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

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***Abstract* — At KIT, a 2 MW single-frequency 170 GHz coaxial-cavity short-pulse pre-prototype gyrotron has been upgraded towards to dual-frequency operation at 170 GHz and 204 GHz. That upgrade includes a modification of the quasi-optical output coupler system. For validation of the proper design a verification of that sub-system at low power is vital. Therefore, an automated quasi-optical mode generator has been developed for the excitation of the high-order rotating $TE_{34,19}$ cavity mode excited at 170 GHz and the $TE_{40,23}$ mode excited at 204 GHz. The $TE_{40,23}$ mode is the mode with the highest eigenvalue ever excited in cold tests with a high mode purity. The measurements results of the quasi-optical output coupler system shows an excellent agreement with the simulation.**

***Keywords* — gyrotrons, quasi-optical output coupler, high-order rotating modes, mode generator setup**

I. Introduction

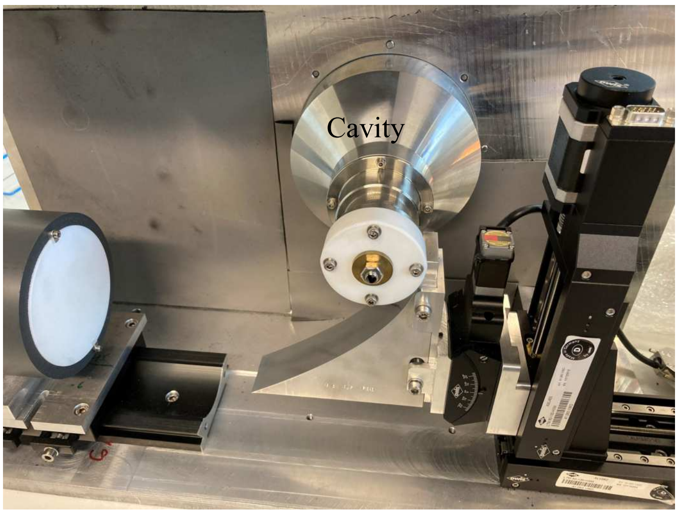
A gyrotron is a vacuum tube providing an RF output power in the Megawatt-level at frequencies above 100 GHz. Those unique performance is required for Electron Cyclotron Resonance Heating and Current Drive (ECRH&CD) systems of nuclear fusion devices that base on magnetically confined plasmas. Gyrotrons are oscillators which rely on the interaction of a weakly relativistic electron beam and a transverse electric cavity mode $TE_{m,p}$. The operation with high-order rotating transversal electric ($TE_{m,p}$) modes in highly oversized waveguides makes it possible to reduce the wall loading inside the cavity. However, because that modes suffer from high attenuation and diffraction losses, those high-order rotating $TE_{m,p}$ modes are not ideal for transmission via a waveguide or quasi-optical transmission line over a large distance of 60-100 m towards a fusion machine, like Wendelstein 7-X, Greifswald, Germany [1] and ASDEX Upgrade [2], Garching, Germany. Same is valid for future ITER [3], Cadarache, France and DEMO [4]. Hence, the operating cavity $TE_{m,p}$ modes are converted into fundamental Gaussian TEM_{00} output beams using an internal quasi-optical output coupler system 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 system is vital before installation of the system into the gyrotron, because the components do not allow any design failures and accept manufacturing tolerances of only few micrometers for a proper operation. This verification is performed in "cold measurements", hence it is done outside of a tube and without excitation of an electron beam. For the verification, first the relevant operating 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, two quasi-optical mode generator setups are described, one for the mode $TE_{34,19}$ mode and another one for the $TE_{40,23}$ mode operating at the given frequencies (170/204 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 mode generator setup is shown in Fig. 1. A step-tapered horn antenna launches a linear polarized Gaussian



Teflon lenses | Quasi-parabolic mirror | High-precision linear drivers

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].

