2.2 MW Record Power of the 0.17 THz European Pre-Prototype Coaxial-Cavity Gyrotron for ITER

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Abstract: A 2 MW, CW, 0.17 *THz* 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 of several 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 (former FZK, Karlsruhe) for experimental verification of the design of critical components, like the electron gun, beam tunnel, cavity and quasi-optical (q.o.) mm-wave output coupler. Recently a significant progress has been achieved which will be reported here after a general introduction to the principles of gyrotrons. In particular, an output power of up to 2.2 *MW* with 30 % output efficiency (non-depressed collector operation) has been obtained in single-mode operation at 0.17 *THz*. Further on, with a newly designed mm-wave output coupler an efficient conversion of the generated mm-wave power into a fundamental Gaussian output beam, with a Gaussian mode content of almost 96 %, has been successfully performed. Recently, the narrow-band fused silica output window has been replaced by a broadband SiN Brewster window in order to be able to study the excitation of additional modes in the frequency range between 0.13 and 0.17 *THz* (tunable multi-frequency gyrotron). In first experiments an output power of 1.8 *MW* with an efficiency of 26% has been obtained in the $TE_{28,16}$ mode at 0.1413 *THz*. In addition, in the next azimuthal neighbor mode $TE_{29,16}$ at 0.1433 *THz*, an output power of 1.25 *MW* has been generated with an efficiency of 23%. Measurements of the power profiles of the mm-wave output beams have confirmed numerical simulations resulting in a very high efficiency and good mode purity of the q.o. output coupler also for these other frequencies and modes.

Keywords: Gyrotron, coaxial cavity, quasi-optical output coupler, frequency step tuning, parasitic oscillations, electron cyclotron heating and current drive of thermonuclear fusion plasmas

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1. General introduction

Conventional microwave tubes operate with longitudinal phase bunching of the interacting electrons and are commonly referred to as slow-wave devices, since in some way, the RF structure is configured such that the phase velocity of the electromagnetic (EM) wave is slowed down to be a little bit lower than the electron beam velocity and is thus less than the velocity of light. This is most evident in the helix-type travelling wave tube (TWT) and backward wave oscillator (BWO) where the transverse RF circuit dimensions are typically a fraction of the wavelength. The dimensions of the interaction circuits of klystrons, extended interaction tubes, magnetrons and cross-field amplifiers also have dimensions in the order of the wavelength or smaller. The inherent power limitation with these conventional microwave tubes is the tremendous decrease in the dimensions of the interaction structure with increasing frequency. Therefore, the possibility of extracting high average power in the mm-wavelength range has been ruled out. In the case of far-infrared LASERs the possible average power decreases with increasing wavelength since the energy between the interacting quantum levels (hf = 0.41 *meV* at 0.1 *THz*) becomes much smaller than the thermal energy at room temperature (kT = 25 *meV*). To close the gap for the achievable average output power in the mm- and sub-mm wavelength range, different interaction mechanisms had to be discovered, which operate in highly overmoded circuits, that means in fast wave circuits where the electron beam is placed well away from the RF structure. With larger dimensions, the power-handling capability is enlarged. Since fast waves have a phase velocity that is larger than the velocity of light, the phase bunching mechanism must be generated by a transverse interaction (stimulated emission of bremsstrahlung), e.g. (a) the electron-cyclotron interaction in a longitudinal magnetic field ("electron cyclotron maser": ECM) or (b) the electron undulation in a wiggler field ("free-electron laser": FEL).

The origin of the ECMs traces back to the late 1950s: Richard Twiss in Australia, Jürgen Schneider in the USA and Andrei Gaponov in Russia. The predominance of the fast-wave ECM resonance with its azimuthal bunching in producing microwaves was experimentally verified in the mid-1960s in the USA (where the term "electron cyclotron maser" was apparently coined) and in Russia (where the term "gyrotron" was introduced). Each conventional linear-beam device (monotron, klystron, TWT, twystron, BWO) has a corresponding gyro-device. The history and state-of-the-art of gyro-devices and microwave free electron lasers (masers), including more than 900 references, is summarized in [1,2].

Gyrotron oscillators (gyro-monotrons or just gyrotrons) were the first ECMs to undergo major development. In September 1964 scientists at IAP Nizhny Novgorod, RAS, operated the first gyrotron (TE101 rectangular cavity, power: 6 *W*, CW, 10 *GHz*). Increases in device power were the result of Russian developments from the early 1970s in temperature limited magnetron injection guns (MIGs), which produce hollow, helical electron beams with the necessary transverse energy and in tapered, open-ended waveguide cavities that maximize efficiency by tailoring the electric field distribution in the resonator.

The condition for stimulated coherent bremsstrahlung generation is satisfied if a bunching mechanism exists to create electron density variations of a size comparable to the wavelength of the imposed EM wave. To achieve such a mechanism, a resonance condition must be satisfied between the periodic motion of the electrons and the EM wave (TE mode) in the interaction region

$$\omega - k_z v_z \cong s\Omega\,, \quad s = 1, 2, ... \quad (k_z v_z = \textit{Doppler term}) \tag{1}$$

where ω and k_z are the angular frequency and characteristic axial wavenumber, respectively, v_z is the translational electron drift velocity, Ω is an effective frequency, which is associated with the macroscopic oscillatory motion of the electrons, and *s* is the harmonic number of the interaction.

The EM energy is radiated by relativistic electrons gyrating in an external longitudinal magnetic field. The effective frequency Ω corresponds to the relativistic electron cyclotron frequency $\omega_c = \Omega$:

$$\omega_c = \Omega_{co} / \gamma \quad \text{with} \quad \Omega_{co} = eB_{cav} / m_0 \quad \text{and}$$

$$\gamma = [1-(v/c)^2]^{-1/2} = 1 + eU_c / m_0 c^2 = 1 + eU_c / 511 \tag{2}$$

where *-e* and m_o are the charge and rest mass of an electron, γ is the relativistic factor, B_{cav} is the magnitude of the cavity magnetic field and U_c is the acceleration voltage in *kV*. The nonrelativistic electron cyclotron frequency is f_o/THz = 0.028 B_{cav}/T. Bunching is achieved because, as an electron loses energy, its relativistic mass decreases and it thus gyrates faster. The consequence is that a small amplitude wave's electric field, while extracting energy from the particles, causes them to become bunched in gyration phase and reinforces the existing wave electric field.

Gyrotrons are devices which usually utilize only weakly relativistic electron beams ($U_c <$ 100 *kV*, $\gamma < 1.2$) with high transverse momentum (velocity ratio $\alpha = v_\perp / v_z > 1$). The wavevector of the EM wave in the cavity is almost transverse to the direction of the external magnetic field ($k_\perp >> k_z$, and the Doppler shift is small) resulting, according to eqs. (1) and (2), in radiation near the relativistic electron cyclotron frequency or one of its harmonics:

$$\omega \cong s\Omega_c ,\, s = 1, 2, ... \tag{3}$$

In the case of cylindrical cavity tubes the operating mode is close to cutoff ($v_{ph} = \omega / k_z >> c$) and the frequency mismatch $\omega - s\Omega_c$ is small but positive in order to achieve correct phasing, i.e. keeping the electron bunches in the retarding phase. The Doppler term $k_z v_z$ is of the order of the gain bandwidth and is small compared with the radiation frequency.

