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Studies towards an upgraded 1.5 MW gyrotron for W7-X

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Abstract. Studies towards a 1.5 MW, 140 GHz CW gyrotron, with the capability of MW-class operation also at 175 GHz, are ongoing at Karlsruhe Institute of Technology in view of a possible future upgrade of the ECRH system of the stellarator W7-X. The upgrade of the existing 1.0 MW, 140 GHz European gyrotron for W7-X has been chosen as a development path. Detailed designs of the cavity, the non-linear uptaper, and the quasi-optical launcher for the upgraded gyrotron have been obtained and have been validated numerically. In parallel, a mode generator, intended for low-power tests of the quasi-optical mode converter system of the upgraded gyrotron, has been designed, manufactured, and successfully tested.

1 Introduction

The stellarator Wendelstein 7-X (W7-X) is equipped with a steady-state (1800 s) Electron Cyclotron Resonance Heating (ECRH) system consisting of ten 1 MW gyrotrons, which operate at 140 GHz [1]. The available electron cyclotron heating and current drive power in the plasma ranges from 7 to 9 MW [2, 3]. Hence, W7-X is using the world's largest ECRH system today. The ECRH is used for plasma start-up, heating and current drive, and plasma vessel conditioning.

The possibility of even higher ECRH power in the future is under discussion. In addition, MW-class microwave power at a frequency around 175 GHz would be attractive for Collective Thomson Scattering (CTS) diagnostics. Motivated by these considerations, studies towards an upgraded 140 GHz, 1.5 MW Continuous Wave (CW) gyrotron, with the option for MW-class operation also at 175 GHz, have been initiated at Karlsruhe Institute of Technology [4]. Several possibilities have been investigated, using successful existing European gyrotron designs as a starting point. It has been identified that the most promising development path, with respect to risk and cost, would be the upgrade of the existing W7-X $TE_{28,8}$-mode gyrotron in order to operate in the $TE_{28,10}$ mode at 140 GHz and in the $TE_{36,12}$ mode at 175 GHz.

Following this outcome, detailed designs for the gyrotron cavity and non-linear uptaper as well as for the launcher of the quasi-optical mode converter system of the gyrotron have been obtained and validated numerically. The designs fulfil the specifications and require the smallest changes with respect to the existing W7-X gyrotron layout. A first assessment of the necessary modifications for the rest of the gyrotron components has also been made. In support to the design work, the components of a mode generator, intended for low-power tests of the quasi-optical mode converter system, have been designed and manufactured. The mode generator is based on the obtained cavity design and is using a coaxial cavity with perforated wall. It has been assembled and experimentally tested, delivering very good results.

This paper is organized as follows: In Section 2, the selection of the operating modes for the upgraded gyrotron, driven by particular specifications and constrains, is described. The designs for the cavity, non-linear uptaper, and launcher are given in Section 3, together with their numerical validation. In Section 4, the design and assembly of the mode generator as well as the results from its experimental testing are presented. Finally, Section 5 gives an outlook to the next steps towards the realisation of the upgraded gyrotron.

2 Operating mode selection

The selection of the operating modes and the design parameters for the upgraded gyrotron for W7-X has primarily been driven by the following list of requirements:

(i) CW operation at 140 GHz with a power of 1.5 MW
(ii) CW MW-class operation at 175 GHz
(iii) Minimization of risk and cost of development
(iv) Use of the existing gyrotron power supplies at W7-X

For the first requirement, the order of the operating TE mode for 140 GHz operation should be high enough to ensure acceptable Ohmic loading of the wall of the

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gyrotron cavity. The limit for the wall loading is 2 kW/cm^2.

The simultaneous fulfilment of the first and second requirement imposes two additional criteria for the selection of the pair of modes for 140 GHz and 175 GHz operation: (a) The ratio of the eigenvalues of the two modes needs to be as close to 175/140 as possible, in order to take full advantage of the corresponding $\lambda/2$ resonances of the output window of the gyrotron and minimize the window reflection. (b) The caustic radii R_{caustic} of the two modes must be very similar, in order to be possible for the electron gun and the quasi-optical launcher to support both modes.

