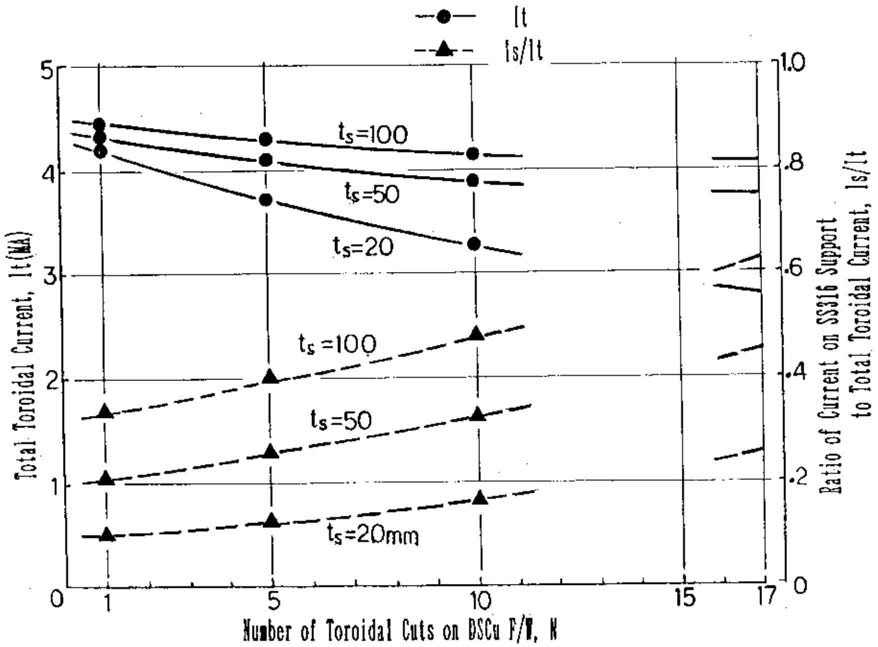


Fig. 11 Effect of Toroidal Cutting in DSCu Heat Sink on Eddy Current Reduction as a function of SS316 Support Thickness in case of 10mm Gap Length.

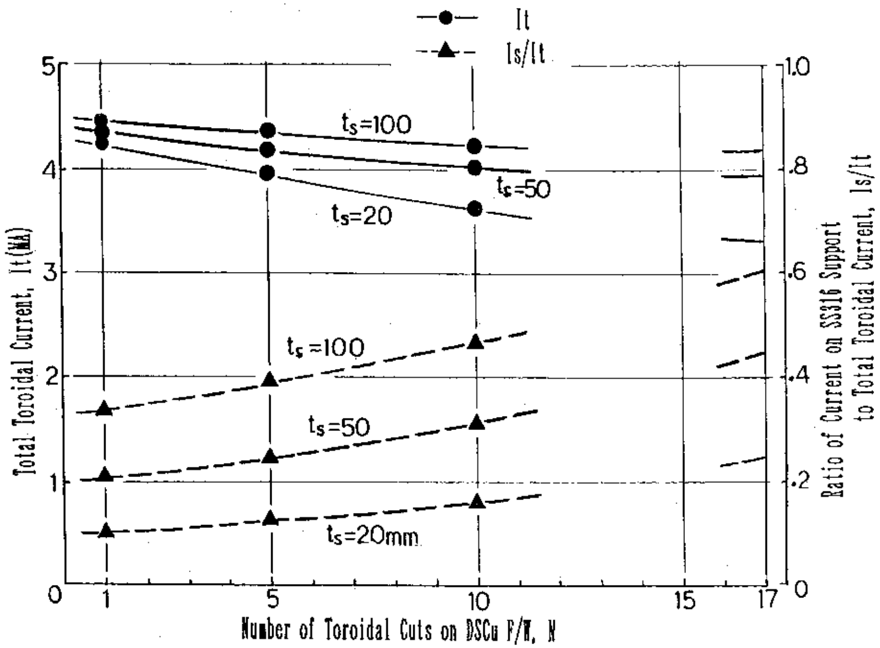


Fig. 12 Effect of Toroidal Cutting in DSCu Heat Sink on Eddy Current Reduction as a function of SS316 Support Thickness in case of 5mm Gap Length.

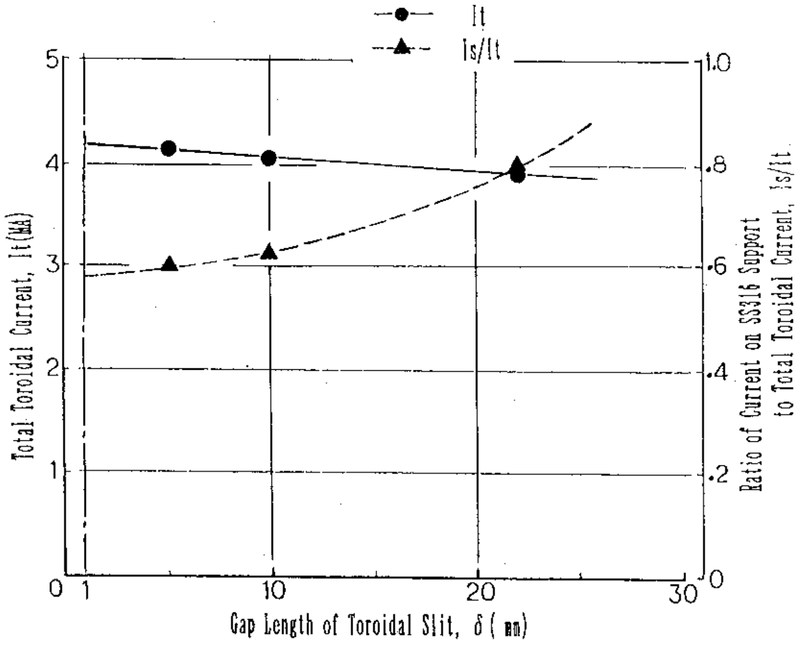


Fig. 13 Effect of Gap Length of Toroidal Slit on Eddy Current Reduction in case With N=17 and ts=100mm.