The diameter *D* of the cavity is approximately given by

$$D / mm \approx 0.095427 \frac{X_{m,n}}{f_c / THz} \tag{4}$$

where $X_{m,n}$ is the nth root of the derivative of the corresponding Bessel function (TE_{mn} mode) and $f_c = \omega_c/2\pi$. In contrast to slow-wave devices, the resonance frequency of the TE_{mn} mode gyrotron cavity is not determined by the characteristic size but by the strength of the cavity magnetic field. According to eq.(4), the operating higher order mode can be selected by the cavity diameter. Gyrotrons are capable of producing very high power radiation at cm-, mm and sub-mm wavelengths since the use of large waveguide or cavity cross sections reduces wall losses and breakdown restrictions, as well as permitting the passage of larger, higher power electron beams. Single-stage depressed collectors (SDC) for electron energy recovery increase the overall efficiency typically to approximately 50% and even above [1,2].

Gyrotrons are foreseen as microwave sources for electron cyclotron heating (ECH), current drive (CD) and stabilization of plasmas in the International Thermonuclear Experimental Reactor (ITER). First plasma experiments in ITER are planned to begin in 2018 [3]. At that time, the ITER microwave system is expected to have an installed RF power of 24 *MW* at 0.17 *THz*, practically in continuous wave (CW) operation in order to deliver 20 *MW* power into the plasma. The delivery of the gyrotrons is equally shared between Japan [4], Russia [5] and EU [6]. To fulfill the needs of ITER "conventional" 1 *MW* gyrotrons with a hollow waveguide cavity are under development in Japan and Russia.

However, in order to keep the number of the required gyrotrons and magnets as low as possible, to reduce the costs of the ITER 24 *MW*, 0.17 *THz* ECRH system and to allow four compact upper launching antennas for plasma stabilization, higher mm-wave power per tube (2*MW*) is desirable. Demands for upgrading the heating power for the further operation of ITER up to ~40 *MW* are already now under discussion. Cylindrical waveguide gyrotron cavities are not suitable for this high frequency, high power regime because of high Ohmic wall losses and/or mode competition problems. However, in coaxial resonators the existence of the longitudinally corrugated inner conductor reduces the problems of mode competition and limiting current, thus allowing one to use even higher order modes with lower Ohmic attenuation than in cylindrical resonators [7]. In addition, the inner rod enables a specific voltage depression scheme for energy recovery and ultra-fast frequency step tuning just by applying an appropriate voltage to this coaxial insert. CVD-diamond windows with a transmission capability of 2 MW, CW are feasible [1].

A European 2 *MW*, CW, 0.17 *THz* coaxial-cavity gyrotron for use in ITER is being developed within the EU gyrotron consortium EGYC [6,7]. The parameters of this gyrotron are described in Chapter 2. In the following, experimental observations and achieved results will be reported. First, in Chapter 3 the occurrence of parasitic low frequency (LF) oscillations will be described and its suppression will be discussed. In Chapter 4 results of microwave generation and problems with parasitic high frequency oscillations, which probably were generated inside the beam tunnel between the electron gun and the coaxial cavity, will be reported followed by the record results achieved with the upgraded tube. Recently, a newly designed launcher has been tested very successfully at low power and in the gyrotron. The results will be presented and discussed in Chapter 5.

2. Parameters of the 0.17 THz coaxial-cavity gyrotron

The design specifications for the European (EU) 0.17 *THz*, 2 *MW*, CW coaxial-cavity gyrotron for the 24 *MW* (installed) ECH&CD system on ITER are summarized in Tab. 1. The coaxial arrangement reduces mode competition in the gyrotron interaction cavity. Thus with cavity modes of very high order χ (eigenvalue >100) stable single-mode operation can be obtained in the multi-megawatt output power range.

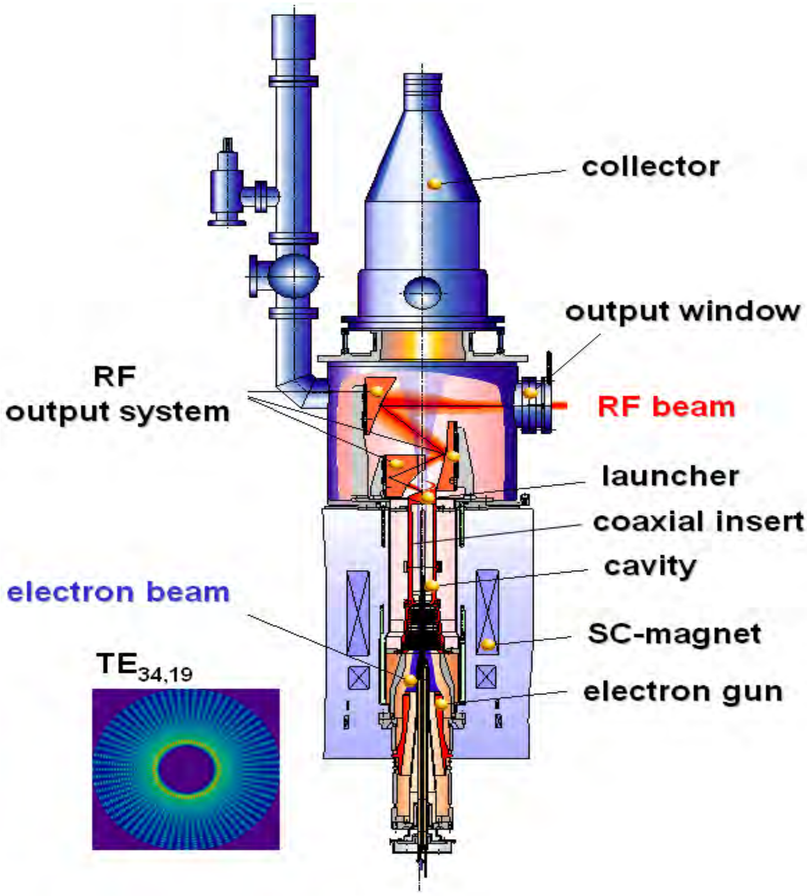

Fig. 1 Short-pulse 0.17 *THz*, 2 *MW* coaxial-cavity gyrotron at KIT (pre-prototype tube).

Operating cavity mode	$TE_{34,19}$
Frequency, f	0.17 THz
Mm-wave 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 %

Tab. 1 Design specifications for the 0.17 *THz* European coaxial-cavity gyrotron for ITER.

However, a consequence of the use of high-order volume modes is among other things, the significant increase of the complexity of the antenna launcher of the quasi-optical (q.o.) mm-wave output coupler which is needed for conversion of the very high order coaxial-cavity mode into the fundamental free space Gaussian mode.

A first industrial prototype of a CW coaxial-cavity gyrotron, which was manufactured at Thales Electron Devices (TED) in France, has already been tested at CRPP Lausanne [6]. Mainly problems with the high voltage stability did not allow to operate the gyrotron at nominal parameters. As a consequence of this an output power of only 1.4 *MW* (instead of 2 *MW*) has been achieved. The reason for the limitations was not clear and is under investigation. To support the activities on the industrial prototype, experimental studies on a short pulse (≤ few *ms*) experimental 0.17 *THz* coaxial-cavity gyrotron ("pre-prototype") are performed at KIT (Fig. 1). The pre-prototype tube utilizes the same TE34,19-cavity mode and the same cavity with up-taper, launcher and mirrors as designed for the industrial prototype and in addition, it uses a very similar temperature limited coaxial magnetron injection electron gun (MIG) and a similar beam tunnel. Therefore the performance of the gyrotron and its main components - electron gun, beam tunnel, coaxial cavity and q.o. mm-wave output coupler – can be studied under fairly relevant conditions and unexpected problems can be discovered and investigated sufficiently in advance.

