2.2 MW Operation of the European Coaxial-Cavity Pre-Prototype Gyrotron for ITER

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Abstract: A 2 MW, CW, 170 GHz coaxial-cavity gyrotron for electron cyclotron heating and current drive in the International Thermonuclear Experimental Reactor (ITER) is under development within an European Gyrotron Consortium (EGYC*), a cooperation between European research institutions. To support the development of the industrial prototype of a CW gyrotron, a short pulse tube (pre-prototype) is used at KIT Karlsruhe for experimental verification of the design of critical components, like the electron gun, beam tunnel, cavity and quasi-optical (q.o.) RF-output coupler. Significant progress was achieved recently. In particular, RF output power of up to 2.2 MW with 30 % output efficiency has been obtained in single-mode operation at 170 GHz. Furthermore, a new RF output system has been designed, with an efficient conversion of the generated RF power into a Gaussian RF output beam. The results have been successfully confirmed, yielding a Gaussian mode content ~96 %.

1. Introduction

The European 2 MW, CW, 170 GHz coaxial-cavity gyrotron for use in ITER is being developed at KIT in cooperation with several European research institutions (EGYC*) [1]. Gyrotrons will be the microwave sources for electron cyclotron heating, current drive and stabilization of plasmas in ITER. To fulfill the needs of ITER, gyrotrons with a hollow waveguide cavity with 1 MW output power are currently under development in Japan and Russia. In contrast to this approach, the EU gyrotron consortium is investigating a coaxial-cavity gyrotron with the potential to produce 2 MW RF output power. Expanded requirements of heating power up to 40 MW are being considered for future ITER experiments. The reduced costs of upgrading the ECRH system with advanced 2 MW coaxial-cavity gyrotrons would be a significant advantage over conventional 1 MW tubes.

The design specifications for the coaxial-cavity gyroton are given in Table I. A single-stage depressed collector (SDC) should allow an efficiency of > 50 %. The coaxial arrangement reduces the mode competition and provides a significant reduction of the voltage depression caused by beam space charge, enabling in an increase of the limiting current. Thus stable single-mode operation can be obtained even with cavity modes of very high order. Since the limited cooling capability due to Ohmic wall loading inside the cavity is a major technical limitation for the obtainable RF power of a gyrotron, the use of very high-order modes in the

Operating cavity mode	$TE_{34,19}$
Frequency, f	170 GHz
RF output power, P_{out}	2 MW
Beam current, I_b	75 A
Accelerating voltage, U_C	90 kV
Velocity ratio, α	~ 1.3
Cavity magnetic field, B_{cav}	6.87 T
Efficiency with SDC	> 50 %

Table I: Design specifications for coaxial-cavity gyrotron.

* European GYrotron Consortium: CRPP, Switzerland; KIT, Germany; HELLAS, Greece; CNR, Italy; ENEA, Italy.

coaxial gyrotron makes it possible to generate RF powers in the multi-megawatt range. One consequence of the use of high-order volume modes is (among other things) the significant increase in the complexity the quasi-optical (q.o.) RF output system needed for conversion of the cavity mode into the fundamental free-space Gaussian mode.

To support the activities towards an industrial prototype [2], experimental studies of a short pulse (~ few ms) 170 GHz coaxial-cavity gyrotron ("pre-prototype") are performed at KIT. The pre-prototype tube utilizes the same $TE_{34,19}$-cavity mode and the same cavity with an up-taper, launcher and mirrors as designed for the industrial prototype. In addition, it uses a very similar electron gun and a similar beam tunnel. Therefore the performance of the gyrotron and its main components - electron gun, beam tunnel, cavity and RF generation, the q.o. RF output coupler – can be studied under fairly relevant conditions to investigate the fundamental physics of the design. Unexpected problems can be discovered and investigated sufficiently in advance.

2. Recent Modifications of the Gyrotron Set-up

The following modifications have been recently made on the pre-prototype gyrotron:

(1) Since the SC gyrotron magnet in use at KIT limits the maximum value of the magnetic field to ~6.7 T, an additional NC coil has been wound directly on the gyrotron body near to the cavity in order to increase the magnetic field to the nominal value of 6.87 T. Further on, the shape of the electron gun's anode has been redesigned to provide a velocity ratio $\alpha = 1.3$ at the design operating parameters (90 kV, 75 A, 6.87 T).

