Automated Generation of High-Order Modes for Tests of Quasi-Optical Systems of Gyrotrons for W7-X Stellarator

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***Abstract*— A test system for the verification of the quasi-optical converter system is vital in the gyrotron development. For this reason, an automated measurement setup has been developed and is benchmarked with the $TE_{28,8}$ mode operating in the cavities of the gyrotrons of W7-X with a high purity of about 95 % and a counter-rotating amount of about 0.3 %. The time duration for the mode generator adjustment has been reduced to two days for this mode. After a successful mode excitation, the quasi-optical mode converter, consisting of a launcher and three mirrors, is measured having a vectorial Gaussian mode content of 97 %.**

I. Introduction

In the recent fusion projects, gyrotrons are the only microwave sources producing a megawatt-level output power in the sub-THz frequency range for efficient electron cyclotron resonance heating and electron cyclotron current drive (ECRH&CD), up to now. In these gyrotrons high order $TE_{m,n}$ modes are operating, which have only a small amplitude level at the cavity wall to reduce the wall loading. However, these modes suffer from high attenuation for long-line transmission. In contrast, modes with lower transmission losses are low order modes, like the HE_{11} in corrugated waveguides and TEM_{00} modes in the quasi-optical transmission. Therefore, the operating $TE_{m,n}$ mode is converted into a low order mode (TEM_{00} mode) using a quasi-optical mode converter consisting of a launcher and three mirrors. These components are the only ones which can be tested before installation into the gyrotron using a cold test setup calling *mode generator* on the basis of a quasi-optical approach [1]. This cold test is mandatory to prevent catastrophic failures in the design and manufacturing process [2]. In previous cases, the adjustment of such a mode generator can be very time consuming because of the manually adjustable sliding units used for the adjustment of the quasi-parabolic mirror. In addition, the previous measurement setup was limited to a frequency of 170 GHz using a D-band network analyzer [3]. Therefore, a new setup has been developed to provide higher accuracies and a wider frequency range (140-330 GHz) using a vector network analyzer. Further, two high precision linear stages are installed to achieve a computer-controlled adjustment of the quasi-parabolic mirror in x- and y-direction without human attendance. This step was the starting point for automation of the whole adjustment procedure. Another major part of the automation was the implementation of mode evaluation techniques to determine the order of the mode and its purity. Therefore, five different subroutines had been developed for determining the azimuthal and radial mode index, the scalar mode content, the counter-rotating amount and the quality factor.

In the following, the results of the excitation of the $TE_{28,8}$ mode at 140 GHz [4] operating in the gyrotrons for W7-X [5] are presented for benchmarking the new system. After successful adjustment of this $TE_{28,8}$ mode the launcher and the mirror system are assembled to the mode generator to measure the Gaussian mode content of the output beam on the window plane and compare it with previous cold and hot measurements.

II. Mode Generator Setup

The mode generator measurement is called “cold” because there is no electron beam to excite the desired mode. The mode is excited by the use of a microwave beam. The signal is generated in the vector network analyzer and is transmitted using a circular HE_{11} mode horn antenna. The lens system, which is shown on the left side of the photo in Fig. 1, converts the spherical wave into an astigmatic Gaussian like beam (TEM_{00} mode). A plane wave is necessary to minimize the phase changes and so, increase the quality of the mode. The

Fig. 1. Photo of the mode generator setup with the lens system, the quasi-parabolic mirror and the mode generator cavity.

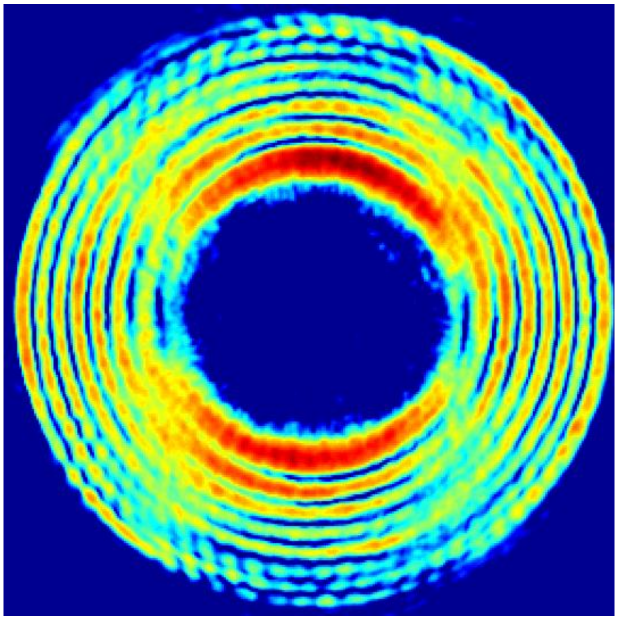

Fig. 2. Measured amplitude pattern of the $TE_{28,8}$ mode operating at 140.01 GHz with a pixel size of 0.2x0.2 mm.

