170/204 GHz Dual-Frequency Mode Generator for Verification of the Quasi-Optical Output Coupler of a 2 MW Coaxial-Cavity Gyrotron

Tobias Ruess
Institute for Pulsed Power and Microwave Technology (IHM)
Karlsruhe Institute of Technology
Karlsruhe, Germany
tobias.ruess@kit.edu

Gerd Gantenbein
Institute for Pulsed Power and Microwave Technology (IHM)
Karlsruhe Institute of Technology
Karlsruhe, Germany
gerd.gantenbein@kit.edu

Jianbo Jin
Institute for Pulsed Power and Microwave Technology (IHM)
Karlsruhe Institute of Technology
Karlsruhe, Germany
jianbo.jin@kit.edu

Tomasz Rzesnicki
Institute for Pulsed Power and Microwave Technology (IHM)
Karlsruhe Institute of Technology
Karlsruhe, Germany
tomasz.rzesnicki@kit.edu

Sebastian Stanculovic
Institute for Pulsed Power and Microwave Technology (IHM)
Karlsruhe Institute of Technology
Karlsruhe, Germany
sebastian.stanculovic@kit.edu

Manfred Thumm
Institute for Pulsed Power and Microwave Technology (IHM)
Karlsruhe Institute of Technology
Karlsruhe, Germany
manfred.thumm@kit.edu

Dietmar Wagner
Max-Planck-Institute for Plasma Physics
Garching, Germany
dietmar.wagner@ipp.mpg.de

John Jelonnek
Institute for Pulsed Power and Microwave Technology (IHM)
Karlsruhe Institute of Technology
Karlsruhe, Germany
john.jelonnek@kit.edu

***Abstract*—The 2 MW 170 GHz single-frequency coaxial-cavity short-pulse pre-prototype is upgraded to operate also at 204 GHz. Therefore, the quasi-optical output coupler, which is a gyrotron key component, has been modified. Before the newly manufactured quasi-optical output coupler is installed into the gyrotron, a low-power cold measurement for the verification is performed. Therefore, a mode generator is designed and adjusted to excite the relevant operating gyrotron modes, namely the TE$_{34,19}$ mode at 170 GHz and TE$_{40,23}$ mode at 204 GHz, with excellent purity and a low counter-rotating amount of < 0.5 % for both modes. The TE$_{40,23}$ mode is the mode with the highest eigenvalue ever excited in cold tests. After the successful mode excitation, first the fabricated launcher and then the entire quasi-optical output coupler are verified, showing excellent agreement with the simulation.**

***Index Terms*—gyrotrons, coaxial-cavity, quasi-optical output coupler, high-order rotating modes, mode generator setup**

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I. Introduction

A gyrotron is a high-power vacuum electron tube providing an RF output power in the Megawatt-level at frequencies currently above 200 GHz. These unique performance in RF power is required for Electron Cyclotron Resonance Heating and Current Drive (ECRH&CD) systems in fusion devices. Gyrotrons are oscillators which rely on the interaction of a weakly relativistic electron beam and a transverse electric cavity mode TE$_{m,p}$, where m describes the azimuthal and p the radial mode index. The utilization of high-order rotating transversal electric modes in highly oversized cavities guarantees an operation at power levels of 2 MW while keeping the wall loading inside the cavity in a reasonable limit of 2 kW/cm^2. However, due to high attenuation and diffraction losses, these high-order rotating gyrotron TE$_{m,p}$ modes are not ideal for transmission through waveguides or quasi-optical transmission lines over a large distance of $60-100$ m towards a fusion machine, like Wendelstein 7-X in Greifswald [1] and ASDEX Upgrade [2] in Garching, Germany. The same is valid for the future ITER [3] in Cadarache, France and a future EU DEMO [4]. Hence, the operating cavity TE$_{m,p}$ modes are converted into fundamental Gaussian TEM$_{0,0}$ output beams using an internal quasi-optical-output coupler consisting of a launcher and three mirrors followed by the vacuum window and a Matching Optics Unit (MOU). A verification of the quasi-optical output coupler at low-power is vital before its installation into the gyrotron, because the components do not allow any design failures and accept manufacturing tolerances of only few micrometres for proper operation. The low-power verification is called cold measurement, hence it is performed without the necessity of a super-conducting magnet, an electron beam nor a high-voltage power supply. For the verification, first the relevant operating gyrotron cavity modes have to be excited using a quasi-optical mode generator [5]. After the successful excitation of the high-order rotating cavity modes, the quasi-optical output coupler is verified. In this paper, a 170/204 GHz dual-frequency quasi-optical mode generator setup and its adjustment is described for the $TE_{34,19}$ mode operating close to 170 GHz and the $TE_{40,23}$ mode operating close to 204 GHz. Finally, the dual-frequency quasi-optical output coupler is measured and verified with the simulation results.

