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WAVEGUIDE ELLIPTIC POLARIZERS FOR ECH
AT DOWN-SHIFTED FREQUENCIES ON PLT

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JANUARY 1986

MASTER

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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CED-3073.

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PPPL--2297

DE86 006364

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ABSTRACT

ECH experiments on PLT with resonance frequencies of 80-90 GHz at the plasma center use 60 GHz extraordinary mode (X-mode) propagation at 30° from the toroidal field. Efficient excitation of this mode requires elliptic polarization of the incident wave at the plasma edge. On PLT the elliptic polarization is achieved outside the vacuum vessel in an elliptically deformed section of circular waveguide propagating TM₁₁, a mode that is intermediate between TE₀₁ and HE₁₁ (which has an ideal radiation pattern). The squeeze and orientation of the TM₁₁ polarizer are adjusted to compensate both for the birefringence of a corrugated bend propagating HE₁₁ and for a flat mirror inside PLT that reverses the sense of rotation of the polarization.

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INTRODUCTION

Since generating high power at millimeter-wave frequencies generally becomes more difficult as the frequency is increased, an electron cyclotron heating (ECH) scheme that reduces the required frequency would appear attractive. For electron temperatures and densities typical of present large tokamaks, large absorption due to energetic electrons can theoretically occur over short path lengths at relatively low frequencies [1]. For example, with cyclotron resonance frequencies of 140 and 80 GHz at the center of TFTR and PLT, respectively, virtually complete absorption not too far from the plasma center should be achievable with incident power at around 100 and 60 GHz.

Optimum absorption at such down-shifted frequencies requires propagation of the extraordinary mode (X-mode) at an angle relative to the toroidal magnetic field [1]. Efficient excitation of this mode requires, in turn, elliptical polarization of the incident wave at the plasma edge.

Previously, for a different application involving X-mode propagation on Doublet III, the required elliptical polarization was achieved by using grooved mirrors at the end of waveguides propagating a linearly polarized TE₁₁ mode [2]. Focusing twist reflectors with curved grooves of varying depth have been used on TMX-U to generate a linearly polarized wave from an incident TE₀₁ mode [3] and could, in principle, generate elliptical polarization as well. These grooved devices generally must be located inside the vacuum vessel.

ECH on PLT uses waveguide mode converters to generate the ideal HE₁₁ mode, which generates a free-space gaussian mode at the open-ended corrugated waveguide inside PLT (see Fig. 1). Elliptical polarization of HE₁₁ is achieved by suitably squeezing a section of waveguide outside PLT propagating the TM₁₁ mode, which is intermediate in the mode conversion process from TE₀₁

to HE₁₁ [4]. Since TE₀₁ is unpolarized and corrugated waveguide propagating HE₁₁ is only slightly birefringent under elliptical deformation [5], the desired polarization conversion must be done on the TM₁₁ mode.

DESIGN

As is well known, a smooth-wall circular waveguide propagating the dominant TE₁₁ mode becomes birefringent when deformed elliptically: the E-field component along the minor axis undergoes more phase shift than the component along the major axis [6]. Circular polarizers using this effect are available commercially for frequencies up to the lower millimeter-wave range [7]. Since TE₁₁ is commonly generated from TE₀₁ in overmoded waveguide systems for ECH [2, 8], the required elliptical polarization could also be generated by squeezing a section propagating TE₁₁. As discussed below, however, the birefringence for TE₁₁ is much smaller than for the TM₁₁ mode used on PLT.

In general, if the radius of a deformed circular waveguide is written in cylindrical coordinates as

$$a(z) = a_0 + \sum_{l=1}^{\infty} a_l(z) \sin l\phi, \quad (1)$$

then incident TE_{pm}^s or TM_{pm}^s modes with radial electric fields varying transversely as $E_r^s \sim \sin p\phi$ will be coupled to TE_{qm}^c and TM_{qm}^c modes with $E_r^c \sim \cos q\phi$, where $l = p - q$. This relation also holds if $q < 0$; hence an $a_{2p}(z)$ deformation causes coupling of the two independent polarizations of TE_{pm} or TM_{pm} (see Fig 2). This coupling may be used to describe the birefringence [9].

