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MICROWAVE TRANSPORT IN EBT DISTRIBUTION MANIFOLDS USING MONTE CARLO RAY-TRACING TECHNIQUES

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ABSTRACT

Ray tracing Monte Carlo calculations have been carried out using an existing Monte Carlo radiation transport code to obtain estimates of the microwave power exiting the torus coupling links in EPT microwave manifolds. The microwave power loss and polarization at surface reflections were accounted for by treating the microwaves as plane waves reflecting off plane surfaces. Agreement on the order of 10% was obtained between the measured and calculated output power distribution for an existing EBT-S toroidal manifold. A cost effective iterative procedure utilizing the Monte Carlo history data was implemented to predict design changes which could produce increased manifold efficiency and improved output power uniformity.

I. INTRODUCTION

Plasma heating in the ELMO BUMPY TORUS[1] is accomplished through the injection of microwave power into each of its twenty-four microwave cavities. For optimum performance, the microwave distribution system must provide uniform microwave heating together with minimum power loss. A critical component in the distribution system is the microwave manifold which splits the power source many times and feeds the power to the plasma.

Typical microwave manifolds consist of an input feed port, a scattering wedge, and a number of output ports or coupling irises which feed power to each torus cavity. The design of the scattering wedge and the sizing of the coupling irises are crucial since these quantities dictate both power loss and injected power uniformity. Because of the complex geometric shapes encountered in microwave manifolds, the analytic determination of optimum wedge design and coupling iris openings is difficult, if at all possible. Thus, the need for Monte Carlo calculations arises since Monte Carlo type procedures are routinely used to analyze physical phenomena in complex geometries.

The applicability of Monte Carlo methods, i.e. ray tracing techniques, requires that the characteristic dimensions of the microwave manifold and the components within the manifold be much larger than the wavelength of the microwaves. Both the EBT-S and EBT-P manifolds satisfy this criteria. Under this condition, the interaction of the microwaves with the surfaces within the manifolds may be treated as plane waves reflecting off-plane surfaces and Monte Carlo ray tracing techniques can provide an acceptable representation of the microwave transport.[2]

In this paper, Monte Carlo ray tracing calculations which were carried out to simulate microwave transport in the existing EBT-S manifold and a proposed EBT-P manifold will be described. The geometric models and calculational procedures employed are described in Section II. In Section III, the results from a few of the calculations are presented and discussed.

II. CALCULATIONAL DETAILS

A. Microwave Manifold Models

The microwave transport calculations were carried out using the Monte Carlo radiation transport code MORSE.[3] The EBT-S and EBT-P microwave manifolds and the various components within these manifolds were modeled using the combinatorial geometry routines contained in the MORSE code package. The surface of the corrogated scattering wedge employed in the EBT-S manifold was, however, approximated using a semianalytic approach which consisted of superimposing a sinusoidal surface onto the surface of a flat scattering wedge.

The EBT-S manifold is a torus having a major radius of 1.02 m and a minor radius of 0.102 m. Twenty-four cylindrical coupling links positioned uniformly around the top of the torus exit inward, i.e., toward the major axis of the torus, at an angle of 45° relative to the plane of the torus. Each coupling link has an inside diameter of 0.154 m and extends approximately 0.32 m from the minor axis of

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the torus. The exit of each coupling link is covered with a flat plate containing a centrally bored circular opening. The radii of these openings which will be referred to as the iris sizes in the remainder of this paper varied between 0.0 and 0.63 m. In addition to the coupling links, six feed ports having inside diameters of 0.13 m and entering vertically are also positioned uniformly around the top of the manifold. However, only one feed port, i.e., the one in actual use, was modeled in the Monte Carlo calculations. Finally, a 90° scattering wedge which is needed to help scatter the microwave power into the manifold is located directly below the feed port opening.

The proposed EBT-P manifold is geometrically much simpler than the EBT-S manifold. The EBT-P manifold consists of six sections. Each section is comprised of two 0.102 m inside diameter cylindrical pipes intersecting at an angle of 30°. A 0.06 m inside diameter horizontal feed port is located at the intersection of the two cylinders and three 0.06 m inside diameter coupling links exit horizontally from each cylinder. Because of alignment considerations with regard to the EBT-P cavities, the coupling links exiting each section are not uniformly spaced nor do they all exit with the same angle relative to the manifold centerline. The EBT-P manifold also contains a scattering wedge positioned horizontally in front of the feed port opening. Because the cylindrical sections intersect at 30°, a 75° wedge was chosen for the EBT-P calculations.