Due to the technical limitation of the superconducting (SC) magnet in use at KIT, the gyrotron was first operated at a reduced magnetic field of approximately 6.7 *T* and, in order to be able to excite the TE34,19 mode at 0.17 *THz*, also at a beam voltage below 80 *kV*. Owing to this a reduced value of the generated mm-wave output power around 1.5 *MW* was expected. To be able to operate the short-pulse pre-prototype under the same conditions as the industrial tube, a normal conducting (NC) coil has been wound directly on the housing of the gyrotron around the position of the cavity. This allows to increase the magnetic field up to the nominal value of 6.87 *T*. Thus the main nominal parameters, shown in Tab. 1, are the same for the TED 2 *MW*, CW industrial prototype and for the KIT pre-prototype tube.

3. Parasitic low frequency oscillations

When the 0.17 *THz* coaxial pre-prototype gyrotron was operated first, the operation was strongly limited due to the excitation of parasitic low frequency (LF) oscillations mainly around 265 *MHz* (Fig. 2). The LF oscillations have been excited inside the tube with very high intensity above beam currents I_b>10 *A* and beam voltages $U_c \gtrsim 40 kV$. Under certain conditions an additional frequency around 332 *MHz* has been observed at somewhat reduced power level.

To study the mechanism of these parasitic LF oscillations, the detailed geometry of the complete gyrotron as installed in the superconducting magnet has been simulated using the 3D code CST Microwave Studio [8]. The simulations resulted in two resonances with frequencies at 267 *MHz* and 339 *MHz* in very good agreement with the experiment. The calculated field distribution at the two resonances has shown that in both cases a very strong concentration of the LF field near the cathode exists (Fig. 3). Due to the interaction of the emitted electrons in the cathode region with the LF field the velocity of the electrons is modulated. This results in a longitudinal bunching of the electron beam. Taking into account

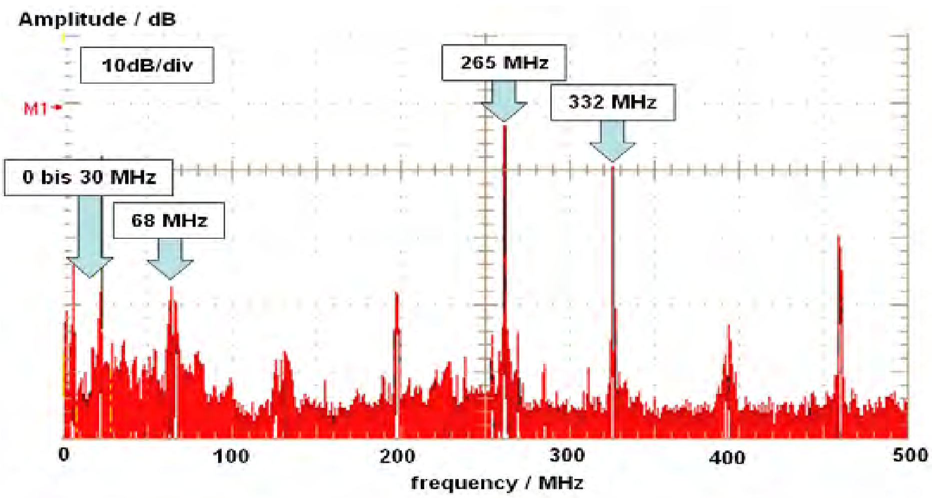

Fig. 2 Measured spectrum of the parasitic low frequency (LF) oscillations.

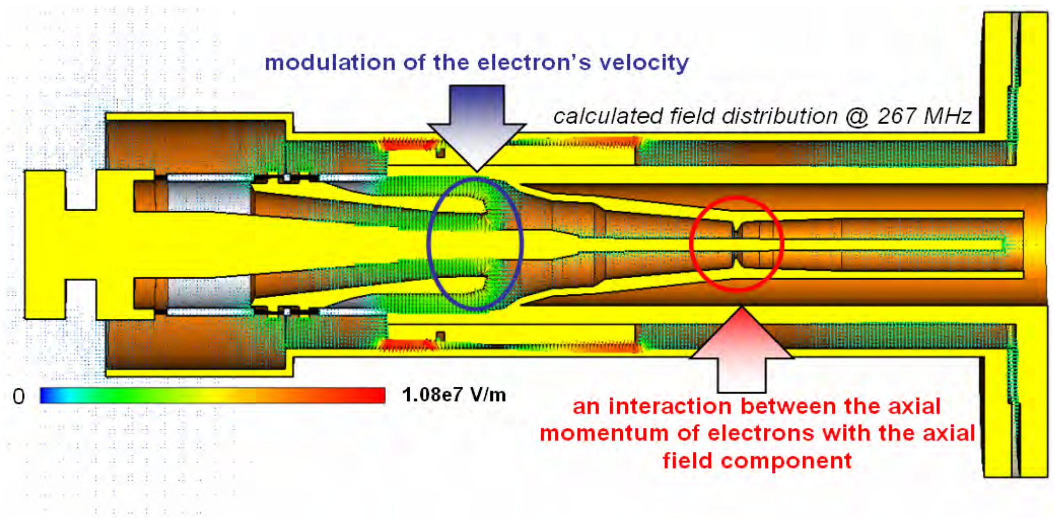

Fig. 3 Calculated field distribution at 267 *MHz* – regions responsible for the excitation of the parasitic oscillation are indicated.

the transit time of the electrons and the calculated distribution of the LF fields, two possible regions of interaction have been found in which an energy transfer between the axially bunched electron beam and the LF field is possible, namely on the cathode side of the coaxial cavity and at the end of the coaxial insert in the q.o. launcher. A detailed analysis has shown that both resonances can be excited due to interaction of the bunched electron beam with the LF field at the cathode side of the coaxial cavity. At this position a radial step in the geometry of the insert resulted in an axial component of the LF field, which can interact with the bunched electron beam. An energy transfer due to interaction of the electron beam with the LF field at the end of the coaxial insert was not possible because of the transit time. Based on this hypothesis the radial step in the geometry of the coaxial insert has been removed. Owing to these modifications, a significant reduction of the level of the LF oscillations has been found in measurements. In particular, the corresponding starting current for excitation of the LF oscillations increased to a value of about 40 *A*. In order to completely suppress these unwanted oscillations an absorber has been placed near the oil tank around the gun in order to reduce the quality factor of the resonances inside the gyrotron structure. The absorbing structure consists of a metallic cylinder filled with the damping material Eccosorb. By these actions the parasitic LF oscillations around 300 *MHz* have been suppressed completely.

