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ABSTRACT

A twist reflector plate is described that linearly polarizes and focuses the TE_{01} circular waveguide mode for heating hot electrons in the thermal barrier of the Tandem Mirror Experiment-Upgrade (TMX-U). The plate polarizing efficiency is 95%, and it has operated satisfactorily at 150 kW power level.

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INTRODUCTION

Electron-cyclotron resonance heating (ECRH) is used in the Tandem Mirror Experiment-Upgrade (TMX-U) to heat the hot electron population required for formation of a thermal barrier.[1] A focusing twist reflector has been used to both linearly polarize and focus the microwave beam that heats the hot electrons.

The 2-1/2-in. diam waveguide transmission system that illuminates the twist reflector is shown in Fig. 1. The system consists of an $m = 0$ rippled-wall mode converter for transforming the gyrotron output power, which is predominantly in the TE_{02} mode, into the TE_{01} mode.[2] Five beat wavelength sections are required for 100% conversion, but only four sections and a straight pipe phase shifter are installed, since about 5% of the gyrotron output power is already in the TE_{01} mode. Directional couplers on the input and output of the converter measure the power in the TE_{01} and TE_{02} modes.

TWIST REFLECTOR

Figure 2 shows the twist reflector plate that converts the incident TE_{01} mode into linear polarization (the vertical direction in Fig.1 for launching the extraordinary mode). The plate is positioned 30 cm from the end of the waveguide. The grooved section measures 22 x 34.5 cm, and the focusing curvature of the plate is evident.

The characteristic dimensions of the twist reflector grooves are shown in Fig. 3. Recall that the twist reflector is the analog of a transmitting half-wave plate in optics where the optical axis is parallel to the groove direction.[3] A wave incident with the electric field perpendicular to the grooves reflects from the bottom of the grooves, and a field parallel to the grooves reflects from the top surface. A differential phase shift of π occurs between the two components of a wave incident at angle Θ. The wave is reflected with the polarization rotated by the angle 2Θ. The electric field directions of the incident TE_{01} mode are circular, whereas the desired polarization of the reflected wave is linear and vertical. The bisection of the change in angle between incident and reflected waves defines the parabola-like pattern of grooves depicted in Fig. 4.

TWIST REFLECTOR DESIGN

Scalar wave components were propagated from the waveguide output to the mirror and from the mirror to the plasma location using Rayleigh-Sommerfield diffraction theory as indicated in Fig. 5.[4] The groove directions are one result of this computation.

An iterative computer calculation was used to determine the plate curvature required for beam focus. The first approximation for the surfacewas an off-axis parabola. The iterative procedure is shown in Fig. 6. The wave U_1 was the TE_{01} output mode of the waveguide, and amplitude U_4 was specified at the plasma. Propagation of U_1 to the mirror determined U_2. Wave U_3 had the amplitude profile of U_2 but unknown phase correction ϕ_3, which defined the mirror curvature and which had to be calculated. The phase ϕ_3 was initially chosen to be random. A correction for ϕ_3 was found by propagating U_3 to the plasma, imposing amplitude $|U_4|$ and back-propagating U_4 using ϕ_4 determined from the previous step. At the mirror $|U_3|$ was again imposed and the cycle was repeated using the corrected value for ϕ_3 until convergence was obtained. The solution for ϕ_3 determined the required curvature correction to the assumed parabola. The plate was fabricated using a five-axis numerically-controlled milling machine.

TEST RESULTS

The twist reflector plate was tested with low power TE_{01} illumination in order to measure the power contours at the plasma location (75 cm mirror-to-plasma separation). We show the results for the designed and cross-polarized components in Fig. 7. About 95% of the total power is in the design polarization.

The power contours reasonably approximate the Gaussian profile used in the design procedure, except for details in the beam near the maximum. Beam size was also sensitive to the angle of incidence of the TE_{01} mode onto the plate surface. The reasons for the differences between theory and measurements are presently under study.

High power test results are shown in Fig. 8. The E-plane power profile on the side opposite the plasma from the reflector was measured using an array of small WR 42 waveguides. The high power profile agrees well with low power measurements. Directional coupler measurements showed that the power ratio $P(TE_{01})/P(TE_{02})$ equalled or exceded 30:1.