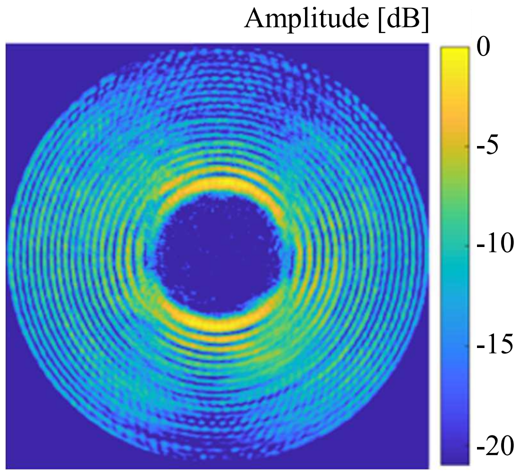


Fig. 2. Measured E-field intensity pattern of the $TE_{34,19}$ mode operating at 170.325 GHz with a pixel size of 0.25x0.25 mm. In this figure the y-polarization is presented.

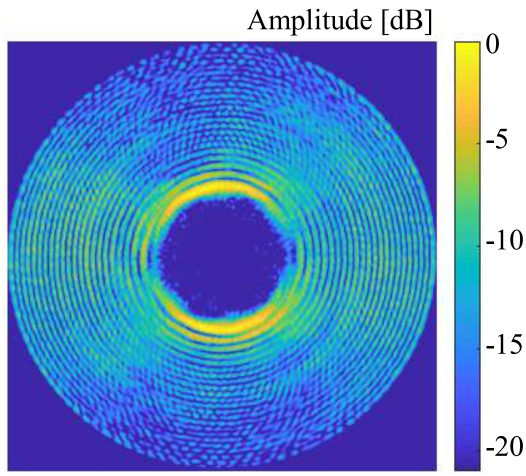


Fig. 3. Measured E-field intensity pattern of the $TE_{40,23}$ mode operating at 204.071 GHz with a pixel size of 0.25x0.25 mm. In this figure the y-polarization is presented.

TEM_{00} beam to a set of Teflon lenses. The Teflon lenses form an astigmatic Gaussian-like beam, which is focused onto a quasi-parabolic mirror. 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. 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) [7]. A non-linear up-taper is assembled at the end of the coaxial-cavity to increase the spatial resolution only for the mode measurements. The field pattern is measured using a standard rectangular waveguide pick-up antenna mounted on a 3D-measurement arm, which does 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.

In an oversized circular waveguide with the radius R, at a given frequency or wavelength λ_0, the number N of TE- and TM modes which can propagate is given by $N = 2.55 \cdot \left(\frac{2R}{\lambda_0}\right)^2$. In the case of 204 GHz operation, more than 4000 modes are able to propagate. This implies the difficulty to excite the high-order TE modes with a sufficient purity in the highly oversized waveguide.

B. Mode Excitation Results

The quasi-optical output coupler is verified at two different frequencies, 170 and 204 GHz. Therefore, two cavities, one for each frequency, were designed and fabricated, with the main difference being the diameter of the holes in the perforated cavity wall, optimized for optimal coupling [8]. The examination of the generated mode is performed using the automated mode generator setup, having different evaluation techniques implemented [9]. Those different mode identification techniques are necessary to determine the mode index in azimuthal m and radial p direction, its quality factor, the amount of counter-rotating mode and the mode content. The two operating modes are the $TE_{34,19}$ mode at 170 GHz and $TE_{40,23}$ mode at 204 GHz. The measured field patterns of the two modes are shown in Fig. 2 and 3, respectively.

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 corresponds to the number of intensity rings and is determined to be 19 at 170 GHz and 23 at 204 GHz. The azimuthal mode index m, can be derived from the number l of phase jumps along a circle segment at a constant radius by $m = l + 1$ [10]. The azimuthal indices were determined to be 34 and 40, respectively. The scalar mode content (amplitude) can be calculated to be 92.1/91.8 % and the diffractive quality factor to 4866/4835 (~4900 simulated) at 170/204 GHz, respectively.