The corrogations in the corrogated wedge employed in the EBT-S manifold ran perpendicular to the wedge vertex and the surface formed by these corrogations closely represented a sinusoidal surface. Thus, if N represents the normal to a flat wedge surface at the point of reflection and S represents a line on the flat wedge surface parallel to the wedge vertex and passing through the point of reflection, the surface of the corrogated wedge may be written

$$g(N,S) = 0 = N - A\cos(2\pi S/P). \tag{1}$$

In Eq. (1), A and P represent the amplitude and period of the corrogations. Their values were estimated to be 5.08 and 30.40 mm from measurements made on the actual corrogated wedge employed in the EBT-S manifold. For small A, the normal to $g(N,S)$ is well approximated by

$$\mathbf{N} = \nabla g \tag{2}$$

evaluated at the point of reflection on the flat wedge surface.

B. Method of Calculation

The ray tracing calculations performed for the EBT-S and EBT-P microwave manifolds required a few modifications to the MORSE radiation transport code. The primary modification was required to properly account for the attenuation and polarization of the microwaves at each surface reflection. The actual procedure employed in the Monte Carlo calculations consisting of treating the microwaves as plane waves and monitoring the reflected power after a plane surface reflection. This procedure required the determination of the electric field vectors associated with the reflected microwaves.

The power associated with a reflected microwave may be written[2]

$$P_r = |\mathbf{E}_r|^2 / |\mathbf{E}_i|^2 \tag{3}$$

where $\mathbf{E}_r$ and $\mathbf{E}_i$ represent the electric field vectors associated with the incident and reflected microwave, respectively. The determination of $\mathbf{E}_r$ requires the decomposition of $\mathbf{E}_i$ into its components perpendicular and parallel to the plane of incidence, i.e., $\mathbf{E}_{i,perp}$ and $\mathbf{E}_{i,par}$, respectively. These components are given by

$$\mathbf{E}_{i,perp} = \mathbf{E}_i \cdot (\mathbf{K}\times\mathbf{N})\,(\mathbf{K}\times\mathbf{N}) / |\mathbf{K}\times\mathbf{N}|^2 \tag{4}$$

and

$$\mathbf{E}_{i,par} = (\mathbf{K}\times\mathbf{N})\times(\mathbf{E}_i\times(\mathbf{K}\times\mathbf{N})) / |\mathbf{K}\times\mathbf{N}|^2 \tag{5}$$

or $\mathbf{E}_{i,par} = \mathbf{E}_i - \mathbf{E}_{i,perp}$.

The vectors **K** and **N** represent the propagation vector of the incident microwave and the surface normal at the point of reflection, respectively. The perpendicular and parallel components of $\mathbf{E}_r$ are then found from[2]

$$\mathbf{E}_{r,perp} = -\, r_{perp}\, \mathbf{E}_{i,perp} \tag{6}$$

$$\mathbf{E}_{r,par} = r_{par}(\mathbf{E}_{i,par} - (2\mathbf{E}_{i,par}\cdot\mathbf{N})\mathbf{N}). \tag{7}$$

The perpendicular and parallel power reflection coefficients, i.e., r_{perp} and r_{par} in Eqs. (6) and (7) are functions of the cosine of the angle of incidence $\mathbf{K}\cdot\mathbf{N}$, the free space impedance η, and the reflecting surface resistivity R_s. The coefficients may be obtained from[2,4]

$$r_{perp}^2 \simeq 1 - 4(R_s/\eta)(K \cdot N) \qquad (8)$$

and

$$r_{par}^2 \simeq 1 - 4(R_s/\eta)/(K \cdot N) \ . \qquad (9)$$

The values for R_s and η used in all of the Monte Carlo calculations were $3.17 \times 10^{-7} f^{1/2}$ and 376.734 ohms, respectively. These values together with a frequency f of 27.86 GHz were taken directly from Ref. 2.

The microwave source was placed at the entrance of an input feed port in each Monte Carlo calculation. Because an accurate description of the actual microwave source was not known, four different source treatments were employed. These four treatments consisted of representing the microwave source using an isotropic point source and a normal disk source and simultaneously considering perpendicular and parallel polarized incoming microwaves. The magnitude of the electric field vector associated with each incoming microwave, i.e., $|E_{i,perp}|$ or $|E_{i,par}|$, was fixed at unity.