To address the third requirement, the upgraded gyrotron should be based on already proven long-pulse gyrotron designs and the deviation from these designs must be as small as possible. With respect to this, the European $TE_{28,8}$-mode 140 GHz, 1 MW CW gyrotron for W7-X [5] and the European $TE_{32,9}$-mode 170 GHz, 1 MW CW gyrotron for ITER [6] have been considered as starting points.

Under the aforementioned considerations, the most promising mode-pairs for the upgraded gyrotron have been identified and are shown in Table 1.

Table 1. Possible modes for the upgraded W7-X gyrotron.

Starting point	W7-X gyrotron	ITER gyrotron
	140 GHz operation	
Operating mode	$TE_{28,10}$	$TE_{32,9}$
Electron beam radius (mm)	10.0	11.4
	175 GHz operation	
Operating mode	$TE_{36,12}$	$TE_{40,11}$
Electron beam radius (mm)	10.2	11.4
Window reflection (%)	0.10	0.15
Difference in R_{caustic} (%)	2.64	0.26

According to Table 1, if the existing 140 GHz $TE_{28,8}$-mode gyrotron for W7-X is used as starting point for the upgrade, then it should be modified for operation with the $TE_{28,10}$ mode, requiring a 10 mm electron beam radius at the cavity. The beam radius of the existing $TE_{28,8}$-mode gyrotron is also 10 mm [5]. This implies that the upgraded gyrotron could use practically the same cathode and beam tunnel as those of the existing W7-X gyrotron. However, this would not be the case if the existing 170 GHz $TE_{32,9}$-mode gyrotron for ITER, which uses a beam radius of 9.44 mm [6], was used as starting point. According to Table 1, the required beam radius for the upgraded gyrotron would then be significantly larger (11.4 mm); thus, a significantly different cathode and beam tunnel should probably be used for the upgraded gyrotron. From this observation, it was concluded that it is preferable, in terms of cost and risk, to use the existing W7-X gyrotron as the basis for the upgraded W7-X gyrotron.

Finally, with respect to the fourth requirement, the capabilities of the existing high-voltage power supplies at W7-X allow for a ~3.3 MW electron beam with cathode voltage up to 65 kV and preferred acceleration voltage in the range of 70-85 kV. The nominal 1 MW operation of the existing $TE_{28,8}$-mode gyrotron calls for an accelerating voltage $V_{\mathrm{acc}} = 81$ kV, a beam current $I_b = 40$ A, and an electron velocity ratio $\alpha = 1.3$ [5]. To support an output power of 1.5 MW, the accelerating voltage and the current should be increased accordingly. Since the margin for accelerating voltage increase is not very large, operating points in the vicinity of $V_{\mathrm{acc}} \sim 80$ kV, $I_b \sim 55$ A, $\alpha = 1.3$ have been considered for the upgraded 1.5 MW gyrotron, in order to be compatible with the existing power supplies at W7-X.

3 Design of components

3.1 Cavity and non-linear uptaper

A cavity and a non-linear uptaper have been designed for the upgraded gyrotron, to allow for 1.5 MW of output power with the $TE_{28,10}$ mode at 140 GHz. To keep the similarity with the existing W7-X gyrotron, the total length of the cavity and uptaper has been kept the same. In addition, the radius at the cavity entrance has been also kept the same to permit the use of a beam tunnel similar to that of the existing W7-X gyrotron. The radius at the cavity midsection is 22.83 mm, which is 2.35 mm larger than that of the midsection of the existing $TE_{28,8}$-mode cavity, to secure oscillation of the higher-order $TE_{28,10}$ mode at 140 GHz. A schematic of the cavity and uptaper design is shown in Fig. 1.

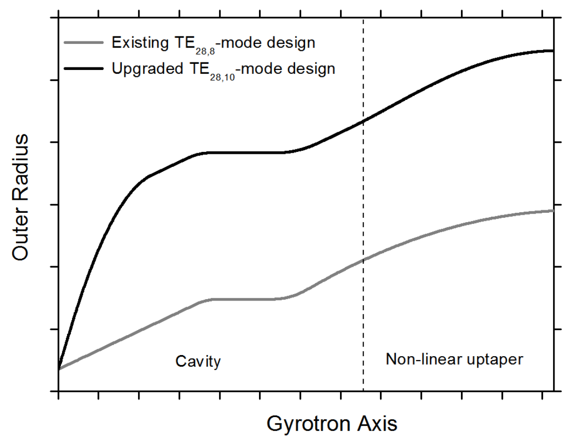

Fig. 1. Schematic of the cavity and non-linear uptaper of the existing W7-X gyrotron and of the upgraded W7-X gyrotron.