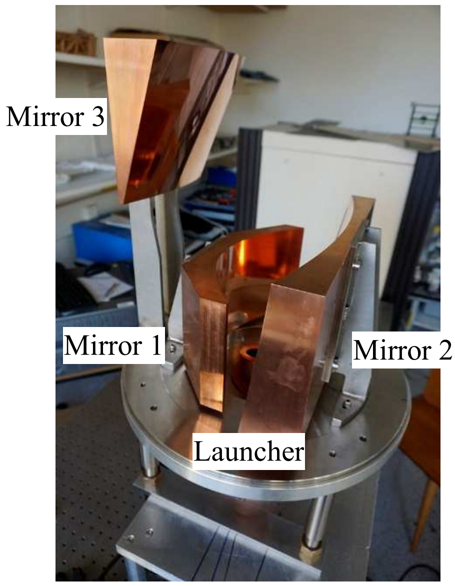


Fig. 4. Photo of the measurement setup for the evaluation of the quasi-optical gyrotron output system consisting of a launcher and three mirrors at 170 GHz and 204 GHz. The quasi-optical output coupler is assembled onto the mode generator setup.

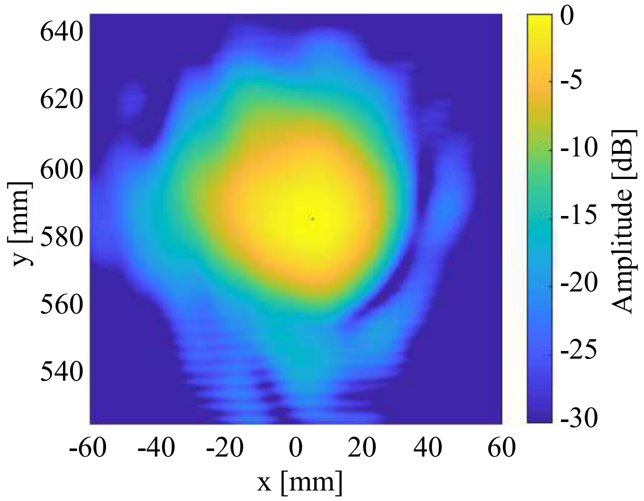


Fig. 5. Simulation of the field intensity of the Gaussian beam after the quasi-optical output coupler at 170 GHz. The field intensity is normalized to its maximum.

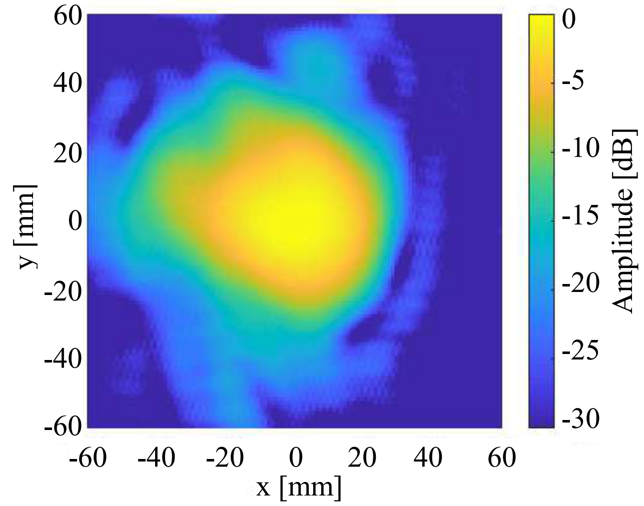


Fig. 6. Measured field intensity of the Gaussian beam after the quasi-optical output coupler at 170 GHz. The measurement is performed at the position of the gyrotron output window. The pixel size is 1x1 mm. The field intensity is normalized to its maximum.

The $TE_{40,23}$ mode, having an eigenvalue of 126.3, is the highest ever excited mode in cold tests. The graphs are in the diagonal direction blurred. This effect is due to the use of the rectangular-waveguide receiving antenna, which measures both field components (radial and azimuthal) in terms of its rotation by 45°.