4. Millimeter-wave power generation

4.1 Operation at reduced cavity magnetic field, B_{cav} =6.7 *T*

Numerous experiments with the pre-prototype gyrotron have been performed at a reduced magnetic field (~6.72 *T*) due to the technical limitation of the superconducting (SC) magnet in use at KIT. In these experiments stable single-mode operation at 0.17 *THz* could be excited up to a beam voltage around 73 *kV* with a maximum mm-wave output power Pout around 1.1 *MW*. Under certain conditions a value of Pout almost 1.4 *MW* has been obtained at I_b=71 *A* with an output efficiency of approximately 26 % (without SDC). Fig. 4 shows the output power in dependence of the cathode voltage Uc obtained in two experimental sessions in July and October 2008. As is shown in this figure, the mm-wave output power of around 1.4 *MW* measured in July 2008 could not be reproduced in the experiments in October 2008. In both experiments parasitic frequency (RF) oscillations in a frequency range between 0.152 and 0.160 *THz* have been observed. However, the parasitic RF oscillations started in the October experiment already at U_c~72 *kV*, about 2 *kV* below the value observed in the July experiment. The occurrence of the parasitic RF oscillations, which are assumed to be excited in the beam tunnel, seem to be responsible for the reduction of the gyrotron performance. There are indications that the starting voltage of the parasitic oscillations decreases with increasing beam current (Fig. 4). A similar type of parasitic RF oscillation has been observed in the conventional-cavity 1 *MW*, 0.14 *THz* gyrotrons for the 10 *MW* ECH system of the stellarator W7-X. In these gyrotrons both the value of the parasitic frequency and the observed damage of the beam tunnel after long-pulse operation suggest that the RF parasites are generated inside the beam tunnel [9]. The original beam tunnel used in the coaxial-cavity gyrotron is similar to the beam tunnel of the conventional cavity gyrotrons and consists of circular copper rings stacked together with lossy ceramic rings in between [10].

4.2 Operation with improved beam tunnel at nominal cavity magnetic field, B_{cav} =6.87 *T*

Recently the following modifications have been performed on the pre-prototype gyrotron:

(1) Since the SC gyrotron magnet in use at KIT limits the maximum value of the cavity magnetic field to around 6.7 *T*, an additional normal conducting (NC) coil has been wound directly on the gyrotron body near to the cavity in order to increase the cavity magnetic field to the nominal value of 6.87 *T*. Further on, the shape of the anode of the coaxial magnetron injection electron gun (MIG) has been redesigned to generate velocity ratio α = 1.3 at the nominal operating parameters (90 *kV*, 75 *A*, 6.87 *T*).

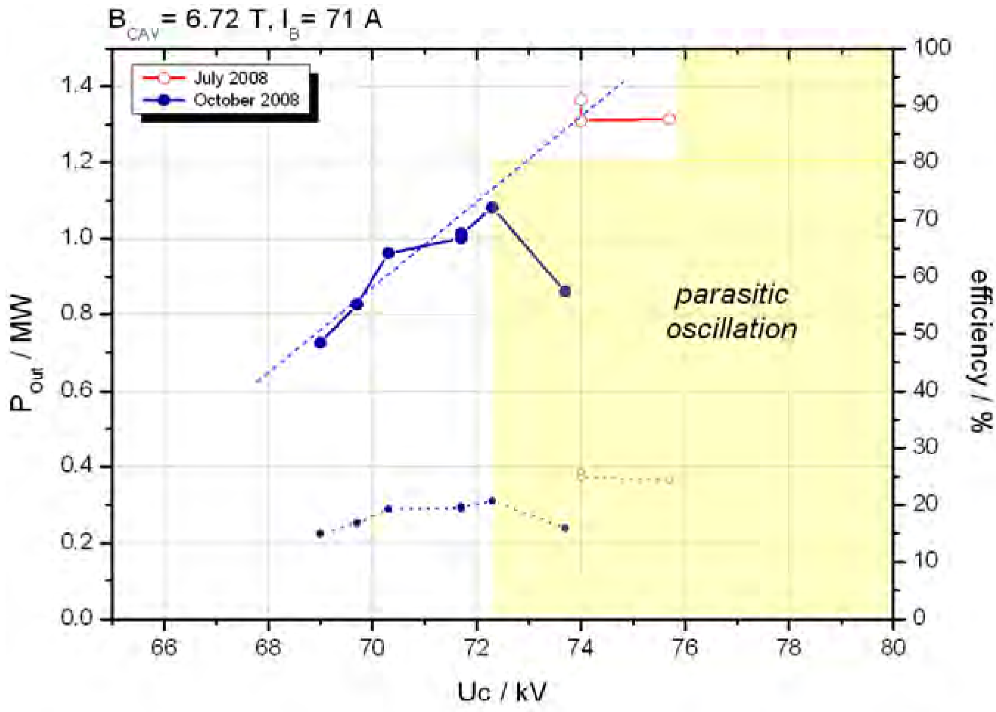

Fig. 4 Measured gyrotron output power and efficiency vs. cathode voltage at reduced cavity magnetic field. Destructive influence of parasitic oscillations around 0.16 *THz* to 0.17 *THz* on the power generation in the coaxial cavity has been observed during the experiment.

(2) To suppress the parasitic RF oscillations a novel beam tunnel has been designed, fabricated and installed in the tube (Fig. 5). The main modification in this new beam tunnel consists in introducing irregular corrugations (longitudinal slots) in the copper rings, in order to destroy the azimuthal symmetry and thus to suppress circular symmetric electric modes which were only weakly attenuated in the former azimuthally symmetric beam tunnel structure. Further on, the arrangement of the ring structure is conical in difference to a stepwise cylindrical arrangement of the previous beam tunnel.

(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 [10]. Before installation in the gyrotron the new q.o. mode converter has been verified in “cold” measurements as described in the next Chapter.

Experiments performed with the modified gyrotron showed a very stable operation of the tube up to U_c= 93 *kV* and 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

TE34,19 mode to higher values of cathode voltage. Around the nominal magnetic field value (6.87 T) a maximum mm-wave output power Pout ≈ 2.2 *MW* has been obtained at U_c= 93 *kV* and I_b=80 *A* with an efficiency of around 30% with 1 ms pulse duration in non-depressed collector operation. If a CVD-diamond window would be installed instead of the fused silica window, the output power would be 2.3 *MW* at an efficiency of 31% due to lower mm-wave absorption in diamond.

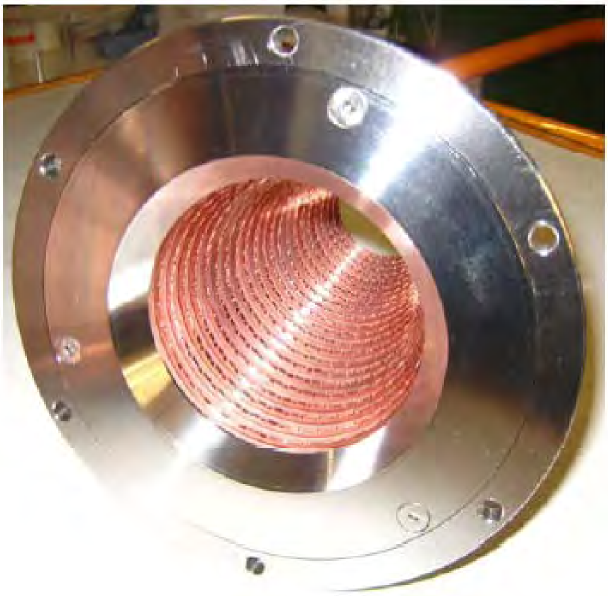

Fig. 5 Photo of the new beam tunnel with irregularly longitudinally corrugated copper rings.