The performance of the non-linear uptaper, in terms of mode conversion, has been validated numerically. The calculated mode conversion is minor, resulting in 99.87% transmission of the $TE_{28,10}$ mode and in 99.81% transmission of the $TE_{36,12}$ mode at the end of the non-linear uptaper.

The performance of the cavity and the non-linear uptaper, in terms of beam-wave interaction, has also been numerically validated using the code-package EURIDICE [7]. The diode start-up is simulated by increasing the beam voltage V_b from 35 kV to 85 kV. The beam voltage is proportional to the electron kinetic energy ($V_b = E_{\mathrm{kin}}/e$) and, during start-up, it follows the increase of the accelerating voltage applied by the power supplies. During the voltage increase in the simulation, the electron velocity ratio is changing adiabatically and the beam current obeys the Schottky formula. A large number of competing modes, with good resonance and coupling with the electron beam, are interacting simultaneously. A realistic magnetic field profile is considered, which is based on the profile of an existing magnet, used to test the gyrotrons for W7-X. In addition, relatively large spreads in the electron energy (1 % rms) and in the velocity ratio α (20 % rms) are assumed. A typical spread of two Larmor radii in the electron guiding-centres is also taken into account. All these considerations make the simulations as realistic as possible with respect to this stage of development.

The operation at 140 GHz, assuming a maximum magnetic field of 5.55 T, is illustrated in Fig. 2. During start-up, a series of modes is excited before the excitation of the operating $TE_{28,10}$ mode at around $V_b = 64$ kV. Then, the operating mode reaches the nominal operating point ($V_b = 78.5$ kV, $I_b = 56$ A, $\alpha = 1.3$) where it delivers 1.68 MW of microwave power at the end of the non-linear uptaper with an interaction efficiency of 39.5 %. Assuming the typical 5% additional losses until the gyrotron window, this corresponds to 1.6 MW of power at the window. There is a stability margin of 2 kV above the nominal point before mode loss. It should be noted here that the recent developments in the control of gyrotron operation [8] show very promising results regarding the feasibility of operation close to the stability limit of the mode.

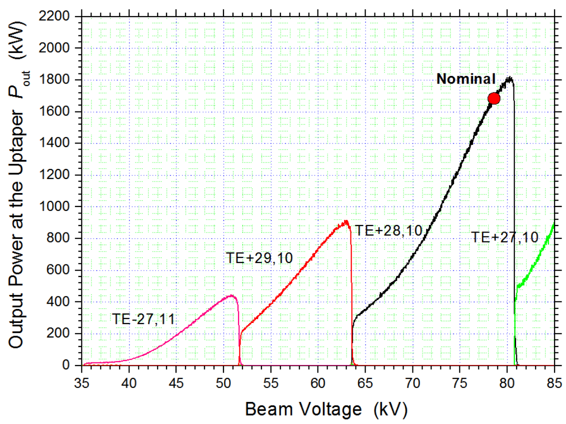

Fig. 2. Multi-mode simulation (36 competing modes) of the diode start-up for gyrotron operation at 140 GHz. A negative azimuthal index denotes a counter-rotating mode.