II. Low Power Excitation of High-Order Modes

A. Quasi-Optical Mode Generator Setup

A photo of the quasi-optical mode generator used for the excitation of the relevant gyrotron cavity modes is shown in Fig. 1. The input of the system is given by a step-tapered horn antenna launching a linear polarized Gaussian $TEM_{0,0}$ beam to a set of Teflon lenses. The Teflon lenses form an astigmatic Gaussian-like beam, which is focused onto a quasi-parabolic mirror (center of the photo). The quasi-parabolic mirror is mounted on two high-precision linear drives, one for the vertical and one for the horizontal movement and a goniometer for the adjustment of the angle (right side of the photo). The quasi-parabolic mirror focuses the beam to the cavity, where the mm-waves couple through the perforated cavity wall. The cavity with coaxial insert is specially designed for the cold tests using a scattering matrix code (mode-matching technique) [7]. A non-linear up-taper is assembled at the end of the coaxial-cavity to increase the spatial resolution. This up-taper will be disassembled for the verification of the quasi-optical output coupler and is only necessary for the mode measurements. The E-field intensity pattern is measured using a standard rectangular waveguide pick-up antenna with a 15° chamfered edge to reduce reflections. The receiving antenna is mounted on a 3D-measurement arm, doing a stepwise scan of the output aperture of the non-linear output taper. The signal is evaluated using a vector network analyser (VNA). Extension Modules are installed to cover the frequency band from 140-220 GHz.

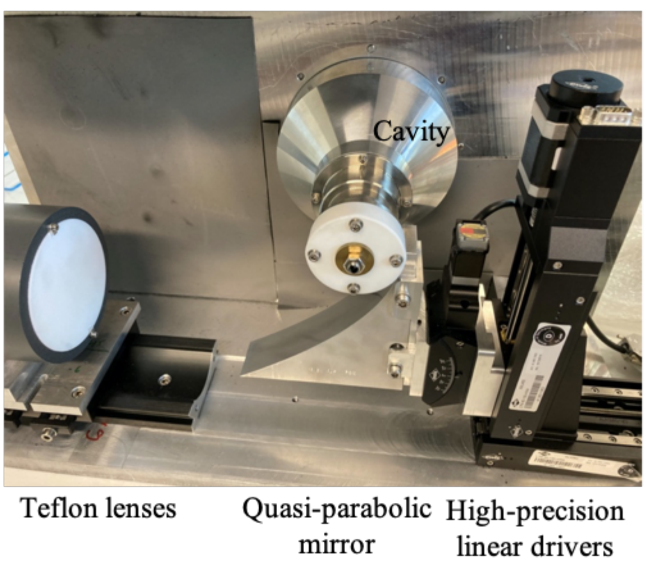


Fig. 1: Photo of the main components of the mode generator setup operating at 204 GHz using a Teflon lens system, a quasi-parabolic mirror, high-precision linear drivers and a cavity with coaxial insert [6].