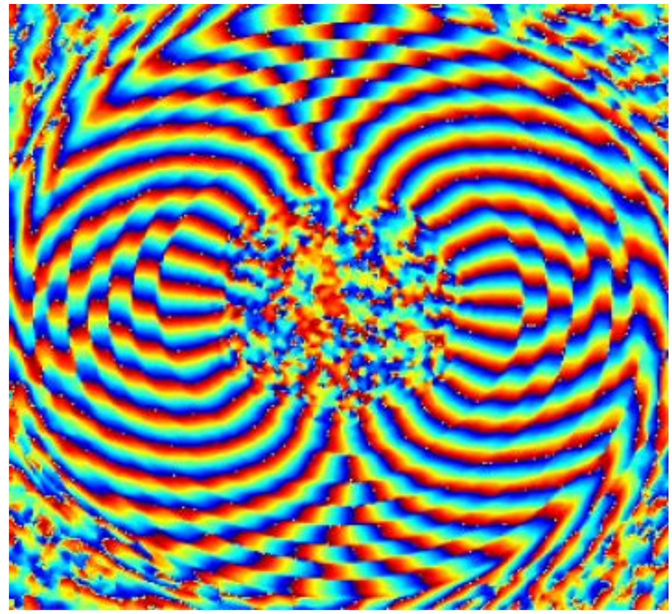

Fig. 3. Measured phase pattern of the $TE_{28,8}$ mode operating at 140.01 GHz with a pixel size of 0.2x0.2 mm.

quasi-parabolic mirror focuses the wave to the caustic of the desired mode in the mode generator cavity. The perforated cavity wall is translucent that the wave can couple into the cavity [6]. The profile of the mode generator cavity is designed using a scattering matrix code [7]. The profile of the mode generator cavity is very close to the hollow cavity design of the actual gyrotron cavity, but with a coaxial insert to improve the mode selection in the cold tests [8,9].

First, a non-linear up taper is mounted on the output of the mode generator cavity to increase its output radius and so, to reduce the requirements on the measurement equipment. The mode pattern is measured using a standard waveguide antenna mounted on a 3D measurement arm, which does a stepwise scan of the output plane at the end of the non-linear up taper.

After a successful excitation of the mode the non-linear up taper is disassembled and the launcher and the three mirrors are mounted at the output of the mode generator cavity and measured using the same hardware equipment as mentioned before.

III. Measurement Results Of The $TE_{28,8}$ Mode Excitation

The automated test system is used to excite the desired $TE_{28,8}$ mode. The measurement results are evaluated using five different evaluation techniques [10]. These different mode evaluation techniques are necessary to evaluate the quality of the excited mode and gives a feedback if the excited mode matches with the desired mode.

The field pattern of the desired $TE_{28,8}$ mode is shown in Fig. 2 with a very high quality using a pixel size of 0.2x0.2 mm. The radial mode index is clearly determined to 8, which corresponds to the number of rings. The azimuthal index is given by the number of phase changes on a circle segment at a constant radius. The receiving antenna is a standard waveguide horn antenna whereby a transformation from polar to Cartesian coordinates occurs. Therefore, the horizontal E_x and vertical E_y components are measured instead of the radial E_r and azimuthal E_φ field amplitudes. This coordinate transformation leads to a reduction of the counted number of phase changes by one [11] and so only 27 phase changes can be counted. The measured phase pattern is presented in Fig. 3.

After finding the correct mode order, the quality of the excited mode is proven. The scalar mode content is calculated to be around 95 % with a very low counter-rotating amount of around 0.33 %, which is determined using the equation given in [12]. The quality factor is determined to be 2548 and is in very good agreement with the designed diffractive quality factor of 2533. A major advantage of the new developed mode generator system is that the adjustment time is reduced to two days having similar or even higher mode purity.