For the operation at 175 GHz, a maximum magnetic field of 7.05 T is assumed. Since an electron gun of the diode type is intended to be used for the upgraded gyrotron, there is some challenge in obtaining the appropriate values for the electron velocity ratio α both at a magnetic field of 5.55 T and at a magnetic field of 7.05 T, which is ~ 30 % higher. If the same electron energy is assumed in both cases, then for $\alpha = 1.3$ at 5.55 T, a first estimation of the achievable velocity ratio at 7.05 T is $\alpha \sim 0.8$ only. However, with a careful electron gun design and a magnet that permits some control over the amplitude and angle of the magnetic field vector in the gun region, higher values for α could be feasible [9]. For this reason, at this stage of studies, two different cases for the operation at 175 GHz have been examined: $\alpha \sim 0.8$ and $\alpha \sim 1.1$. The simulation results for operation at 175 GHz in the $TE_{36,12}$ mode are shown in Fig. 3. It turns out that stable MW-class operation is possible for both cases. In the case of $\alpha = 1.1$, the nominal operating voltage is not chosen on the grounds of a 2 kV stability margin but is limited to a lower value to secure a cavity wall loading of 2 kW/cm^2. Since operation at 175 GHz is required for CTS diagnostics, the spectral purity of the gyrotron signal is of paramount importance and, therefore, studies on the spectral purity of the present design are planned. Nevertheless, previous studies on a gyrotron for 60 GHz CTS [10] indicated that a spectral purity of ~100 dB within ±5 GHz of the central frequency can be expected.

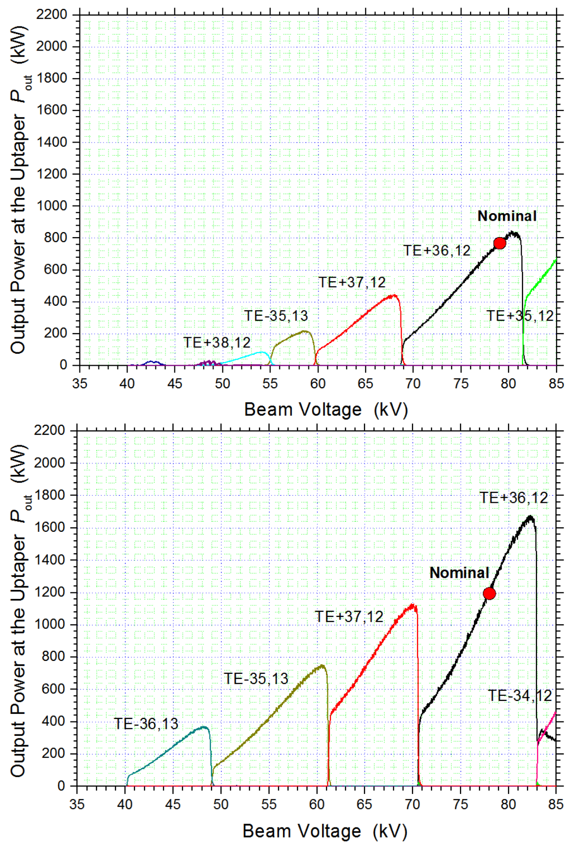

Fig. 3. Multi-mode simulation (46 competing modes) of the diode start-up for gyrotron operation at 175 GHz, assuming $\alpha = 0.8$ (top) and $\alpha = 1.1$ (bottom). A negative azimuthal index denotes a counter-rotating mode.

The operating parameters and the calculated performance of the upgraded gyrotron at 140 GHz and 175 GHz are summarized in Table 2. The cavity radius has been chosen in a way to give an oscillating frequency of 140.4 GHz for the $TE_{28,10}$ mode, in order to anticipate a frequency down-shift due to the cavity thermal expansion during long-pulse operation [11].

Table 2. Operating parameters and calculated performance of the upgraded W7-X gyrotron.

	140 GHz operation	175 GHz operation
	Operating parameters	
Operating mode	$TE_{28,10}$	$TE_{36,12}$
Electron velocity ratio α	1.30	0.82/1.13
Electron beam radius (mm)	10.0	10.2/10.3
Maximum magnetic field (T)	5.55	7.05/7.00
Beam voltage (kV)	78.5	79.0/78.0
Accelerating voltage[1] (kV)	82.1	81.8/81.0
Beam current (A)	55.7	55.8/55.6
	Calculated performance	
Frequency (GHz)	140.4	175.8
Power at end of uptaper (MW)	1.68	0.78/1.22
Interaction efficiency (%)	39.5	17.6/28.0
Ohmic wall loading[2] (kW/cm^2)	1.8	1.1/2.0
Power at window[3] (MW)	1.60	0.74/1.16
Total efficiency w/o depressed collector[1-3](%)	35.0	16.2/25.8