The number N of TE- and TM- modes, which can oscillate in an oversized circular waveguide cavity with radius R, operating at a given frequency or wavelength λ_0, can be calculated by $N = 2.55 \cdot (2R/\lambda_0)^2$. In the case of operation at 204 GHz and a cavity radius of 29.55 mm, more than 4000 modes are able to propagate. This implies the difficulty to excite a specific high-order $TE_{m,p}$ mode with a sufficient purity in the highly oversized waveguide.

B. Adjustment and Mode Excitation Results

The quasi-optical output coupler is verified at two different frequencies, 170 and 204 GHz. Two coaxial-cavities are designed where the diameter of the coupling holes [8] are optimized for maximum coupling in both cases. The verification of the generated mode is performed using the automated mode generator setup where different evaluation techniques are implemented [9]. Those different mode identification techniques are necessary to determine the mode index in azimuthal m and radial p direction, its quality factor Q,

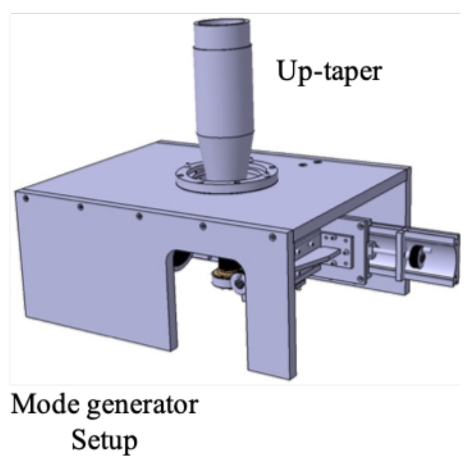


Fig. 2: Schematic of the quasi-optical output system with assembled up-taper to increase the spatial resolution in mode excitation measurements.

the amount of counter-rotating mode and the scalar mode content. The two operating modes are the $TE_{34,19}$ mode close to 170 GHz and the $TE_{40,23}$ mode close to 204 GHz. According to the measurement procedure presented in [9], first the resonance frequency has to be identified. Therefore, the up-taper is assembled to the quasi-optical output system as presented in Fig. 2. The resonance frequencies are determined to be 170.300 GHz and 204.071 GHz, according to the graph exemplarily shown in Fig. 3 (around 204 GHz). The diffractive quality factor is determined to be 4750/4835 (4900 simulated) at 170/204 GHz, respectively.

In the next step, the quasi-parabolic mirror has to be adjusted to excite the given mode with a high purity. The adjustment is computer-controlled via two high-precision linear drives, one for vertical and one for horizontal movement and a goniometer for the angle. A prior estimation of the quasi-parabolic mirror is performed using MATLAB calculations to set the starting values. The movement takes place within a defined area. The receiving antenna is placed at the expected field maxima of the desired mode. The CW frequency is applied which corresponds to the value determined before. Fig. 4 presents exemplarily two measurements having different angles (-1°/-2°) within a movement of 6 mm in horizontal and 8 mm in vertical direction. The step size of the high-precision linear drivers is 100 µm in both directions. The linear drives and goniometer are set close to the maximum field value because studies show that at these points the highest quality factors can be achieved. However, there are always two possible "optimal" excitation points (the second is not presented here in terms of visibility). The second can be found if the area of the quasi-parabolic mirror movement is increased strongly. Then, the counter-rotating mode can be excited with also a very high purity. Basically, in a E-field pattern as presenting in the following only the phase can indicate if the excited mode is rotating in the co- or counter-direction.