All of the Monte Carlo calculations were performed using 10 batches of 1000 histories. Batches were employed simply to obtain batch statistics. In general, each calculation for the EBT-P manifold, i.e., 10,000 incoming microwaves, required approximately 20 min. of CPU time on an IBM model 370/3033. The same number of incoming microwaves required approximately 80 min of CPU time for the more complicated EBT-S toroidal manifold.

III. DISCUSSION OF RESULTS

A. EBT-P Manifold Calculations

A comparison of the power out each iris opening in the EBT-P manifold with the entrance of the feed port either totally open or totally closed is presented in Table I. In general, the Monte Carlo statistics associated with the values in Table I ranged between 2 and 4 percent. The feed port is located between the third and fourth irises. Closing the feed port was accomplished by placing a flat plate over its entrance and reflecting the microwaves exiting the feed port back into the manifold. In an actual microwave distribution system, the connecting link between the gyrotron and feed port is constructed to maximize reflection. The opening size of each iris in these calculations was the maximum allowable size, i.e., the 0.06 m inside diameter of the coupling links.

Table I. Comparison of Open and Closed Feed Power Distributions for the EBT-P Manifold

	Relative Power					
Iris	Isotropic Source			Normal Source		
No.	F.O.[a]	F.C.	F.C./F.O.	F.O	F.C.	F.C./F.O.
1	0.126	0.150	1.19	0.088	0.112	1.36
2	0.120	0.142	1.18	0.123	0.161	1.31
3	0.150	0.175	1.17	0.131	0.179	1.36
4	0.138	0.164	1.14	0.123	0.173	1.40
5	0.132	0.153	1.16	0.117	0.159	1.36
6	0.133	0.155	1.17	0.087	0.121	1.39
Feed	0.150	0	-	0.266	0	-

[a] F.O. and F. C. designate feed open and feed closed cases, respectively.

The ratio of the power exiting each iris with the feed port closed to that with the feed port open can be estimated by assuming the microwaves which reflect back into the manifold have the same spatial and angular distribution as the source microwaves. In other words, they only differ from the source microwaves in terms of power. Thus, if I represents the total power out all six irises due only to source microwaves, i.e., the total iris output power with the feed port open, and F represents the power out the feed port, then IF is the total power out the irises due to those microwaves which have reflected only once in the feed port. After two reflections, the total power due only to those microwaves reflecting twice is IF^2 and similarly after n reflections, it is IF^n. Summing over all reflections yields the total power out the irises or transmission of the manifold with the feed port closed, i.e.,

$$T = I \sum_{n=0}^{\infty} F^n = I/(1-F) \qquad (10)$$

and the ratios in Table I may be approximated by

$$F.C./F.O. \simeq T/I = 1/(1-F) \ . \qquad (11)$$

For the isotropic point source case, Eq. (11) predicts power ratios of 1.18 and for the normal source case ratios of 1.36 are predicted. On an individual iris basis, the closed feed to open feed power ratios agree very favorably with the total power ratios predicted by Eq. (11).

The total power out all the irises or transmission of the EBT-P manifold predicted by Eq. (10) is 0.940 for the isotropic source case and 0.911 for the normal source case.

The Monte Carlo calculated values are 0.939 and 0.905, respectively. These calculations were performed with a 75° flat scattering wedge positioned in the manifold directly in front of the feed port opening. The drop in transmission with the normal source could be due to focusing.

To investigate the effects associated with focusing, additional calculations were performed in which the feed port opening diameter was varied. The results from these calculations for the normal source are summarized in Table II. The standard deviations resulting from the Monte Carlo procedures on the values in Table II ranged between 2 and 4 percent except for the power exiting the smallest feed port opening which had a standard deviation of 29 percent due to its very low value.

The effects associated with focusing are sharply illustrated by the rather drastic increase in power out the number one iris as the feed port opening and normal disk source size are decreased. This behavior is due to more and more source microwaves being focused such that their first reflection occurs on the vertical center of the scattering wedge near its vertex. These microwaves travel almost directly along the manifold centerline and undergo their second reflection very close to the center of the manifold end plate which is tilted 75° relative to the manifold centerline. Their next three reflectons occur in the manifold, but their sixth reflection occurs in the number one coupling link which allows their escape out the first iris. The same result is not obtained with the sixth iris because of the manifold asymmetry. The focusing illustrated by these results for the normal disk source did not occur with the isotropic point source.