[1]Assuming a 60 % neutralization of the beam space charge [11]
[2]Assuming an effective conductivity of 1.73×10^7 S/m
[3]Assuming 5 % internal losses between uptaper and window

3.2 Quasi-optical launcher

A quasi-optical launcher has been designed for the upgraded gyrotron, taking into account the possibility for operation both at 140 GHz and at 175 GHz. The initial radius and taper angle of the launcher wall are compatible with the end of the non-linear uptaper in Fig. 1. The overall length of the launcher has been kept similar to that of the existing launcher of the $TE_{28,8}$-mode gyrotron at W7-X. The launcher is of the hybrid type [12] and the design of its perturbed inner wall is shown in Fig. 4. In the figure, the axis z of the cylindrical coordinate system coincides with the gyrotron axis. The azimuthal coordinate is denoted by α. The calculated performance of the launcher is very good. Assuming operation with the $TE_{28,10}$ mode at 140.0 GHz, a Gaussian microwave beam with a Gaussian mode content of 97.4% at the launcher aperture is generated. For operation with the $TE_{36,12}$ mode at 175.4 GHz, the Gaussian mode content of the generated microwave beam at the launcher aperture is 95.3%. The contour plots of the normalised amplitude of the electric field on the launcher surface are shown in Fig. 5. It should be noted that the two frequencies used in the calculations are the expected operating frequencies after the thermal expansion of the cavity. The Gaussian mode content in both cases is expected to be further increased with the help of the gyrotron mirror system, which will be designed at a next stage.

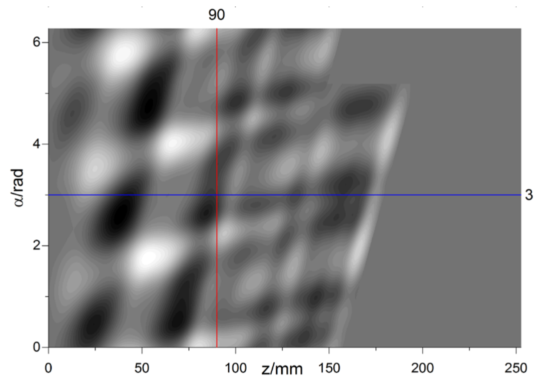

Fig. 4. Contour plot of wall perturbations of the designed hybrid-type quasi optical launcher for the upgraded gyrotron.

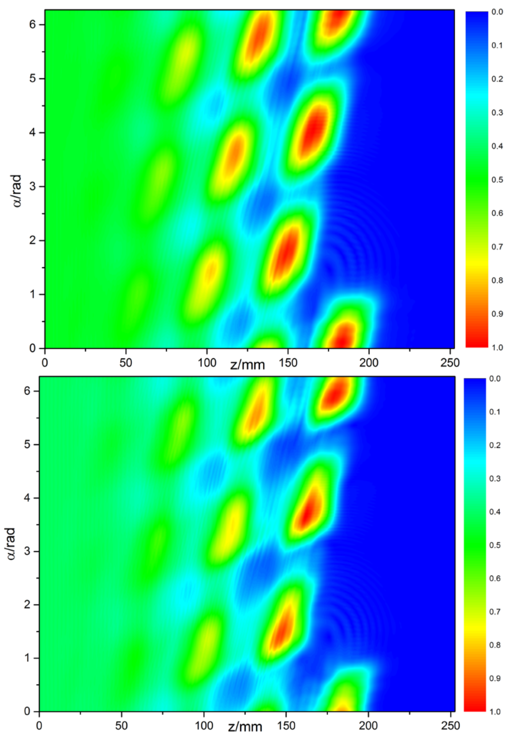

Fig. 5. Contours of the normalised amplitude of the electric field on the launcher surface for 140.0 GHz operation (top) and for 175.4 GHz operation (bottom).

4 Mode generator

A mode generator is necessary for low-power tests of the quasi-optical mode converter system of the gyrotron (launcher & mirrors). Based on the cavity and non-linear uptaper of Fig. 1, the components for a mode generator, namely the cavity and the uptaper, have been designed and manufactured. The assembled mode generator is shown in Fig. 6.