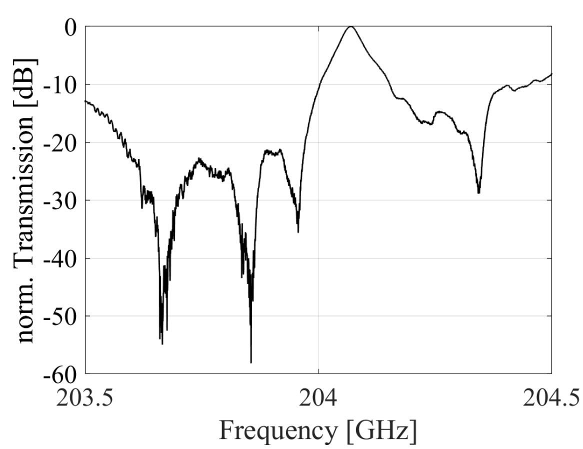
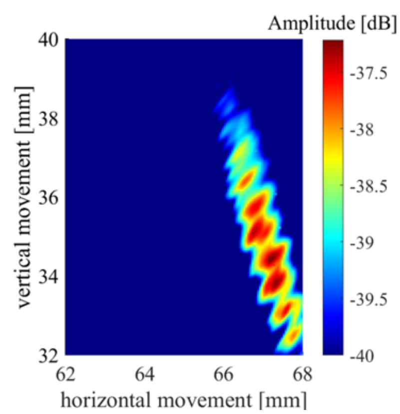
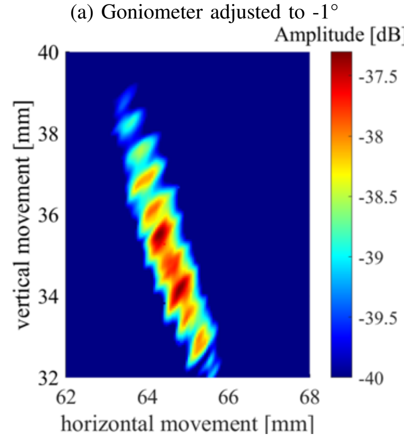


Fig. 3: Determination of the operating resonance frequency for the given coaxial-cavity for the operation with the TE40,23 mode. The resonance frequency has been determined to 204.071 GHz with a quality factor of 4835 (4900 simulated).

Finally, a full mode pattern can be taken. The measured field patterns at 170 GHz and 204 GHz of the two modes are presented in Fig. 5 [10]. The resolution of the mode patterns is given by 0.25x0.25 mm according to the step width of the 3D measurement arm. The radial mode index p can be calculated by the number of rings in the amplitude pattern and is determined to be 19 at 170 GHz and 23 at 204 GHz. The azimuthal mode index m can be calculated by the number l of phase jumps along a circle segment at a constant radius by $m = l + 1$ [11]. This technique is most robust if the chosen radius is close to the field maxima. The azimuthal indices were determined to be 34 and 40, respectively. The scalar mode content (only amplitude) can be calculated to be 92.1/91.8 %. The counter-rotating amount is calculated to be < 0.5 % in both cases. The $TE_{40,23}$ mode, having an eigenvalue of 126.3, is the highest ever excited mode in cold tests. In terms of the fact that the receiving antenna is orientated vertically only the vertical polarization is measured. The E-field intensity in the diagonal direction of the mode patterns are blurred because the radial and azimuthal field is measured simultaneously. A detailed description is given in [9].