If the integral of the deformation satisfies

$$|K| \int_{-L/2}^{L/2} a_{2p}(z) dz = \pi/4, \quad (2)$$

where K is the relevant coupling coefficient, then an incident TE_{pm} or TM_{pm} mode with fixed polarization can be converted to rotating polarization and vice versa [9]. When $p = 1$, the rotating polarization is called circular polarization.

The coupling coefficient K in Eq. (2) varies approximately as λ/a_0^3 for large a_0/λ and is $-j1.44 \text{ in.}^{-2}$ for TM_{11} at 60 GHz in WC109 waveguide ($2a_0 = 1.094 \text{ in.}$). The coupling coefficient for TE_{11} in this case is $+j0.60$, or 2.4 times smaller. The sign difference corresponds to opposite signs for the birefringence.

To avoid coupling to unwanted modes, the polarization converter must not be too short and the deformation should vary smoothly. For a TM_{11} polarization converter, TE_{31} is the most important unwanted mode, because the phase velocities of these two modes are very close. Also important is coupling to TE_{11} .

The results of numerical integration of the coupled mode equations are shown in Figs. 3-5. The incident mode is linearly polarized in the vertical direction and the elliptical deformation is oriented as in Fig. 2. A smooth cosine-squared variation for the magnitude of the deformation along the converter is suitable for minimizing spurious mode generation and is easily approximated in practice.

For the circular polarizer of Figs. 3 and 4, the output power should ideally be divided equally between the horizontally and vertically polarized components, and the relative phase should be 90° . The latter requirement can

be satisfied at relatively short converter lengths; the former requires a converter length of 15 to 20 inches for TM₁₁ and at least 30 inches for TE₁₁. The much larger spurious mode generation in the TE₁₁ converter for a given length is caused by the need to increase the magnitude of the distortion to compensate for the much lower coupling coefficient K.

To rotate the polarization of a linearly polarized mode by 90° requires a doubling of the distortion integral in Eq. (2) to $\pi/2$. This corresponds to a phase shift of 180° between the components parallel and perpendicular to the ellipse major axis (see Fig. 2). As shown in Fig. 5, a vertically polarized TM₁₁ mode can be well converted to horizontal polarization in an elliptically deformed waveguide 25 to 30 inches long. For the PLT configuration, the desired elliptical polarization required a distortion integral of 0.41π (see discussion below); hence a length of 28 inches for the distortion was chosen to ensure low spurious mode generation.

FABRICATION

To generate an elliptic deformation that is smoothly varying and zero at each end, the fixture shown in Fig. 6 was convenient. Two thick aluminum plates squeezed by a bolt at $z = 0$ and restrained at each end generated an $a_2(z)$ variation approximately equal to $\cos^2 (\pi z/L)$. The waveguide was standard WC109, with an initial O.D. of approximately 1.222 in. Before assembly into the frame, the waveguide was annealed with a hand-held torch enough to allow squeezing in place without excess torque but not so much as to make the waveguide flatten out under the squeeze. The diameter squeeze at the center needed to produce a TM₁₁ circular polarizer was about 0.085 in., in close agreement with Eq. (2) and the coupling coefficient cited above. The

average diameter decreased by less than 0.005 in. at the center and should cause no significant mode conversion.

MEASUREMENT

The TM₁₁ polarization converter was placed between the TE₀₁ to TM₁₁ and TM₁₁ to HE₁₁ converters described in Ref. 4. The major and minor axes were oriented at 45° from the direction of polarization of the field incident from the TE₀₁ to TM₁₁ converter. A small aperture linearly polarized receiving horn was located 24 inches from the open end of the TM₁₁ to HE₁₁ converter.

To facilitate finding the optimum squeeze of the polarization converter, and also to verify the sense of rotation of the polarization, a low-power rotatable polarizer with parallel plate waveguides [10] could be placed in front of the receiving horn. The phase shift between field components parallel and perpendicular to the plates was 90°. When this polarizer was used, a glass lens was placed between it and the open-ended TM₁₁ to HE₁₁ converter to collimate the beam at the polarizer. The parallel plates were oriented at 45 degrees from the vertical (Fig. 7), and the TM₁₁ polarization converter was squeezed until the field at the receiving horn was linearly polarized (as determined by rotating the horn). The TM₁₁ polarization converter was then a circular polarizer; the measured sense of rotation agreed with the theory.