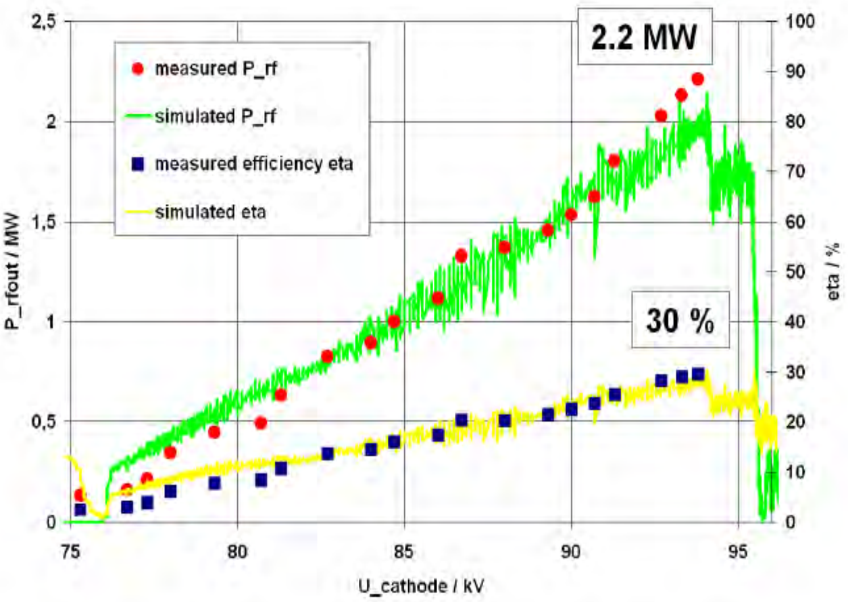

Fig. 6 Measured and calculated gyrotron output power and efficiency vs. cathode voltage at the nominal magnetic field of 6.87 *T*.

The measured mm-wave output power and efficiency versus the cathode voltage is shown in Fig. 6. The figure also contains the results of numerical simulations performed with the KIT multi-mode, self consistent code SELFT taking into account 5 % transverse electron velocity spread. The agreement between experiment and simulations is very good if approximately 10 % of the generated output power in the nominal mode is assumed to be lost inside the tube due to stray radiation, Ohmic losses and absorption in the output window (see Tab. 2). The operation of the gyrotron with the modified beam tunnel resulted in a significant improvement of the stability and single-mode generation over a very broad parameter range. No parasitic oscillations excited outside the gyrotron cavity could be found at the nominal parameters of the gyrotron. Due to the use of the new q.o. mm-wave output system, the amount of stray radiation inside the tube has been reduced to P_{stray} ~(7±2)% of the output power Pout, to be compared with (8±2)% with the previous launcher. The numerical multi-mode simulations suggest that approximately 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 internal losses and the stray radiation captured inside the tube is shown in Tab. 2. To verify these theoretical estimations more detailed investigations are planned.

	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 %**

Tab. 2 Estimated relative internal mm-wave losses and internal stray radiation.

Under certain operating conditions ($U_c \approx 60$ *kV* and $I_b > 50$ *A*) a LF oscillation at 112 *MHz* has been observed both with an antenna outside the tube and 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 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. However, the excitation mechanism seems to be different from the LF oscillations described in Chapter 3. In particular, no destructive influence of these LF oscillations on the gyrotron efficiency has been observed. Furthermore, measurements have shown that no modulation of the main design frequency at 0.17 *THz* has been observed like in the 0.105-0.143 *THz* multi-frequency gyrotron at KIT [10]. This result suggests that the oscillation is generated in the region after the cavity. The excitation mechanism of the 112 *MHz*-oscillation requires further investigation.

Recently the gyrotron output window has been replaced by a broadband silicon-nitride Brewster window supplied by NIFS in Japan in order to be able to study the excitation of additional modes in the frequency range between 0.13-0.17 *THz*. The capability of multi-frequency operation of the gyrotron could have significant advantage in application both for plasma heating and suppression of plasma instabilities in a fusion reactor [12]. Simulations have shown that the q.o. output coupler with the new launcher has a good conversion efficiency for a number of modes between 0.13 and 0.17 *THz* [13]. In first experiments the excitation of modes around 0.14 *THz* has been investigated. The measurements have been concentrated on the excitation of the $TE_{28,16}$ mode at 0.1413 *THz*. The achieved results are promising with respect to the generated mm-wave power and efficiency as shown in Fig. 7.

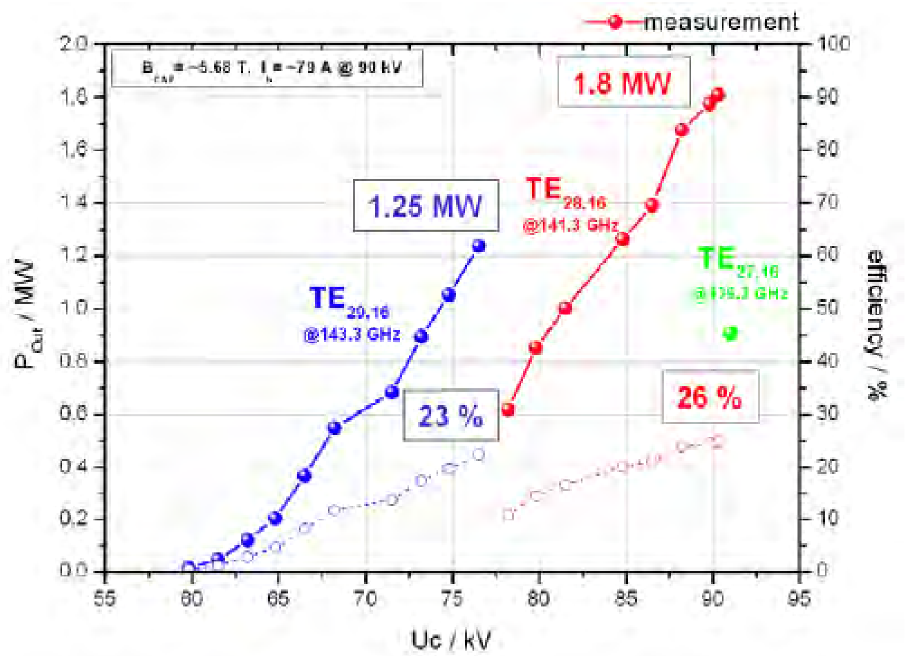

Fig. 7 Measured output powers and efficiencies vs. cathode voltage during frequency-step tunable operation in the $TE_{28,16}$ mode at 0.1413 *THz* and the $TE_{29,16}$ mode at 0.1433 *THz*.

As shown in Fig. 7 an output power of 1.8 *MW* with an efficiency of 26 % has been obtained in the $TE_{28,16}$ mode at 0.1413 *THz*. In addition, in the $TE_{29,16}$ mode at 0.1433 *THz* (the next azimuthal neighbor) an output power of 1.25 *MW* with 23 % efficiency has been generated. The measurements of the profile of the mm-wave output beam with an infrared camera (see Chapter 5) have confirmed the simulations resulting in a very good efficiency of the new quasi-optical output coupler. The measured output powers in these experiments were limited by the vacuum conditions, which could not be further improved due to lack of time. Since in simulations for all investigated modes output powers above 2 *MW* have been found, a further increase in measured powers in the coming experiments is expected.