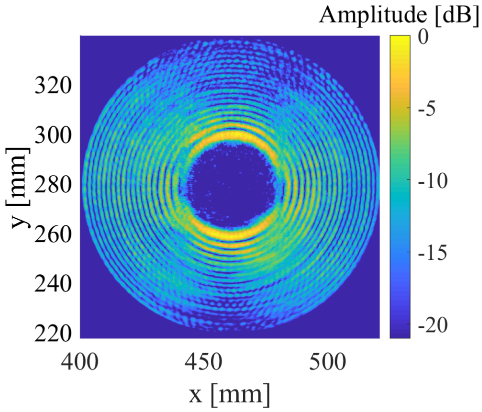


(a) Goniometer adjusted to -1°

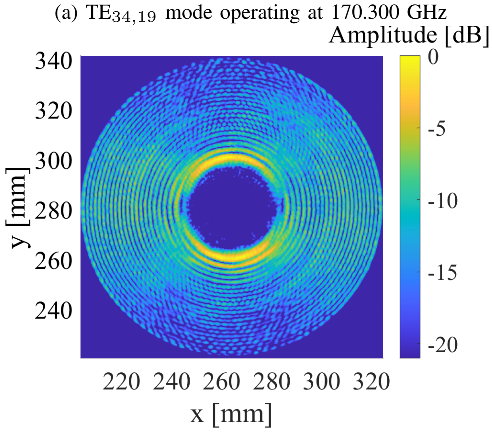


(b) Goniometer adjusted to -2°

Fig. 4: E-field intensity measured at the expected field maxima of the desired mode while adjusting the quasi-parabolic mirror. The graphs are made exemplarily for the excitation of the $TE_{40,23}$ mode at 204.071 GHz.



(a) $TE_{34,19}$ mode operating at 170.300 GHz

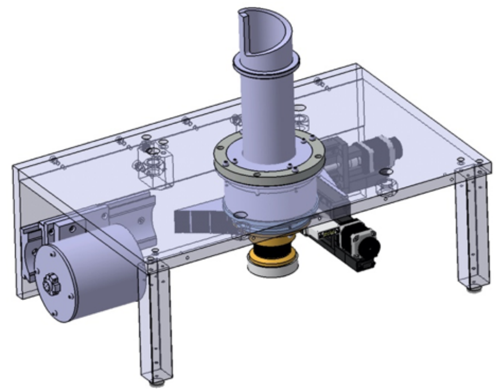


(b) $TE_{40,23}$ mode operating at 204.071 GHz

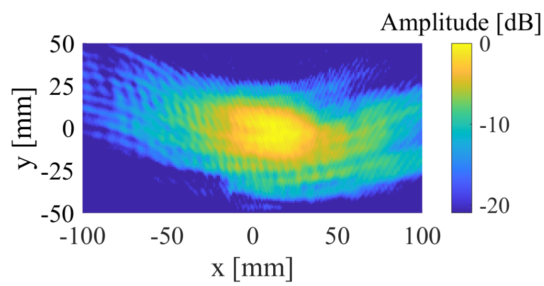
Fig. 5: E-field intensity measured at the expected field maxima of the desired mode while adjusting the quasi-parabolic mirror. The graphs are made exemplarily for the excitation of the $TE_{40,23}$ mode at 204.071 GHz.

III. Verification of the Quasi-Optical Output Coupler

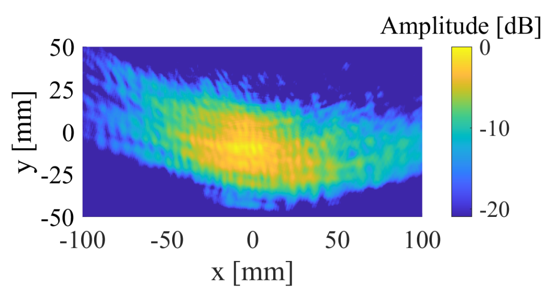
The components of the gyrotron quasi-optical output coupler (launcher and three mirrors) were manufactured of OFHC copper. The launcher shows fabrication tolerances of < 20 µm, which is in the accepted specifications to guarantee a proper operation. Before the whole quasi-optical output coupler is verified, first the radiated E-field intensity of the launcher is measured, giving a first indication about the performance of the dual-frequency launcher. The schematic of the assembly is presented in Fig. 6a, where the non-linear up-taper is replaced by the launcher. The E-field intensity pattern is shown in Fig. 6b and 6c for 170 GHz and 204 GHz, showing a good agreement with the simulations. The iterations in the diagrams refer to a certain amount of the counter-rotating mode or some other modes that can never be prevented. But, especially the counter-rotating mode vanishes in the graphs latest after the first mirror. The phase pattern is not presented, because the phase gives no further information at this position. In principle, this measurement gives a first indication about the proper operation of the dual-frequency launcher. However, a comprehensive statement about the performance can be done using the entire quasi-optical output coupler. Therefore, additionally to the launcher also the mirrors are installed onto the mode generator setup, as presented in the schematic in Fig. 7 The mirror system contains one quasi-elliptical (mirror 1) and two curved mm-wave beam shaping mirrors (mirror 2 and 3) [12].