(2) To suppress the parasitic RF oscillations a novel beam tunnel has been designed, fabricated and installed in the tube (Fig. 1). The main modification in the new beam tunnel consists in the introduction of corrugations (longitudinal slots) in the copper rings. These slots destroy the azimuthal symmetry of the geometry [3]. Furthermore, the arrangement of the ring structure is now conical instead of the stepwise cylindrical arrangement used in the previous tunnel.

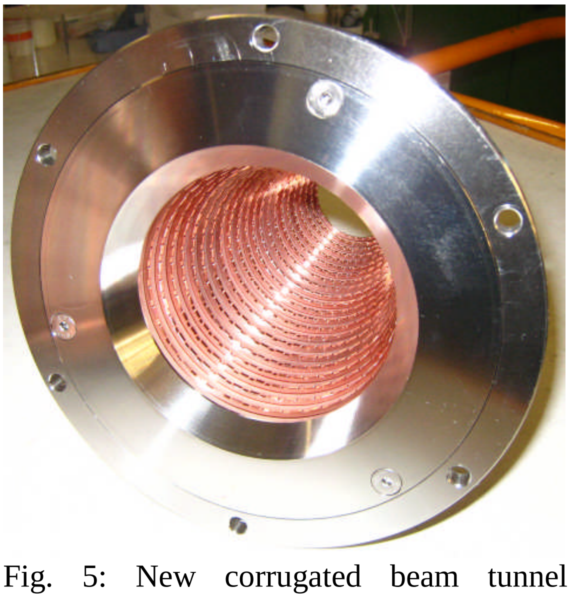

Fig. 5: New corrugated beam tunnel prototype.

(3) A new q.o. output coupler has been installed in the gyroton. The design of the significantly improved system is based on a launcher optimized with a novel optimization method [4]. The new q.o. mode converter has been verified in cold-test measurements prior to installation. These measurements will be described in chapter 4.

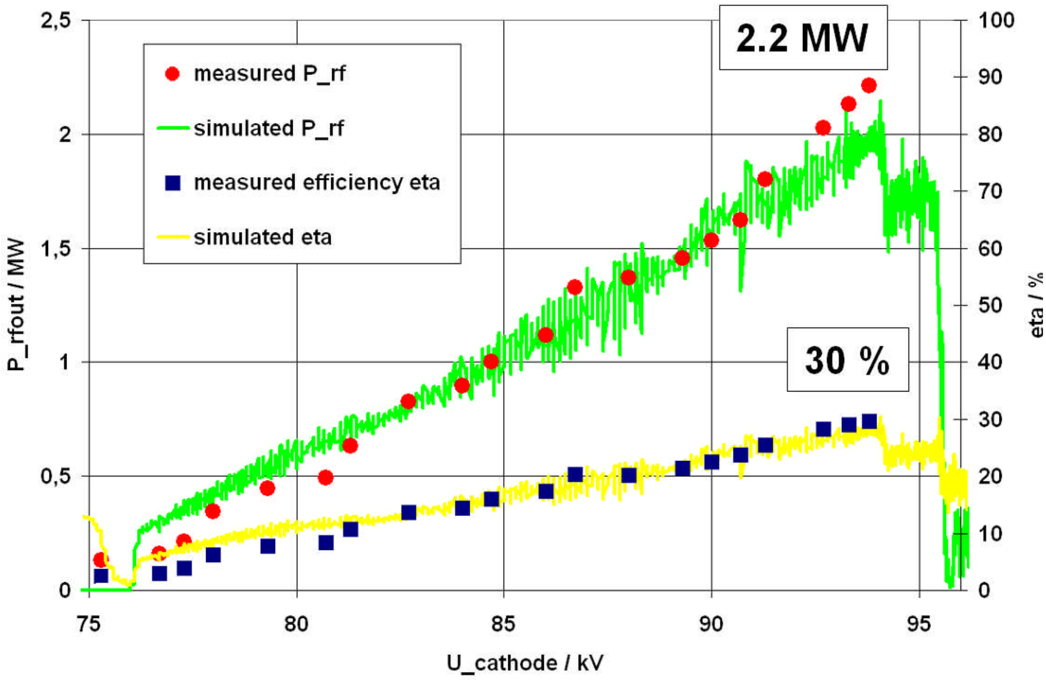

Fig. 2: RF output power and gyrotron efficiency vs. cathode voltage measured and calculated at nominal magnetic field (short pulse, non-depressed collector operation).