The radiation field was then checked without the parallel plate polarizer and collimating lens. The peak-to-peak variation in the field received by the linearly polarized horn as it was rotated was only 0.6 dB. The measured radiation patterns for various orientations of the horn were almost identical, and the sidelobes were at least 23 dB down.

In the waveguide leading to the top port of PLT there is a 90° bend in the HE₁₁ mode (see Fig. 1). This bend is also birefringent due to a difference in one of the modes coupled by the bend: either TE₀₁ or TM₀₂ for H and E plane bends, respectively. To measure the birefringence, a 90° bend was placed after the TM₁₁ polarizer and the TM₁₁ to HE₁₁ converter. The rotatable parallel plate polarizer and the rotatable receiving horn were used to analyze the elliptic polarization radiated from the bend. From this analysis it was determined that the E-field component perpendicular to the plane of the bend was delayed in phase by approximately 59° relative to the component in the plane of the bend. This agreed well with a relative phase shift of 56° predicted by numerical integration of the coupled wave equations, assuming an effective corrugation depth of $0.7 \lambda/4$.

We now adjusted the TM₁₁ polarization converter to compensate for the birefringence of the 90° HE₁₁ bend (item D in Fig. 1), the 102° orientation of this bend (see Fig. 1), and the reversal of the sense of rotation of the polarization at the flat mirror (item H in Fig. 1). Theoretically, the squeeze axis of the polarization converter should be changed from 45° to 26° from the vertical, and the squeeze increased to increase the relative phase shift of the field components parallel and perpendicular to the major axis of the deformation ellipse from 90° (for the circular polarizer) to 147.5° .

This adjustment should have given left-handed elliptical polarization before the mirror with a 1.2 ratio of the magnitudes of the electric field components perpendicular and parallel to the toroidal field B_T . In the laboratory, using the setup shown in Fig. 8, the proper orientation of the elliptical polarization was observed, and the ratio of the field component magnitudes was measured to be approximately 1.3. This still should provide a good match at the plasma edge to an extraordinary wave propagating at a 30° angle relative to B_T (Fig. 1) (see, for example, Ref. 11, section 1.4).

ACKNOWLEDGMENTS

The author acknowledges helpful discussions with E. Mazzucato, M.A. Goldman, and H. Hsuan, and the help of J. Boychuk, S. Luyber, and E. Hall in fabricating the TM11 polarization converter.

This work was supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

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FIGURE CAPTIONS

Fig. 1. Schematic of top launch on PLT. A: TE₀₁-TM₁₁ mode converter; B: TM₁₁ polarization converter; C: TM₁₁-HE₁₁ mode converter; D: HE₁₁ bend; E: straight corrugated waveguide; F: corrugated taper from 1.094 to 2.5 inch I.D.; G: window; H: smooth mirror at end of 2.5 inch I.D. corrugated waveguide.

Fig. 2. A 2-foil (elliptical) deformation a_2 oriented to couple the horizontally and vertically polarized components of a TE_{1m} or TM_{1m} mode.

Fig. 3. Effect of TE₁₁, TE₁₂, TE₃₁, and TM₃₁ spurious modes on a TM₁₁ circular polarizer at 60 GHz in 1.094 in. I.D. waveguide. The magnitude of the elliptical distortion, oriented as in Fig. 2, with a cosine squared variation along the converter, is adjusted for each length to produce circular polarization at the output in the absence of spurious modes. The input is vertically polarized.

Fig. 4. Effect of TE₁₂, TM₁₁, TE₃₁, and TM₃₁ spurious modes on a TE₁₁ circular polarizer with a vertically polarized input. Parameters same as Fig. 3.

Fig. 5. Effect of TE₁₁, TE₁₂, TE₃₁, and TM₃₁ spurious modes on a converter to rotate the polarization of a linearly polarized incident TM₁₁ mode by 90°. Parameters same as Fig. 3.

Fig. 6. TM₁₁ polarization converter in squeeze frame. Overall length: 32 inches.

Fig. 7. Parallel plate polarizer.

Fig. 8. Laboratory setup for analysis of elliptical polarization following components A thru D connected as in Fig. 1.

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a) Top View

b) Side View

Fig. 1

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Fig. 2

Fig. 3

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Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

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