(a) Schematic for the verification of the launcher.



(b) E-field intensity of launcher aperture at 170.300 GHz



(c) E-field intensity of launcher aperture at 204.071 GHz

Fig. 6: a) Schematic of the verification of the launcher. Measured E-field intensity pattern of the launcher with b) $TE_{34,19}$ mode operating at 170.300 GHz and c) $TE_{40,23}$ mode operating at 204.071 GHz with a pixel size of 1x1 mm. In these figures only the horizontal polarization are presented.

Fig. 8a presents the simulation of the quasi-optical output coupler at 170 GHz. The vectorial (including phase)/scalar (amplitude only) Gaussian mode content is given by 97.5/98.9 %, respectively. In simulations, the beam waist is determined to be 21.57 mm in x-direction and 24.63 mm in y-direction. The beam is shifted by 4.5/4.0 mm in x-/y-direction. The measurement of the E-field intensity of the Gaussian beam at the position of the gyrotron output window is presented is presented in Fig. 8b. The pixel size of the measurement is 1x1 mm. The simulation and measurement is normalized for a comparison. The simulation and measurements are in very good agreement. The calculated vectorial/scalar mode is 95.0/97.8 %, considering also phase from Fig. 8c for the calculation of the vectorial Gaussian mode content. The beam waist is 25.66 mm in x- and 24.15 mm in y-direction. The center of the beam is shifted by 2.2/1.8 mm into the x-/y-direction.

The simulation of the E-field intensity pattern at 204 GHz is presented in Fig. 9a. The simulation gives a vectorial/scalar Gaussian beam of 96.7/98.6 % and a beam waist of 19.27 mm in x- and 24.2 mm in y-direction. The beam is shifted by -3.7/0.0 mm into the x-/y-direction. Fig. 9b presents the measured E-field intensity pattern at 204 GHz and Fig. 9c the phase distribution. The pixel size of 0.5x0.5 mm. The vectorial/scalar mode content is calculated to be $\approx$ 94.8/98.5 % with a beam waist of 23.65 mm in x- and 22.41 mm in y-direction. A shift of -1.8/0.0 mm in x-/y-direction can be determined. A certain number of other modes are always excited in addition to the desired mode, which increases the background noise during measurement.

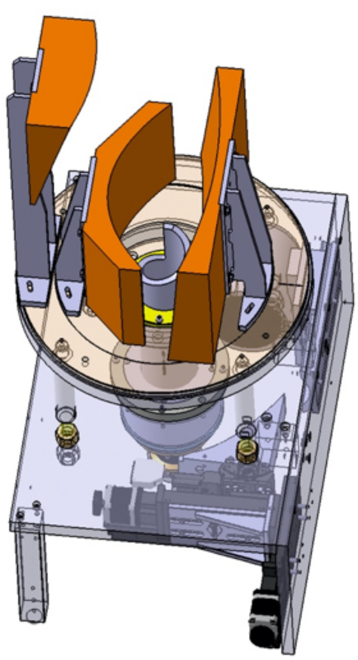
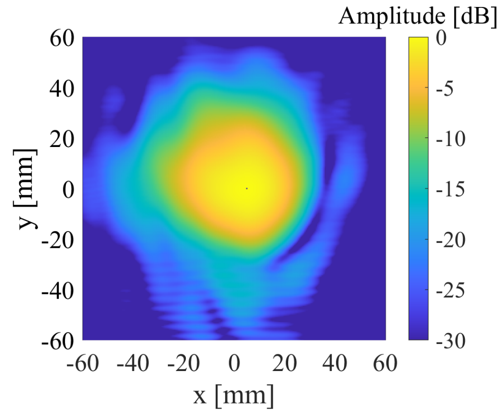
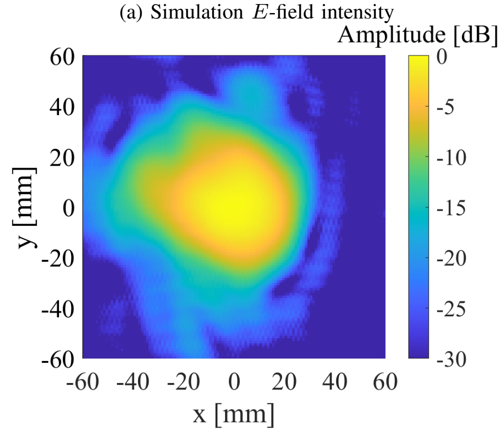