3. Operation with Modified Beam Tunnel and Nominal Magnetic Field

With these modifications the tube has been operated up to a beam voltage of U_c= 93 kV and a beam current I_b = 80 A. In agreement with expectations, the increase of the magnetic field by applying the NC-coil resulted in a shift of the excitation region of the $TE_{34,19}$ mode to higher values of cathode voltage. Around the nominal magnetic field value (6.87 T) a maximum RF output power $P_{out} \approx 2.2$ MW has been obtained at U_c=93 kV and I_b=80 A with an efficiency of ~30 % with pulse length of ~1 ms in non-depressed collector operation. The measured RF output power and efficiency versus the cathode voltage is shown in Fig. 2.

Figure 2 also contains the results of numerical simulations performed with the KIT multi-mode self consistent code using the experimental data as input and assuming a 5 % transverse velocity spread. The agreement between experiment and simulations is good if 10 % of the generated microwave power is assumed to be lost inside the gyrotron due to stray radiation, Ohmic losses and absorption in the RF output window (see Table II). The operation of the gyrotron with the modified beam tunnel resulted in a significant improvement of the stability and purity of single-mode generation over a very broad parameter range. No spurious parasitic oscillations excited

	Losses @ nominal mode	Total stray radiation
Spurious cavity modes ($TE_{n,19}$; n=36,35,33,32)	---	3 %
Ohmic losses of cavity and uptaper	2.2 %	---
Mode conversion losses of uptaper	0.2 %	0.2 %
Ohmic losses of launcher	1.8 %	---
Reflection of launcher	0.3 %	0.3 %
Stray radiation of launcher	0.7 %	0.7 %
Ohmic losses of 3 mirrors	0.5 %	---
Diffraction losses of 3 mirrors	1.1 %	1.1 %
Absorption losses of quartz window	3.3 %	---
Reflection of window	0.4 %	0.4 %
Total	**10.5 %**	**5.7 %**

Table II: Theoretical losses and internal stray radiation.

outside the gyrotron cavity could be found around the nominal parameters of the gyrotron. Due to the use of the new q.o. RF output system, the amount of stray radiation inside the tube has been reduced relatively to the previous launcher by about 14 %. Thus the total value of measured stray radiation losses was ~7 % (absolute measurement error about 2 %). The numerical multi-mode simulations suggest that nearly half of P_{stray} could result from modes, which are excited simultaneously with the $TE_{34,19}$ mode in the cavity. The theoretical balance of the gyrotron internal losses and of the stray radiation captured inside the gyrotron is shown in Table II. To verify these theoretical estimations more detailed investigations are planned.

Under certain operating conditions (U_c~60 kV and I_b>50 A), an LF oscillation has been observed at 112 MHz both with an antenna outside the tube, and on a capacitive probe placed at the end of the beam tunnel (just before the cavity). The frequency was constant over a wide parameter range within the accuracy of the measurements (~0.4 MHz). The oscillation often remained during only the initial part of the pulse length. There was some correlation between the intensity of this oscillation and the generated microwave power. The origin of these LF oscillations is unclear.

Recently the gyrotron output window has been replaced by a broadband silicon-nitride-Brewster-window supplied by NIFS, Japan, in order to be able to study the excitation of additional modes in the frequency range between 130-170 GHz. The capability of multi-frequency operation of the gyrotron could have significant advantage for both plasma heating and suppression of plasma instabilities in a thermonuclear reactor [5].