Table II. Power Distributions for the EBT-P Manifold for Different Feed Port and Normal Disk Source Sizes

Iris No.	Relative Power: Feed Port and Normal Disk Source Dia. (mm) 1.588	12.700	43.940	63.500
1	0.563	0.283	0.122	0.088
2	0.083	0.113	0.166	0.123
3	0.068	0.141	0.151	0.131
4	0.092	0.147	0.154	0.123
5	0.073	0.109	0.112	0.117
6	0.064	0.100	0.119	0.087
Feed	0.001	0.040	0.100	0.266
T[a]	0.944	0.926	0.913	0.911

[a]The transmission, T, was estimated from Eq. (10).

B. EBT-S Manifold Calculations

The EBT-S toroidal manifold has been in operation for some time and a number of measurements have been made to infer the power exiting each of its twenty-four irises. A comparison of the measured and calculated power distributions for the iris opening sizes corresponding to iris modification #6 is presented in Table III. The Monte Carlo statistics on the calculated iris output power ranged between 4 and 8 percent. Uncertainties on the measured values are not known. Both the measured and calculated power distributions were obtained with the 90° corrogated scattering wedge in the manifold.

The iris output powers are only presented for the first twelve irises in Table III. Since the irises in the EBT-S manifold are numbered consecutively beginning on one side of the feed port, the locations of iris number n and iris number 25-n are geometrically equivalent with respect to the feed port. A small degree of asymmetry does exist because irises numbered 14 and 23 are closed. However, for the sake of brevity, only the results of the first twelve are presented.

Table III. Comparison of Measured and Calculated Power Distributions for Modification #6 Iris Sizes in the EBT-S Manifold

Iris No.	Iris Radius(mm)	Relative Power: Calculated[a]	Relative Power: Measured[b]	%DIF[c]
1	19.76	0.031	0.022	41
2	20.97	0.042	0.040	5
3	22.23	0.044	0.046	-4
4	23.48	0.034	0.036	-6
5	24.79	0.039	0.035	11
6	26.09	0.037	0.038	-3
7	27.41	0.040	0.036	11
8	28.75	0.042	0.029	45
9	30.12	0.042	0.043	-2
10	31.48	0.042	0.040	5
11	32.88	0.051	0.044	16
12	34.29	0.049	0.051	-4

[a]Calculated using a linear average of isotropic point source and normal disk source. [b]Measured power normalized to total calculated power. [c]% DIF = $(P_{calc.} - P_{meas.})/P_{meas.} \times 100$.

In general, the agreement between the measured and calculated powers is very good, particularly in view of the 4 to 8 percent standard deviations on the calculated values. The rather low measured power for iris number 8 is due to the presence of other experimental equipment. The reason for the similarly low measured power at iris number 1 is not known. However, the total calculated power or transmission for iris modification #6 was calculated to be 89.5 ± 0.14% which agrees extremely well with the reported measured transmission of 89.9 ± 0.47% given in Ref. 2.

As noted in the introduction, the sizing of the iris openings plays an important role in microwave manifold design. For a given design, large iris openings yield increased output power or manifold transmission. In addition, the distribution of iris opening sizes dictates the output power distribution. For these reasons, an iterative procedure, which uses the Monte Carlo ray tracing results, has been developed to predict optimal iris opening sizes.

The iterative procedure is based on the assumption that the power exiting a given iris is proportional to the irises' opening area, i.e.,

$$P_i \simeq cA_i = c'r_i^2 \tag{12}$$

where A_i and r_i represent the area and radius of the ith iris opening. P_i is the Monte Carlo calculated power out the ith iris opening. Thus, if $\bar{p}$ represents the average power out N irises, i.e.,

$$\bar{p} = \sum_{i=1}^{N} P_i/N \ , \tag{13}$$

an estimate of the iris radius needed to produce a uniform power distribution can be obtained from

$$r_i' \simeq r_i \ (\bar{p}/p_i)^{1/2} \ . \tag{14}$$

If the largest iris opening is forced to be equal to the maximum allowable iris opening size, $\bar{p}$ is arbitrary and Eq. (14) may be rewritten