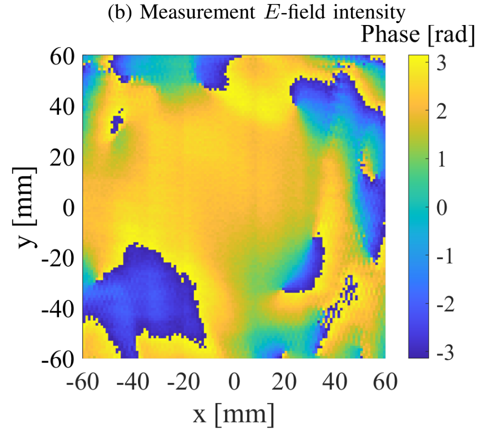
Fig. 7: Schematic of the measurement setup for the evaluation of the quasi-optical gyrotron output coupler consisting of a launcher and three mirrors at 170 GHz and 204 GHz. The quasi-optical output coupler is assembled onto the mode generator setup via the gyrotron plate.



(a) Simulation E-field intensity



(b) Measurement E-field intensity

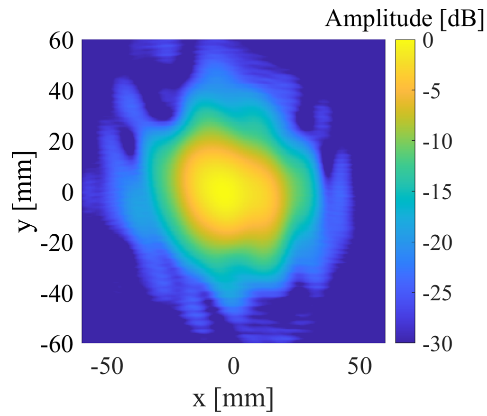


(c) Measured phase pattern

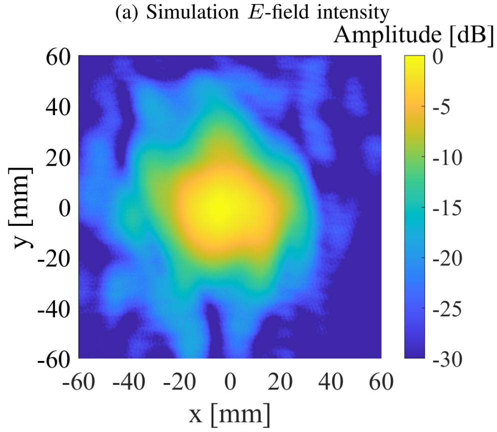
Fig. 8: a) Simulated, b) measured E-field intensity and c) measured phase pattern of the Gaussian beam after the quasi-optical output coupler at the position of the gyrotron output window at 170.300 GHz using the $TE_{34,19}$. The pixel size is 1x1 mm.