SUMMARY

The plate has been operated at power levels of 150 kW or greater without evidence of arcing, in an environment of plasma bombardment with energetic neutrals (∿10 keV deuterium), 100-keV electrons, and many titanium getter cycles. We achieved good coupling efficiency to the plasma in the experiment using the plate and demonstrated power efficiencies for producing hot electrons as large as 42% (defined by the hot-electron stored energy rate of rise and antenna power).[5]

The twist reflector has attractive features needed for future higher frequency and higher power microwave sources. It does not have the undesirable (diameter)$^2/\lambda$ length scaling of waveguide modulated wall mode converters. Power density on the plate can be made arbitrarily small with greater separation between waveguide and plate. The design algorithums permit an arbitrary mode or modes of illumination of the plate.

REFERENCES

1. D. E. Baldwin and B. G. Logan, Phys. Rev. Lett. 43, 1318 (1979).
2. N. L. Kovalev, et al., Izvo. Vyssh. Uchebn. Zaved. [Sov. Radiophys.] 11, 783 (1968).
3. J. D. Hanfling, G. Jerinic, and L. R. Lewis, IEEE Trans. on Antennas and Propag., AP-29, 622 (1981).
4. F. E. Coffield, B. Felker, N. C. Gallagher, Jr., et al., Proc. Tenth Symposium on Fusion Engr. (IEEE) (Philadelphia, PA, 1983).
5. B. W. Stallard, W. F. Cummins, A. W. Molvik, et al., Fourth Int. Symposium on Heating in Toroidal Plasmas (Rome, Italy, March 1984).

Figure Captions

Fig. 1. The waveguide transmission system and twist reflector in an end cell of TMX-U.

Fig. 2. Photograph of the twist reflector plate. The grooved dimensions are 22 x 34.5 cm.

Fig. 3. Polarization rotation grooves of the twist reflector.

Fig. 4. Twist reflector groove pattern for transforming the TE_{01} mode electric field to vertical linear polarization.

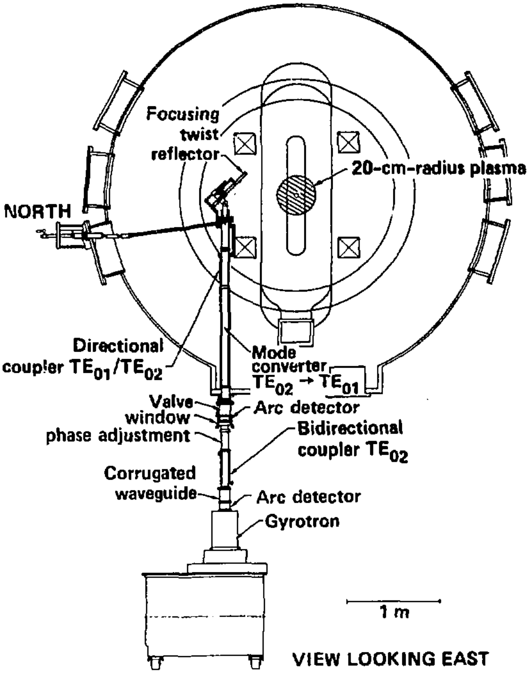
Fig. 5. The wave propagation design procedure.

Fig. 6. The iterative scheme for designing the mirror shape.

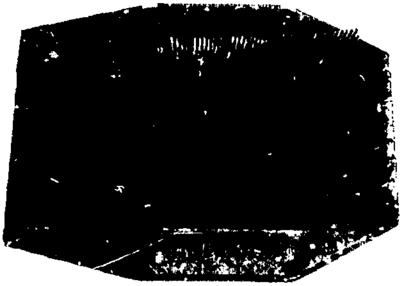
Fig. 7. Low power measurement of power contours at the plasma location.

Fig. 8. High power measurement of the twist reflector plate's E-plane power profile.