Simulations have shown that the q.o. output system with the new launcher has a good conversion efficiency to a Gaussian RF beam for a number of modes between 130-170 GHz [6]. The performance of the gyrotron and of the RF output system for selected modes around 140 GHz have been verified experimentally. The measurements have been concentrated on

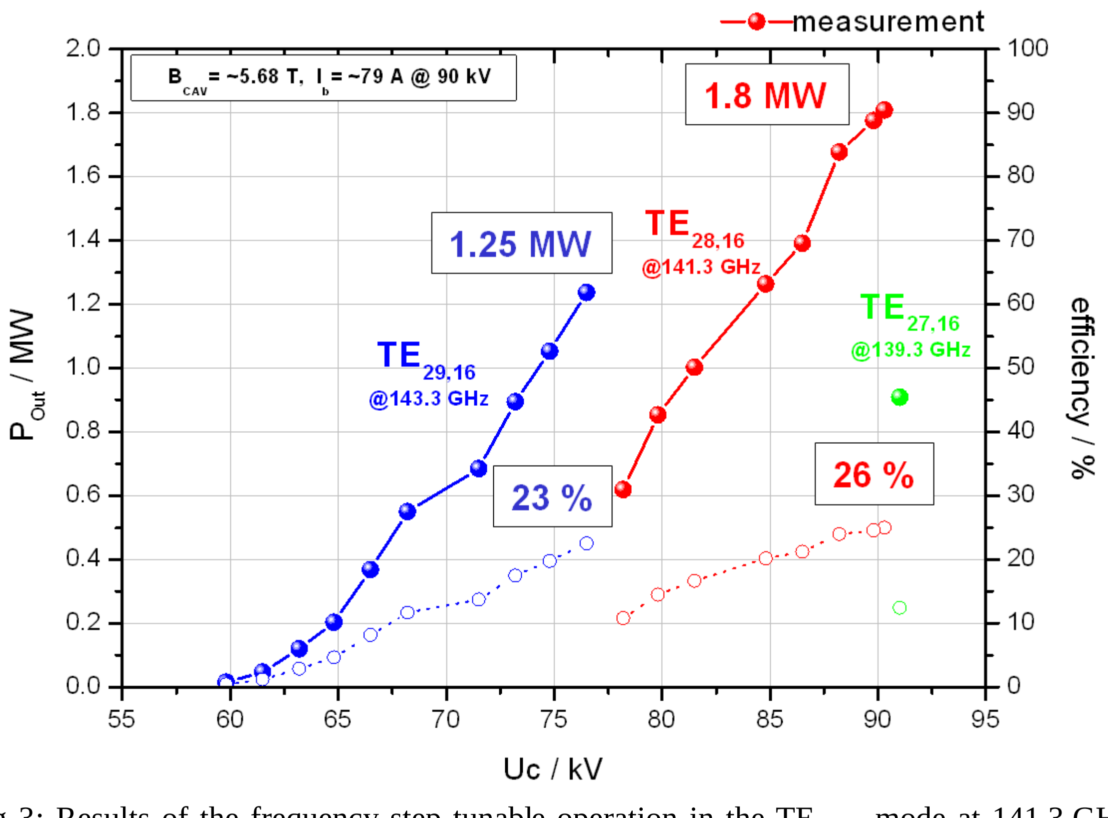

Fig 3: Results of the frequency-step tunable operation in the $TE_{28,16}$ mode at 141.3 GHz and $TE_{29,16}$ mode at 143.3 GHz.

the excitation of the $TE_{28,16}$ mode at 141.3 GHz. The achieved results are promising with respect to the generated RF power and efficiency as shown in Fig. 3.

As shown in Fig. 3 an output power of ~1.8 MW with an efficiency of 26 % has been obtained in the $TE_{28,16}$ mode at 141.3 GHz. In addition, 1.25 MW was generated in the $TE_{29,16}$ mode (the next azimuthal neighbour) at 143.3 GHz with 23 % efficiency. Measurements of the profile of the RF output beam with an infrared camera (see chapter 4) have confirmed the simulations given in [6] resulting in a very good efficiency of the new quasi-optical RF output system. The measured output powers in these experiments were limited by the internal gyrotron conditions, which could not be further improved due to lack of time. Since these modes were found to deliver above 2 MW in the simulation, we expect an increase of the output power in further experiments under optimized conditions.