IV. Conclusion

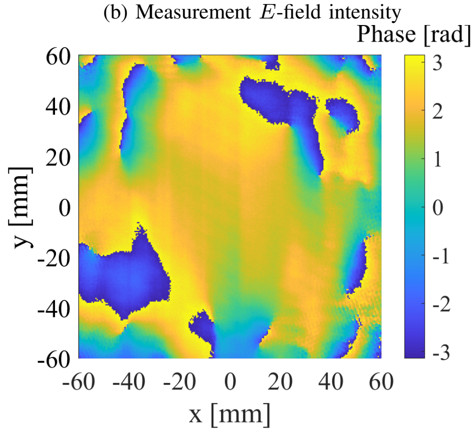
This paper presents the successful verification of the designed and manufactured quasi-optical output coupler for the KIT 2 MW 170/204 GHz dual-frequency coaxial-cavity short pulse pre-prototype in cold-tests using a quasi-optical mode generator. First, a quasi-optical mode generator test stand has been developed and adjusted where the nominal cavity modes $TE_{34,19}$ operating at 170 GHz and $TE_{40,23}$ at 204 GHz, respectively, are excited. The evaluation techniques show a high purity. The $TE_{40,23}$ is the mode having the highest eigenvalue which has been ever excited. Afterwards, the quasi-optical mode generator is used to verify the quasi-optical output coupler converting the high-order rotating gyrotron cavity modes into a Gaussian beam. The cold measurements of the Gaussian beams at the location of the window plane are in very good agreement with the simulations having > 95 % vectorial Gaussian mode content.



(a) Simulation E-field intensity



(b) Measurement E-field intensity



(c) Measured phase pattern

Fig. 9: a) Simulated, b) measured E-field intensity and c) measured phase pattern of the Gaussian beam after the quasi-optical output coupler at the position of the gyrotron output window at 204.073 GHz using the $TE_{40,23}$ mode. The pixel size is 0.5x0.5 mm.

References

[1] R. Wolf et al., "Major results from the first plasma campaign of the Wendelstein 7-X stellarator," Nuclear Fusion 57, 102020.

[2] J. Stober et al., "ECRH on ASDEX Upgrade – System status, feed-back control, plasma physics results," EPJ Web of Conferences 32, 02011, 2012. doi:10.1051/epjconf/20123202011.

[3] C. Darbos et al., "Status of the ITER EC system," in: Proc. IEEE PPS, San Francisco, USA, 2013, pp. P5–P22.

[4] G. Frederici et al., 'Overview of EU DEMO design and R&D activities," Fusion Engineering and Design 882–889, 2014.

[5] N. L. Alexandrov et al., "Low-power excitation of gyrotron-type modes in a cylindrical waveguide using quasi-optical techniques," International Journal of Electronics 79, 215–216, 1995.

[6] R. Ruess et al., "Frequency and mode measurement techniques for megawatt-class gyrotrons," Technisches Messen, De Gruyter, 2021, DOI: 10.1515/teme-2021-0039.

[7] D. Wagner, J. Pretterebner, M. Thumm, "Design of coaxial gyrotron cavities using a scattering matrix code," in: 5th Joint Russian-German Meeting on ECRH and Gyrotron, pp. 555–565, 1993.

[8] M. Pereyaslavets, et al., "Improvements of mode converters for low-power excitation of gyrotron-type modes," International Journal of Electrons, 82:1, 107-116, DOI: 10.1080/002072197136291.

[9] T. Ruess et al., "Computer-controlled test system for the excitation of very high-order modes in highly oversized waveguides," Journal of Infrared, Millimeter, and Terahertz Wave 40, 257–268, (2019), doi:10.1007/s10762-018-0566-3.

[10] T. Ruess, et al., "Verification of the 170/204 GHz quasi-qptical output coupler of the 2 MW coaxial-cavity gyrotron using a mode generator setup," 2022 14th German Microwave Conference (GeMiC), 2022, pp. 5-8.

[11] M. Thumm, "Gyro devices – natural sources of high-power high-order angular momentum millimeter-wave beams," TST, 13 1 (2020) 1-21, DOI: https://doi.org/10.1051/tst/2020131001.

[12] J. Jin et al., "Design of a Quasi-Optical Mode Converter for a Dual-Frequency Coaxial-Cavity Gyrotron," 2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), 2019, pp. 1-2, doi: 10.1109/IRMMW-THz.2019.8873692.