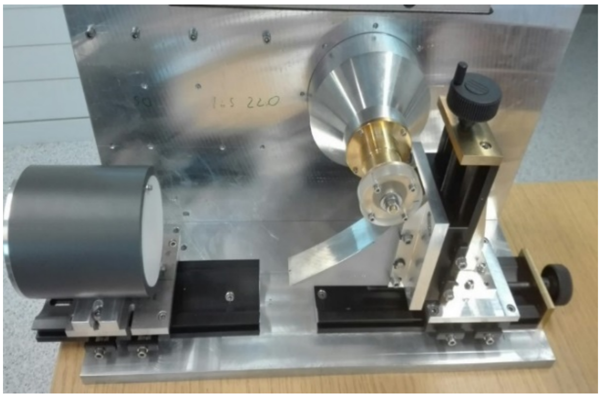

Fig. 6. Mode generator set-up.

The high-frequency wave is generated by a network analyser and is transmitted, using a horn antenna, as a spherical wave. The spherical wave is converted into a plane wave with a lens system (component at the left hand side in Fig. 6). A quasi-parabolic mirror is required to focus the wave on the caustic radius of the rotating mode to be excited in the cavity of the mode generator. The cavity (gold-coloured component near the centre of Fig. 6) has been designed using a scattering matrix code [13]. For easier excitation of the mode, a coaxial cavity is used. The cavity wall is perforated so that the wave can propagate from the quasi-parabolic mirror into the cavity [14].

The excited mode in the cavity needs to have a high purity, in order to resemble the gyrotron mode and make the low-power tests of the quasi-optical mode converter system reliable. In order to check the purity of mode excitation in the cavity, a non-linear uptaper is mounted after the cavity, to reach a diameter of 70 mm for better resolution in the measurements. (For the low-power test of the gyrotron launcher this uptaper will be removed and replaced by the launcher.) The excited mode is measured using a pick-up open-ended rectangular waveguide, which scans stepwise the plane in front of the non-linear uptaper. The measured signal is evaluated using the network analyser.

The frequency of the $TE_{28,10}$ mode and of the $TE_{36,12}$ mode in the mode generator cavity was found to be 140.155 GHz and 175.992 GHz, respectively. These frequencies are somewhat higher than the nominal frequencies because there is some uncertainty in the resonant frequencies in the cavity design because of the perforations. The diffractive quality factor of the cavity was measured to be 2600 and is in good agreement with the simulation. The mode pattern (electric field amplitude – vertical polarization) has been acquired using stepwise scanning with the pick-up waveguide. The resolution on the plane of measurement is 0.2 mm × 0.2 mm. Figure 7 shows the pattern of the $TE_{28,10}$ mode at 140.155 GHz and of the $TE_{36,12}$ mode at 175.992 GHz. The plots are normalized to the highest amplitude and values below -21 dB are clipped. The results are in very good agreement with the simulations. The azimuthal nodes are not clearly seen because the excited mode is by intention a rotating mode, as is the mode in the gyrotron cavity. Since only one polarization is measured, the first ring at the caustic radius is not closed. For the same reason, the rings are blurred in the area which is 45° inclined with respect to the linear polarization. This is a typical effect corresponding to the measurement setup [15]. The purity of mode excitation is good. The measured amount of the counter-rotating mode at the caustic radius is 0.88 % for the $TE_{28,10}$ mode and 0.42 % for the $TE_{36,12}$ mode. This means that the mode generator performs very well and is ready to be used for low-power measurements of the quasi-optical mode converter system of the upgraded gyrotron when available.