4. Launcher and Quasi-Optical RF Output System

4.1 Design of the Launcher Antenna

One of the most critical components of the coaxial-cavity gyrotron is the q.o. RF output system. The general task of the q.o. system is to convert the RF power generated in the cavity mode into a free-space beam with a high content of the fundamental Gaussian mode. The q.o. RF system consists of a launcher antenna and three mirrors. To achieve an efficient coupling of the $TE_{34,19}$ mode into a free-space beam, we choose a launcher with a dimpled wall structure. The wall perturbations of a dimpled wall launcher produce a radiated field with a higher Gaussian mode content in comparison to a launcher with a smooth surface. In addition, the decreased amplitude of the microwave field at the cut of the launcher reduces the diffraction losses, limiting the amount of microwave stray losses inside the gyrotron tube.

In order to improve both the conversion efficiency and the RF beam quality, we have developed a novel optimization method based on the quasi-optical propagation theory of modes inside oversized waveguides. This approach has been successfully applied for the optimization of an improved launcher design [4]. The new code employs the solution of the scalar diffraction integral equation and performs a numerical optimization of the launcher surface to achieve a Gaussian-like field distribution at the last section of the launcher wall. As a result, a complicated surface contour is obtained which cannot be described by analytic functions. How-

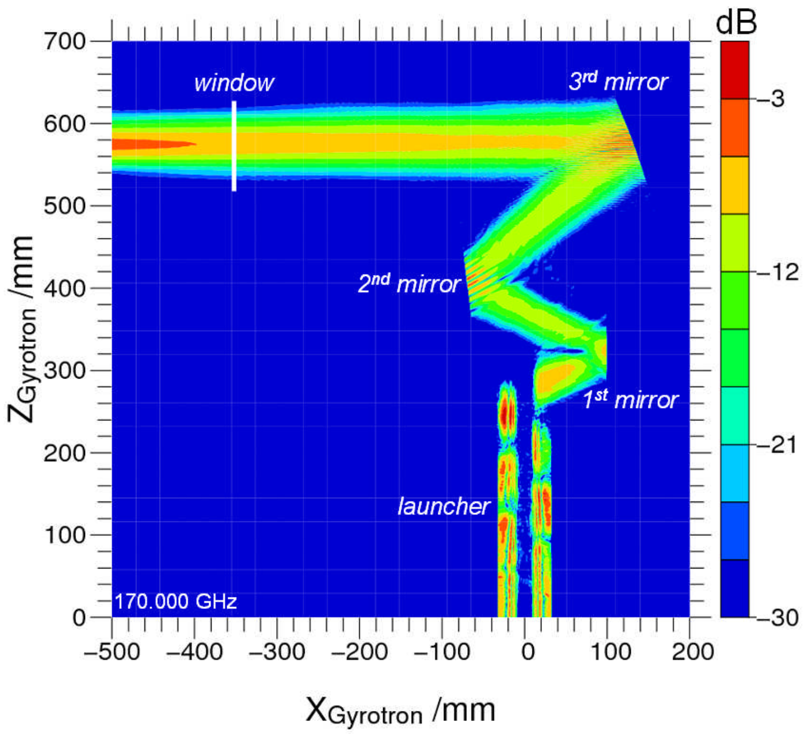

Fig. 4: Calculated microwave beam propagation in the improved RF output system.

ever, the manufacturing is technically feasible.

For the new improved design of the launcher antenna a suitable mirror system has been optimized. According to numerical simulations the improved q.o. RF system has an efficiency of ~96 % for the conversion from the cavity mode into a Gaussian beam. The design of the new mode converter has been successfully verified by using the SURF3D-code [7]. Furthermore, this code predicts the amount of microwave stray radiation losses trapped inside the gyrotron (Table II) caused by the main mode conversion process to be about 2 %. Fig. 4 shows the calculated RF beam propagation inside the gyrotron. In addition, the simulations show that the conversion performance of the new q.o. RF system remains high for several high order modes between 130 and 210 GHz with a caustic radius similar to the radius of the $TE_{34,19}$ mode. In particular, the Gaussian mode content obtained in the simulations was between 92 and 96 % [6].