5. Quasi-optical coaxial-cavity gyrotron output coupler

5.1 Improved design of the waveguide antenna launcher

One of the most critical components of the coaxial-cavity gyrotron is the q.o. mm-wave output coupler. The general task of the q.o. system is to convert the mm-wave power generated in the very high order cavity mode into a free-space beam with a high content of the fundamental Gaussian mode. The q.o. system consists of a launcher antenna and three mirrors. To achieve an efficient coupling of the $TE_{34,19}$ cavity mode into a free-space beam, a launcher with a perturbed wall structure has been chosen. Due to the wall perturbations the Gaussian mode content of the field radiated from the launcher cut is increased in comparison to a launcher with a smooth inner waveguide surface. In addition, the decreased amplitude of the mm-wave field at the cuts of the launcher reduces the diffraction losses and thus results in a decrease of the mm-wave diffraction losses which leads to stray radiation inside the gyrotron tube.

In the past the conversion efficiency of the mm-wave system from the cavity mode to the fundamental "Gaussian" $TEM_{0,0}$ mode was not satisfactory, namely only about 80 %. In addition, the amount of internal stray radiation losses was as much as (8±2)% of the mm-wave output power. The poor performance of the q.o. system is due to the fact that for the $TE_{34,19}$ mode with a ratio of the caustic to cavity radius of about 0.3 a high conversion efficiency of the launcher cannot be obtained with acceptable length by using the traditional method [14] employing the coupled-mode equation theory. Therefore, in order to improve both the conversion efficiency and the mm-wave beam quality a novel optimization method based on the quasi-optical propagation theory of modes inside oversized waveguides has been developed and recently successfully applied for the optimization of an improved launcher design [11]. The new code employs the scalar diffraction integral equation and performs an iterative numerical optimization of the inner launcher surface to achieve a Gaussian-like field distribution at the last section of the launcher wall. As result a very complicated surface contour is obtained, which cannot be described by analytic functions. However, the manufacturing is technically feasible. The launcher can be seen as an in-waveguide line of mode-converting and phase-correcting mirrors with non-quadratic surface contour function.

Based on the new improved design of the waveguide antenna launcher a suitable mirror system has been optimized. According to numerical simulations the improved q.o. output coupler has an efficiency of approximately 97% for the conversion from the coaxial-cavity mode into a free space Gaussian beam. The design of the new mode converter has been successfully verified by using the SURF3D code for analysis [15]. Further on, with this code the amount of mm-wave stray radiation losses captured inside the gyrotron (see Tab. 2) caused by the mode conversion process has been calculated to be about 2 %. Fig. 9 shows the calculated mm-wave beam propagation inside the gyrotron.

In addition, the conversion performance of the q.o. output coupler has been simulated for several very high order modes between 0.13 and 0.21 *THz* with the result, that the conversion efficiency is very high for modes with a caustic radius similar to the caustic radius of the

$TE_{34,19}$ mode. In particular, the Gaussian mode content obtained in the simulations was between 90.3 and 96.3 % [13].

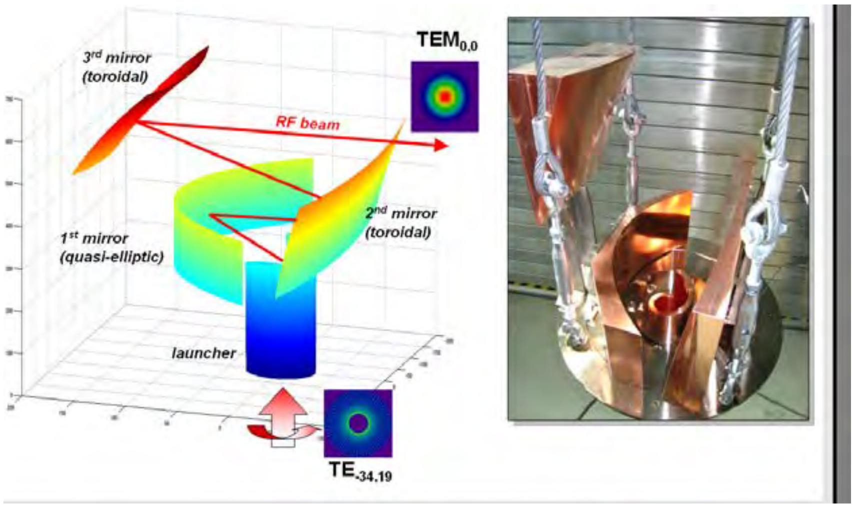

Fig. 8 Quasi-optical mm-wave output coupler of the coaxial-cavity gyrotron.

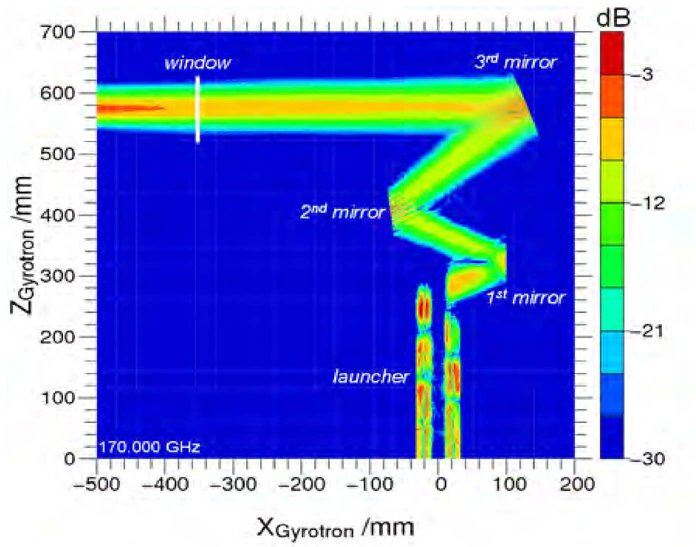

Fig. 9 Millimeter-wave beam propagation in the improved q.o. output coupler calculated with the SURF3D code [15].

5.2 Verification of the improved quasi-optical mm-wave output coupler

To verify the theoretical efficiency of the new mode converter low power "cold" measurements have been done for the $TE_{34,19}$ mode at 170.325 *GHz* (operating frequency of the low power mode generator at KIT) with an experimental arrangement described in [16]. "Cold" measurements have been performed at several positions inside and outside the q.o. output coupler (Fig. 10-11). The achieved results have been directly compared with calculations. A very good agreement has been observed. The high conversion efficiency of the q.o. mode converter of almost 97 % has been confirmed by a Gaussian mode content analysis of the measured patterns performed at different distances from the position of the gyrotron window.