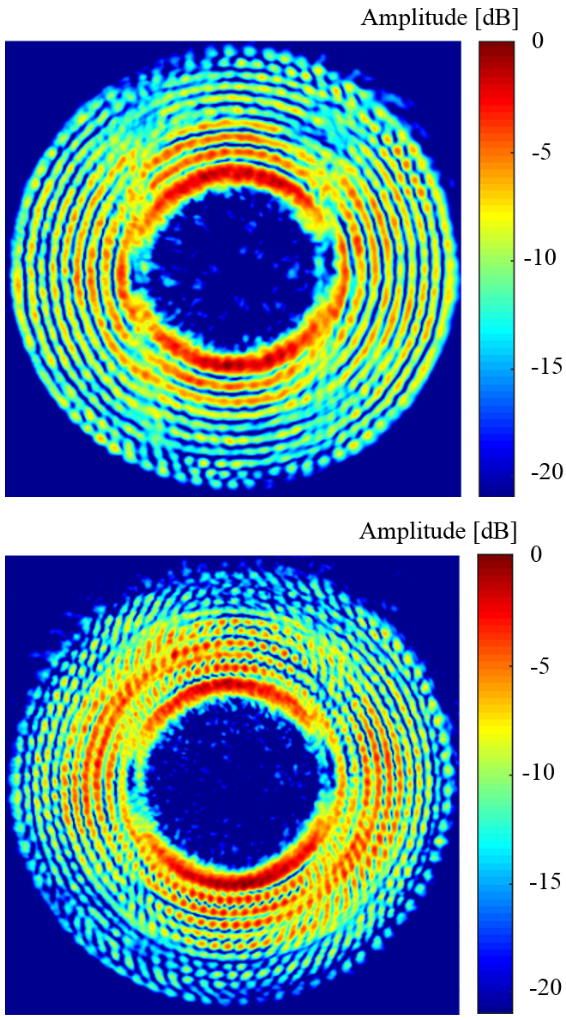

Fig. 7. Measured normalized pattern (electric field amplitude – vertical polarization) of the $TE_{28,10}$ mode at 140.155 GHz (top) and of the $TE_{36,12}$ mode at 175.992 GHz (bottom). The plots refer to a 70 mm × 70 mm domain.

5 Outlook and discussion

As next step, the design of further components for the upgraded gyrotron is planned, as described below.

(i) Diode electron gun. The existing cathode of the W7-X gyrotron could be used (maybe with some minor modifications), given that both the existing and the upgraded gyrotron require the same electron beam radius. However, the anode needs to be redesigned, in order to ensure optimum electron beam parameters at the required operating current of ~56 A, which is significantly higher than the current of 40 A used in the existing gyrotron. The capability of the gun to provide reasonable beam parameters also at ~ 30 % higher magnetic field (for 175 GHz operation) should also be taken into account.

(ii) Beam tunnel. Given again that the upgraded and the existing W7-X gyrotron require the same electron beam radius, the stacked beam tunnel of the existing gyrotron could, in principle, be also used for the upgrade. A minor redesign of the corrugations of the copper rings should be made, in view of the operation at 175 GHz. However, although the existing beam tunnel has shown satisfactory suppression of parasitic modes when operating with a 40 A beam current [16], it is not guaranteed that this would still be the case for operation at 56 A. A proposal would be to test the beam tunnel performance at higher beam current using one of the existing W7-X gyrotrons. Even short-pulse operation can clarify whether parasitic mode excitation is present.

(iii) Mirror system. The positions of the three mirrors inside the mirror box after the launcher in the upgraded gyrotron are not expected to be much different compared to the existing W7-X gyrotron. However, the surface and shape of the mirrors have to be redesigned. Given that the difference in caustic radius between the $TE_{28,10}$ mode and the $TE_{36,12}$ mode is 2.64 %, some difference in the direction of the microwave output beam for 140 GHz and 175 GHz operation is expected. This should be considered in the orientation of the third mirror before the gyrotron window. The optimum solution would be a steerable third mirror.

(iv) Window. The operating frequencies of the upgraded gyrotron have been chosen in a way that the existing diamond window of the W7-X gyrotron (with a thickness of 1.8 mm) can be used for the upgrade.

(v) Collector. The collector of the upgraded gyrotron would need to withstand 50 % more power compared to the existing collector. This requires an assessment of the existing collector in terms of operation at higher power levels and, if its capability is limited, a redesign of the collector with respect to size, shape, and electron beam sweeping options.

The design of all the components for the upgraded gyrotron will use well-established ideas as a starting point. However, in the course of the studies, the possibility of incorporation of innovative, newly verified concepts will also be assessed. These include improvements in the cooling of cavity and collector, different technologies for the emitter ring, and different materials for the beam tunnel.

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