4.2 Verification of the RF output system

To verify the theoretical efficiency of the new mode converter, low power cold-test measurements [8] have been done with the $TE_{34,19}$ mode at 170.325 GHz, the operating frequency of the mode exciter. Cold-test measurements have been taken at several positions inside and outside the q.o. RF output system (Fig. 5). The achieved results have been directly compared with the calculations. A very good agreement has been observed. The predicted efficiency of ~96 % of the mode converter has been confirmed by a Gaussian mode content analysis of the measured patterns performed at the position of the output window.

The final validation of the performance of the q.o. RF output system was made by measuring the intensity profile of the RF beam produced by the gyrotron (hot-test measurements). The intensity profile of the RF beam has been determined by measuring the temperature distribution on a PVC target after short RF beam pulses with an infrared camera

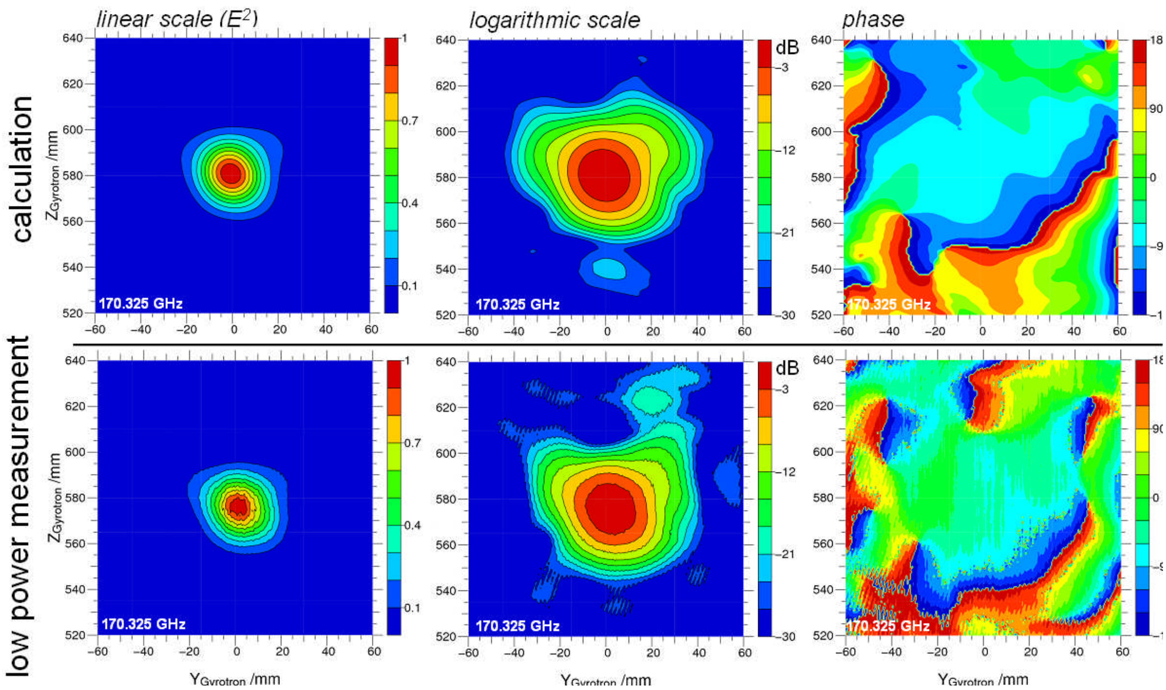

Fig. 5: Calculation (top) and low power measurement (bottom) of the RF beam profile at a distance of 500 mm from the gyrotron window.