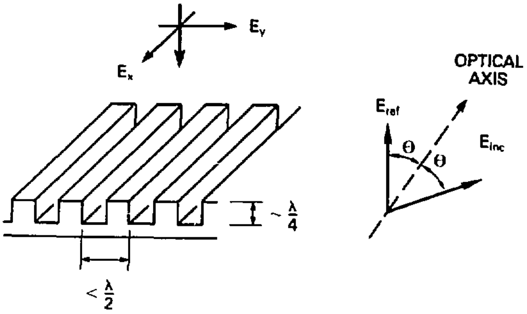
B. W. Stallard et al. - Figure 1



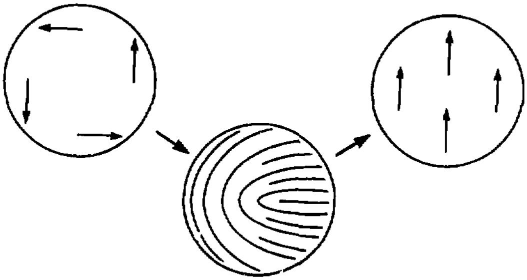
B. W. Stallard et al. - Figure 2



B. W. Stallard et al. - Figure 3

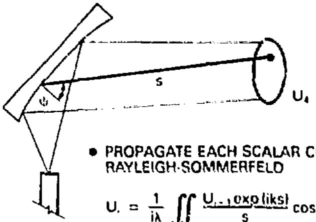


B. W. Stallard et al. - Figure 4



TWIST REFLECTOR

B. W. Stallard et al. - Figure 5

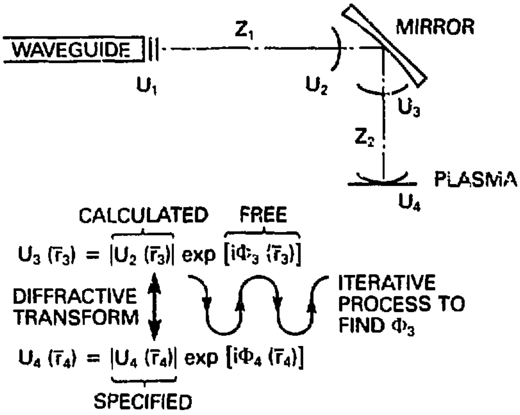


- PROPAGATE EACH SCALAR COMPONENT USING RAYLEIGH-SOMMERFELD

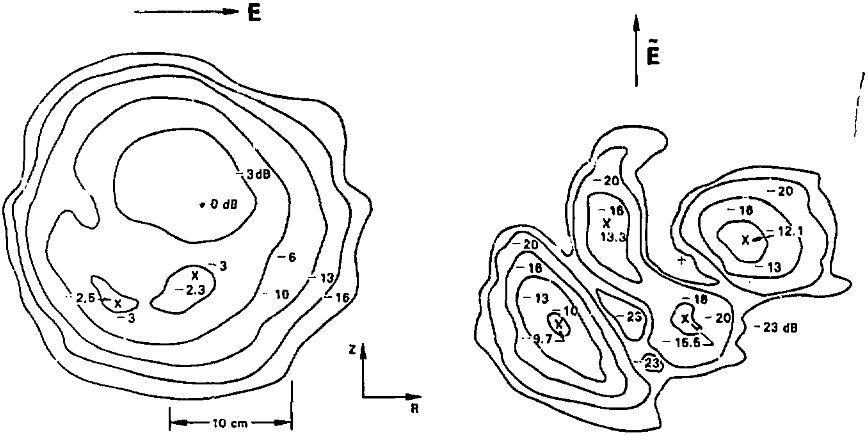
$$U_i = \frac{1}{i\lambda} \iint_{\Sigma} \frac{U_{i-1} \exp(iks)}{s} \cos\psi \, dS.$$

- FIRST APPROXIMATION IS PARABOLIC MIRROR
- USE THE ITERATIVE PROCEDURE TO FIND CORRECTION TO MIRROR SURFACE

B. W. Stallard et al. - Figure 6



B. W. Stallard et al. - Figure 7



Desired polarization

Cross polarization

B. W. Stallard et al. - Figure 8