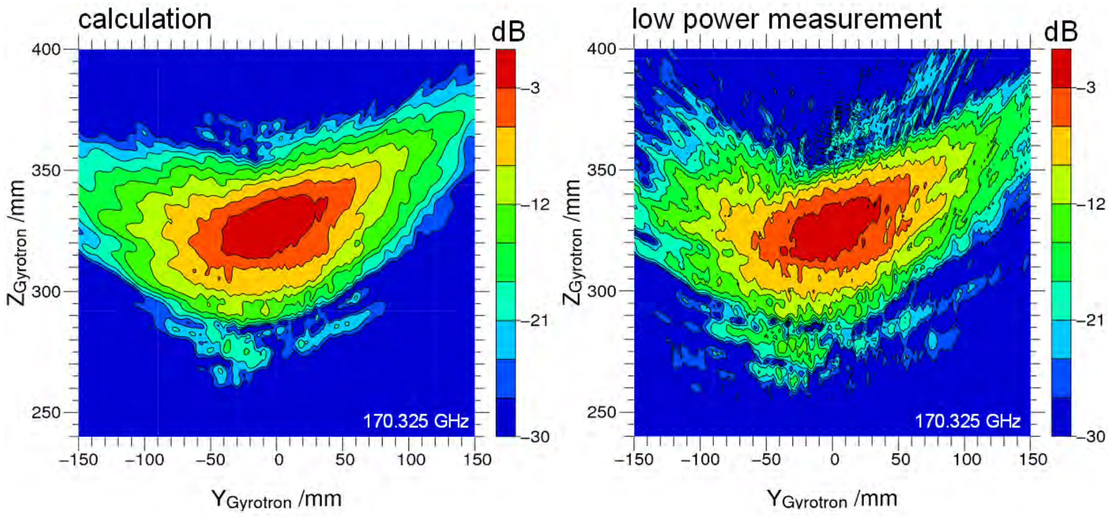

Fig. 10 Radiated field of the new launcher in a plane at a distance of 100 *mm* from the launcher axis, calculated using the SURF3D code (left) and measured at low power (right).

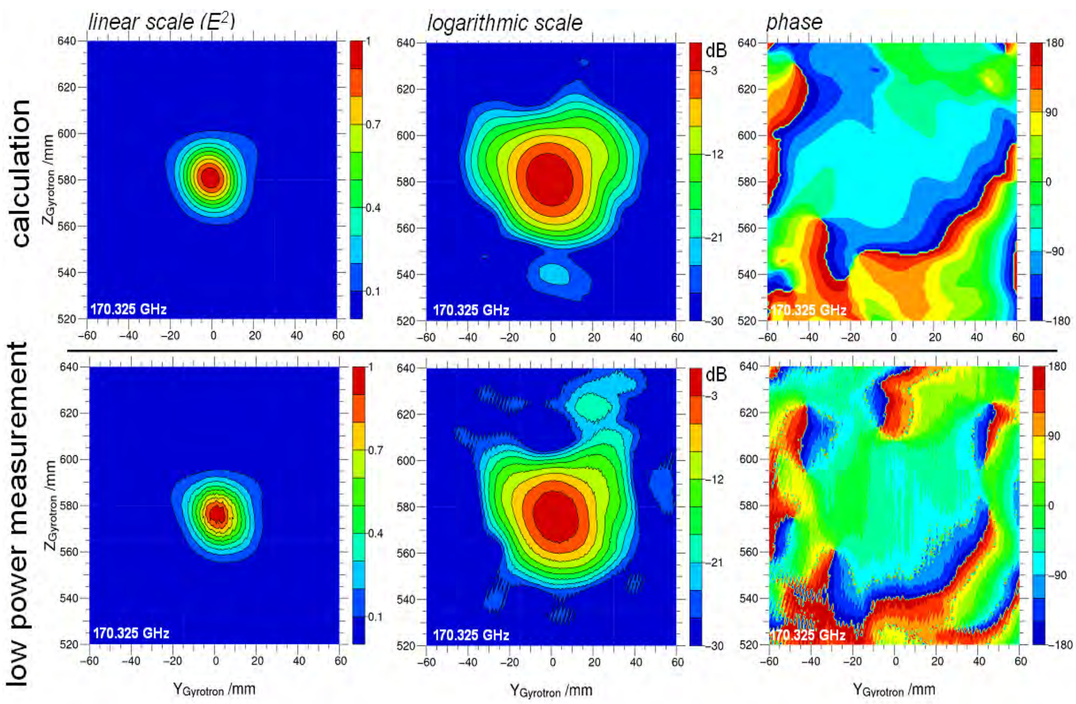

Fig. 11 Calculation (upper) and low power measurement (lower) of the mm-wave beam profile and phase distribution at a distance of 500 *mm* outside the gyrotron window.

The final validation of the performance of the q.o. output coupler was performed by measuring the intensity profile of the mm-wave output beam of the coaxial-cavity gyrotron ("hot" measurements). The intensity profile of the mm-wave beam has been obtained by measuring the temperature distribution on a PVC target with an infrared camera (IR) after short gyrotron pulses.The mm-wave beam profile has been measured in planes with different distances from the gyrotron window outside the gyrotron in order to be able to reconstruct the phase distribution of the mm-wave beam. From the reconstructed phase distribution the Gaussian mode content can be evaluated. The measured profile of the "hot" mm-wave beam has been found to be in very good agreement both with the simulations and with the results of "cold" measurements. As example, Fig. 12 shows the measured "hot" beam profile and the results of simulations at distances of 68 *mm* and 1148 *mm* from the gyrotron window. From the phase reconstruction of the measured beam profiles a Gaussian content of almost 96 % has been obtained in very good agreement with the corresponding value achieved from simulations. Furthermore, the "hot" measurements have confirmed the simulated propagation of the mm-wave beam. Only a small shift of a few mm of the beam center with respect to the window axis has been observed over a distance of about 1 m from the window.

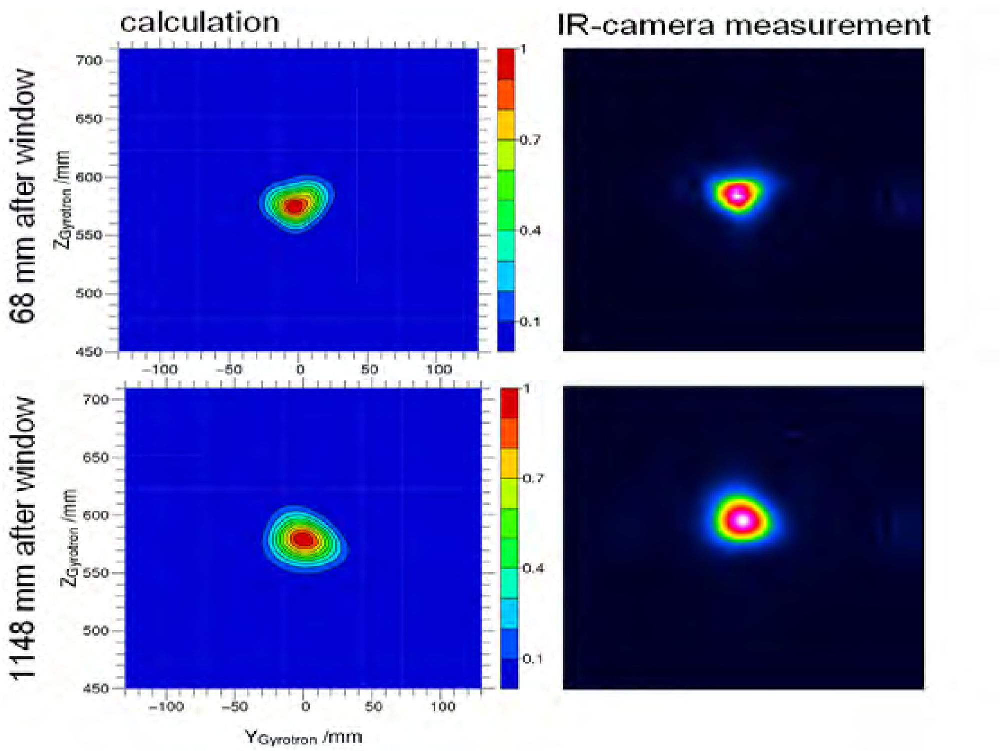

Fig.12 Calculations (left) and high-power IR-camera measurements (right, with the same scales) of the mm-wave beam profile for the gyrotron operation at 0.17 *THz* in the $TE_{34,19}$ mode.