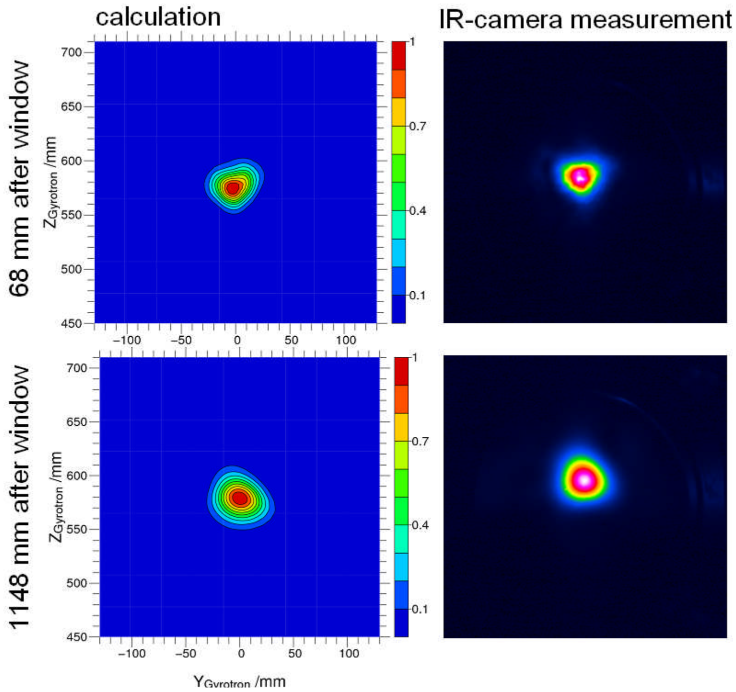

Fig. 6: Calculation (left) and high power measurement (right, using a PVC target and an IR camera) of the RF beam profile for gyrotron operation at 170 GHz in the $TE_{34,19}$ mode.

in order to be able to reconstruct the phase distribution of the RF beam. From the reconstructed phase distribution the Gaussian mode content can be evaluated. The measured profile of the "hot" RF beam has been found to be in very good agreement both with the simulations and with the results of cold-test measurements. As an example, Fig. 6 shows the hot-test measurements of the RF field profile and the simulated results at a distance of 68 mm and 1148 mm from the gyrotron window. From the phase reconstruction of the measured RF profiles a Gaussian mode content of ~96 % has been obtained at the window, which agrees with the simulation values. Furthermore, the hot-test measurements confirmed the simulated propagation of the microwave beam. The beam center shifts by only a few mm with respect to the window axis over a distance of about 1 m.

Similar measurements of the RF beam profile have been performed for the $TE_{28.16}$ mode at 141.3 GHz. The measurements are in good agreement with calculations, the Gaussian mode content was > 92% (to be compared with 95% from calculations).

5. Summary and Conclusions

Significant progress has been made on recent investigations of the improved short pulse 2 MW, 170 GHz coaxial-cavity gyrotron at KIT. RF-parasitic oscillations around ~150 - 160 GHz have been successfully suppressed by modifying the beam tunnel. The modification destroyed the azimuthal symmetry by introducing irregular longitudinal corrugations in the copper rings. As a result of these changes, a single-mode operation was considerably improved. The magnetic field was increased to the nominal value (~6.87 T) by using an additional normal conducting coil, which allows us to test the pre-prototype tube at a similar operation point as the industrial CW gyrotron. At the design parameters, a record RF output power of 2.2 MW has been achieved, with an efficiency of ~30 % (without depressed collector). A novel q.o. RF output system has been designed based on a new launcher. We have obtained an RF output beam with excellent quality (Gaussian mode content of ~96%) using this system with the gyrotron. The results of hot- and cold-test measurements have been found to be in very good agreement with the simulations. The amount of stray losses inside the tube is reduced in comparison to the previous system. In particular, a total amount of ~7 %

has been measured in comparison to 8 % with the previous q.o. output coupler. Efficient operation of the gyrotron at several frequencies and corresponding operating modes has been demonstrated. Particularly, the $TE_{28.16}$ mode has been generated at 141.3 GHz with an output power of 1.8 MW, corresponding to an efficiency of 26%. The next azimuthal neighbour, the $TE_{29,16}$ mode, produced 1.25 MW at 143.3 GHz with an efficiency of 23 %. The quality of the RF output beam was very good for both modes. Besides other investigations, we plan to further study the operation of the pre-prototype at different frequencies. The output beam patterns of these modes will be measured, and we expect an increase of the power in these modes above 2 MW.

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