III. Verification of the Quasi-Optical Output Coupler

The components of the gyrotron output coupler (launcher and three mirrors) were manufactured of OFHC copper. The launcher shows fabrication tolerances of < 20 µm. A cooling structure is missing. It shows that this quasi-optical output coupler can only be used for short-pulse operation. A photo of the output coupler, designed for an operation at 170 GHz and 204 GHz [11] is shown in Fig. 4. The quasi-optical output coupler is assembled on the mirror plate of the gyrotron which is mounted on the mode generator setup. The mirror system contains one quasi-elliptical (mirror 1) and two curved beam shaping mirrors (mirror 2 and 3).

Figure 5 presents the simulation of the quasi-optical output coupler at 170 GHz. The vectorial (including phase)/scalar (amplitude only) Gaussian mode content is 97.5 % / 98.9 %, respectively. The simulated beam waist is 21.57 mm in x-direction and 24.63 mm in y-direction. The beam is shifted in the simulations by 4.5/4.0 mm in x-/y-direction. For comparison, in Fig. 6 the measured field intensity of the Gaussian beam at the position of the gyrotron output window is presented. The pixel size of the measurement is 1x1 mm. The measured data is normalized to its maximum for a better comparison with the simulation results. It can be stated, that there is a very good agreement between the measurement and the simulation. The calculated vectorial/scalar mode is ~95.0 % / 97.8 %. The vectorial calculation takes into account the phase distribution from Fig. 7. The beam waist is 25.66 mm in x- and 24.15 mm in y-direction. The beam is shifted by 2.2/1.8 mm into the x-/y-direction. The contour of the beam of the simulation and the measurement is in very good agreement.

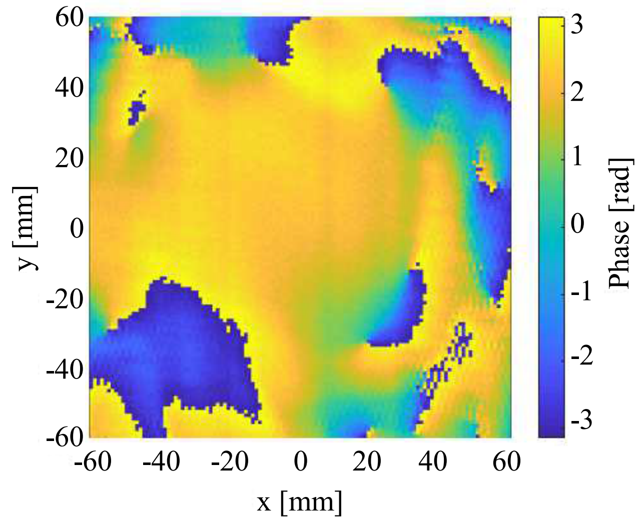


Fig. 7. Measured phase of the Gaussian beam after the quasi-optical output coupler at 170 GHz. The measurement is performed at the position of the gyrotron output window. The pixel size is 1x1 mm.

The simulation of the field intensity pattern at 204 GHz is presented in Fig. 8. The simulation results are 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 mm/0.0 mm into the x-/y-direction. Again, for comparison in Fig. 9 the field intensity pattern at 204 GHz and in Fig. 10 the phase distribution are shown with a pixel size of 0.5x0.5 mm. The vectorial/scalar mode content amounts to ~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.