Similar measurements of the mm-wave beam power profile have been performed for the $TE_{28.16}$ mode at 0.1413 *THz* at the distances 468 and 1148 *mm* from the center of the gyrotron Brewster window. As can be seen from Fig. 13 that the beam quality is very good, too. The measurements are in good agreement with the calculations.

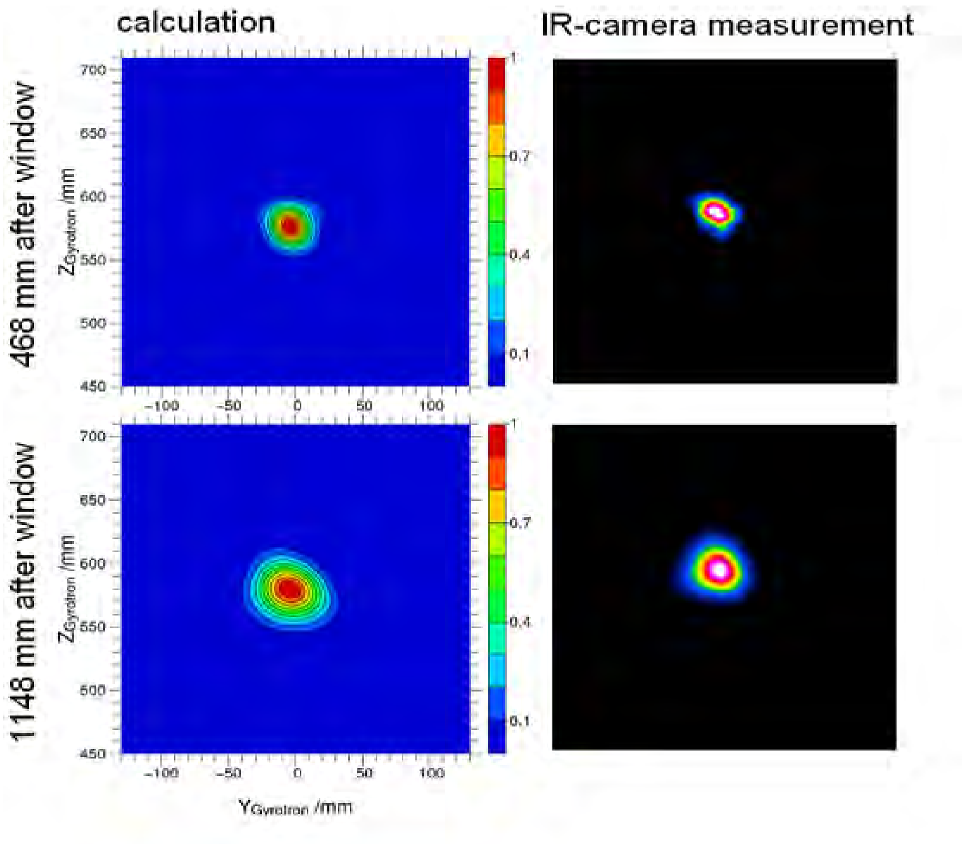

Fig.13 Calculations (left) and high-power IR-camera measurements (right, with the same scales) of the mm-wave beam profile for the gyrotron operation at 0.1433 *THz* in the $TE_{29,16}$ mode.

6. Summary, Conclusions and Prospects

Significant progress and improvement have been obtained in recent investigations on the short-pulse 2 *MW*, 0.17 *THz* coaxial-cavity gyrotron at KIT. Low-frequency (LF) parasiticoscillations around 265 *MHz* and parasitic RF oscillations in the region of 0.15 to 0.16 *THz* have been successfully suppressed. In case of the LF oscillations a mechanism responsible for the excitation inside the coaxial gyrotron has been found. The amplitude of the parasitic LF oscillations has been significantly reduced by avoiding radial steps in the contour of the coaxial insert. With an absorber placed around the electron gun a complete suppression of these oscillations has been obtained. The parasitic high frequency oscillations observed in the frequency band from 0.15 to 0.16 *THz* have been eliminated by improving the beam tunnel. The modification consists mainly in a destruction of the azimuthal symmetry by introducing irregular longitudinal corrugations in the copper rings in order to suppress weakly damped circular electric modes. A result of these changes was a considerable improvement of the stability of single-mode operation. The increase of the cavity magnetic field to the nominal value of 6.87 *T* by using an additional normal conducting coil allows to operate the pre-prototype tube at the same parameters as the industrial CW gyrotron. At the nominal conditions a record output power of 2.2 *MW* with an efficiency of up to 30 % (without depressed collector) has been achieved. Up to now the short-pulse pre-prototype gyrotron has been equipped with a fused silica vacuum barrier window which absorbs 3.3 % of the generated mm-wave beam power. With a synthetic diamond window, as required and foreseen for the industrial CW gyrotron, the output power would have been 2.3 *MW* at 31 % efficiency which is even more above the specified value of 2 *MW*. Employing a single-stage depressed collector (SDC) the efficiency will be raised above the specified value of 50 %.

During the operation with a novel q.o. output coupler, based on a newly designed launcher, excellent quality of the mm-wave output beam (Gaussian content of almost 96%) has been obtained. The results of "hot" and "cold" measurements have been found to be in very good agreement with the simulations. The amount of stray radiation losses inside the tube is reduced in comparison to the previous output coupler. In particular, a total amount of (7±2) % has been measured in comparison to (8±2) % with the previous q.o. output coupler. The modified beam tunnel and the novel q.o. output coupler will be integrated into the refurbished industrial CW prototype gyrotron manufactured by TED. This tube will be tested at CRPP Lausanne from August 2010.

An efficient operation of the pre-prototype gyrotron at several frequencies and corresponding operating modes has been demonstrated. In particular, in the $TE_{28.16}$ mode at 0.1413 *THz* an output power of 1.8 *MW* with 26% efficiency has been generated and in the next azimuthal neighbor, the $TE_{29,16}$ mode at 0.1433 *THz* an output power of 1.25 *MW* with 23% efficiency has been obtained.These results have not been experimentally optimized because of lack of time and can be further increased – simulations predict output powers above 2 *MW* for a variety of frequencies between 0.13 and 0.17 *THz* (even 0.21 *THz*, if the corresponding magnetic field would be available).

The quality of the mm-wave output beam has been very good for both modes. Besides other investigations, it is planned in the coming experimental campaigns to further study the operation of the pre-prototype gyrotron at different frequencies. The mm-wave output beam patterns generated with these modes will be measured, and a further increase of the output power above 2 *MW* is expected.

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