IV. Measurement Results Of The Quasi-Optical Mode Converter System

After the successful excitation of the operating $TE_{28,8}$ mode the non-linear up taper is disassembled and a dimpled-wall waveguide launcher and three mirrors (one quasi-

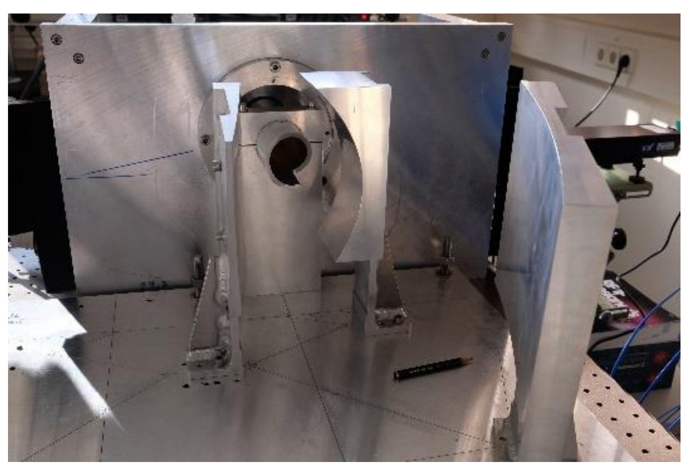

Fig. 4. Photo of the measurement setup to evaluate the mode converter system consisting of the launcher and three mirrors.

elliptical and two toroidal mirrors [13]), designed for the $TE_{28,8}$ mode, are mounted at the end of the mode generator cavity, as can be seen in the photo of the measurement setup in Fig. 4. The frequency extension modules used for covering the frequency range from 140 – 220 GHz and can be seen on the right-hand side of the photo. The measured launcher is manufactured only for the cold test purpose and is not capable for a long pulse operation because of the missing cooling rings. The converted Gaussian output beam is then measured in the plane where the diamond output window disk is placed in the gyrotron design. The measured field amplitude is presented in Fig. 5, while its phase pattern is shown in Fig. 6. The evaluation area is limited to the output window radius of 44 mm. The vectorial Gaussian mode content of the presented measurement is calculated to be 97 %. The scalar mode content is calculated to be 98.3 % and is 2 % higher than the scalar mode content presented in [13]. The results from the cold measurements are in very good agreement with the hot measurement results.

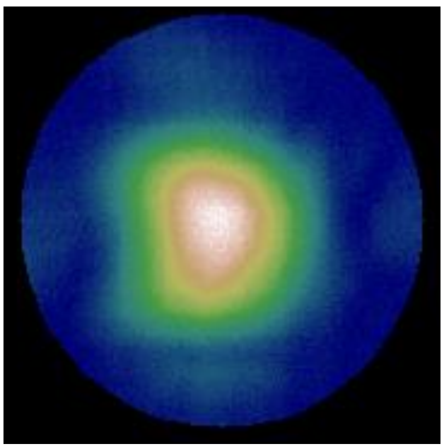

Fig. 5. Measurement of the amplitude of the Gaussian beam after the mode converter system. The depiction is limited to the output window radius of 44 mm of the gyrotrons for W7-X.

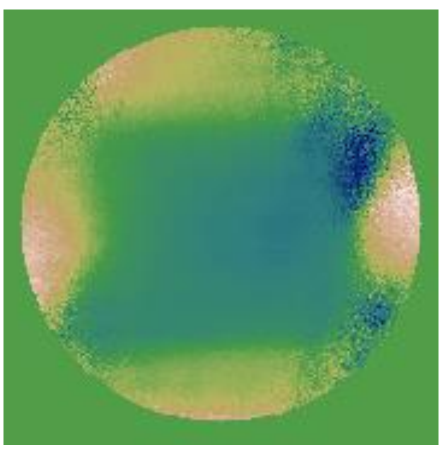

Fig. 6. Measurement of the phase of the Gaussian beam after the mode converter system. The depiction is limited to the output window radius of 44 mm of the gyrotrons for W7-X.

V. Conclusion

An automated measurement setup has been presented which is capable to excite the high order $TE_{28,8}$ mode at 140.01 GHz with a scalar purity of 95 % with a counter-rotating amount of 0.33 % within two days without human attendance. After the successful excitation of the desired $TE_{28,8}$ mode the mode converter system consisting of a dimpled-wall waveguide launcher, a quasi-elliptical mirror and two toroidal mirrors, are assembled to the mode generator setup. The receiving antenna is positioned at the plane of the output window. The measured scalar and vectorial Gaussian mode content at the plane of the output window is calculated to be 98.3 % and 97 %, respectively.

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