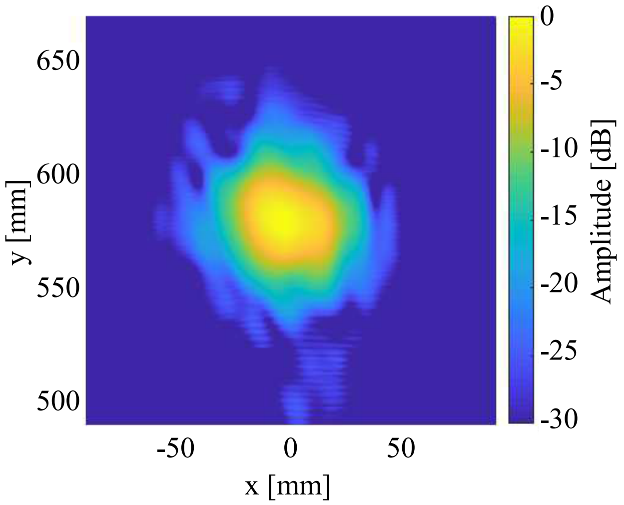


Fig. 8. Simulation of the field intensity of the Gaussian beam after the quasi-optical output coupler at 204 GHz. The field intensity is normalized to its maximum.

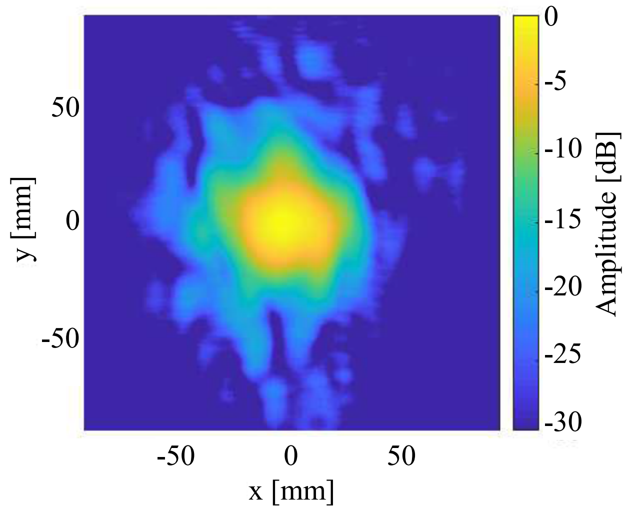


Fig. 9. Measured field intensity of the Gaussian beam after the quasi-optical output coupler at 204 GHz. The measurement is performed at the position of the gyrotron output window. The pixel size is 0.5x0.5 mm. The field intensity is normalized to its maximum.

IV. Conclusion

In this paper, a quasi-optical output coupler for gyrotron operation at 170 and 204 GHz has been successfully verified in cold test. For this purpose, a quasi-optical mode generator test stand has been developed where the nominal cavity modes $TE_{34,19}$ and $TE_{40,23}$ at 170/204 GHz, respectively, are excited with a high purity. The $TE_{40,23}$ is the mode having the highest eigenvalue which has been ever excited. The mode generator is used to generate the cavity mode for the verification of the quasi-optical output coupler. The designed quasi-optical output coupler converts the high-order rotating gyrotron mode into a Gaussian beam. The simulation shows a Gaussian mode content of > 96 % at both frequencies. The measurements are in very good agreement having > 95 % vectorial Gaussian mode content.

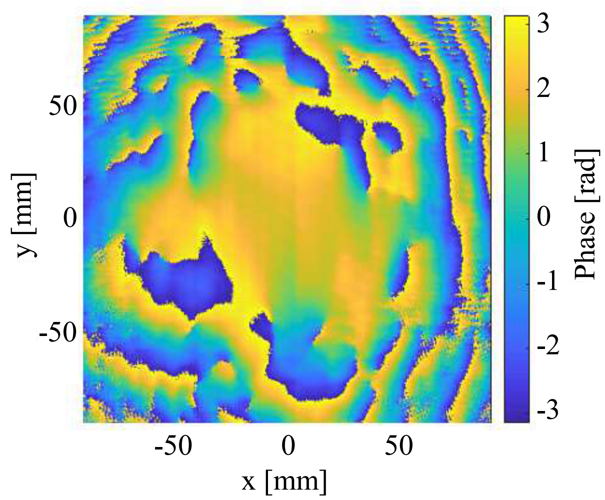


Fig. 10. Measured phase of the Gaussian beam after the quasi-optical output coupler at 204 GHz. The measurement is performed at the position of the gyrotron output window. The pixel size is 0.5x0.5 mm.

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