$$r_i' = r_i / \ P_i^{1/2} \tag{15}$$

or

$$r_i' = r_i + \Delta r_i \tag{16}$$

where

$$\Delta r_i = r_i(1-P_i^{1/2})/P_i^{1/2} \tag{17}$$

When two or more irises are closely coupled, i.e., the change in power out one iris is strongly influenced by the change in power out another iris, Eq. (17) yields very large Δr's which produce oscillations in the iris opening size distribution. To overcome these oscillations, Eq. (17) was damped and new estimates of the iris opening radii were obtained from

$$r_i' = r_i + \Delta r_i/D \tag{18}$$

or

$$r_i' = r_i\left[(D-1)P_i^{1/2} + 1\right]/(P_i^{1/2}D) \tag{19}$$

where D represents the damping factor. The iterative procedure described by Eq. (19) thus consists of performing a Monte Carlo calculation to obtain the iris output power distribution, i.e., the P_i's, estimating the new r_i's from Eq. (19) and repeating this sequence until a flat power distribution is obtained.

As noted earlier, each Monte Carlo calculation for the EBT-S toroidal manifold required approximately 80 min. of CPU time on an IBM model 370/3033. Thus, the computational time and associated cost for a large number of iterations would be prohibitive. Fortunately, the need for the additional Monte Carlo calculation with each new set of radii can be eliminated by simply writing a history tape. Every time a microwave reflects off the plate which covers each coupling link exit, the corresponding iris number, batch number, distance from the center of the iris opening, and power of the reflecting microwave before the reflection were written on tape. With this information, the power distribution associated with a new set of radii may be computed directly from the history tape provided the new radius of each iris opening is larger than its radius in the initial Monte Carlo calculation. The power distributions computed from the history tape required less than 10 s of CPU time.

The convergence of a set of large iris opening sizes to obtain a flat power distribution in the EBT-S manifold is illustrated by the results presented in Table IV. Again, for the sake of brevity, only results for irises numbered 1 through 12 are given. The initial Monte Carlo calculation was carried out for the iris modification #6 iris opening sizes using the isotropic point source. The flatness of the power distribution for these iris opening sizes is illustrated by the percent differences listed for the 0th iteration. The flatness of the power distribution with the final radii is illustrated by the relatively small percent differences after only four itera-

Table IV. Convergence of Large Iris Opening Sizes to Obtain a Flat Power Distribution in the EBT-S Manifold

Iris No.	Initial Radius (mm)	$(P_i-\bar{p})/\bar{p} \times 100$ Iteration No. 0	2	4	Final Radius (mm)
1	19.76	9.92	-8.2	-0.49	29.03
2	20.97	11.33	-8.93	0.02	31.65
3	22.23	11.86	-6.07	-0.22	35.89
4	23.48	7.95	-3.02	-1.71	39.20
5	24.79	4.49	-7.58	-2.58	41.25
6	26.09	4.10	-0.67	1.00	47.01
7	27.41	0.93	-1.01	-0.56	51.13
8	28.75	1.85	4.13	-0.46	55.38
9	30.12	-6.68	6.77	0.96	61.56
10	31.48	-6.37	5.26	3.05	63.14
11	32.88	-31.62	14.62	1.58	63.50
12	34.29	-11.98	6.03	2.28	63.37
Transmission (%)	89.8	95.8	95.6		

tions. In addition, an increase in transmission from 89.8 to 95.6% is obtained by letting the maximum iris opening radius increase from 34.29 mm to 63.50 mm. This increased transmission represents more than a factor of two decrease in the amount of microwave power lost in the manifold.

In all of the calculations discussed above, both for the EBT-S and EBT-P microwave manifolds, the incoming microwaves were perpendicularly polarized, i.e., their initial electric field vectors were chosen perpendicular to the plane formed by their propagation vectors and a vector along the centerline of the feed port. These calculations were also performed with parallel polarized incoming microwaves, but the differences in all the results due to the two polarizations were in all cases much smaller than the Monte Carlo standard deviations.

IV. SUMMARY AND CONCLUSIONS

The calculated results presented above demonstrate the usefulness of the Monte Carlo method in obtaining estimates of the effects associated with design changes in EBT microwave manifolds. In addition, its use as a design tool to aid in predicting design changes which can lead to improved microwave output power transmission and uniformity was also demonstrated. However, comparative results indicate the need for an accurate description of the incoming microwave source before a statement of absolute credibility can be made.

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