Experimental Investigations on the Pre-Prototype of the 170 GHz, 2 MW Coaxial Cavity Gyrotron for ITER

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Abstract. The first industrial prototype of a 2 MW, CW, 170 GHz coaxial cavity gyrotron, which is under development for use in ITER, has been tested recently at CRPP Lausanne. As part of this European development of the 2 MW, 170 GHz coaxial cavity gyrotron, investigations have been performed on a short pulse coaxial tube (pre-prototype) at the Forschungszentrum Karlsruhe (FZK). The pre-prototype tube utilizes the same $TE_{34,19}$ mode and the same cavity with up-taper, launcher and mirrors and a very similar electron as used in the industrial prototype. Thus the obtained results and observed problems are considered to be relevant for the prototype. Within this investigations parasitic low frequency (LF) oscillations have been studied and the intensity has been significantly reduced by performing some geometrical modifications. Recently in operation at higher voltages near the nominal parameters, parasitic high frequency oscillation around 160 GHz appears simultaneously with the desired gyrotron working mode. There are indications, that the high frequency parasites are excited in the beam tunnel. Investigations to suppress the oscillations are going on. The improvement of the performance of the q.o. RF-output system is a very important task. Extensive simulations and measurements have been done in order to enhance the performance of the RF beam. With a newly developed code a launcher has been designed which delivers a microwave beam with a Gaussian content around 95%.

1. Introduction

Between European research centres and together with an European industrial partner a 170 GHz coaxial cavity gyrotron with an output power of 2 MW, CW is under development for use in ITER. A first industrial prototype has been tested recently at CRPP Lausanne [1]. To support this development experimental studies with a short pulse (≤ few ms) experimental 170 GHz coaxial cavity gyrotron ("pre-prototype") have been performed at FZK. This pre-prototype utilizes the same $TE_{34,19}$ mode and the same cavity with up-taper, launcher and mirrors as designed for the industrial prototype and in addition, a very similar electron gun. However, there is a difference in the operating parameters, since the SC-magnet used for operation of the pre-prototype tube allows only to generate a magnetic field of up to about 6.7 T in comparison to the value of 6.86 T which is used as nominal field in the industrial tube. As a consequence of this, it became necessary to reduce the operating voltage in the pre-prototype tube to values below 80 kV, in order to be able to excite the $TE_{34,19}$ mode at 170 GHz. Thus the pre-prototype gyrotron allows it to study the performance of the main gyrotron components - electron gun and beam, cavity and RF interaction and the quasi-optical (q.o.) RF output system - under more or less relevant conditions and to discover and investigate unexpected problems sufficiently in advance. The main nominal design parameters are summarized in *TAB. 1*, both for the 2 MW, CW industrial prototype and for the short pulse pre-prototype tube. The difference in the operating parameters (magnetic field, voltage) of the pre-prototype tube in comparison to the industrial prototype results in the lower expected value of the RF output power (~ 1.5 MW). The experimental set up has been described in [2] and first experimental results have already been presented in [3]. In the following results obtained recently are presented and compared with simulations. In addition, ongoing activities towards the improvement of the gyrotron operation are described and discussed.

	prototype	pre-prototype
operating cavity mode	$TE_{34,19}$	
frequency, f	170 GHz	
RF output power, P_{out}	2 MW	~ 1.5 MW
beam current, I_b	75 A	
Acceleratine voltage, U_c	90 kV	80 kV
velocity ratio, α	1.3	1.3
cavity magnetic field, B_{cav}	6.87 T	~ 6.7 T

TAB. 1. Design parameters of the prototype and the pre-prototype tube.

2. Parasitic low frequency (LF) oscillations

When the gyrotron was operated first, the operation was strongly limited due to the excitation of parasitic LF oscillations with very high amplitude mainly around 265 MHz [3]. Those LF oscillations have been excited inside the tube with very high intensity above beam currents I_b>10 A and beam voltages U_c>~40 kV. The measured frequency spectrum of the parasitic oscillations is shown in *FIG. 1a*. The parasitic oscillations were dominated by two strong resonance oscillations at 265 and 332 MHz. The frequency values have been found to be practically independent from the beam voltage.

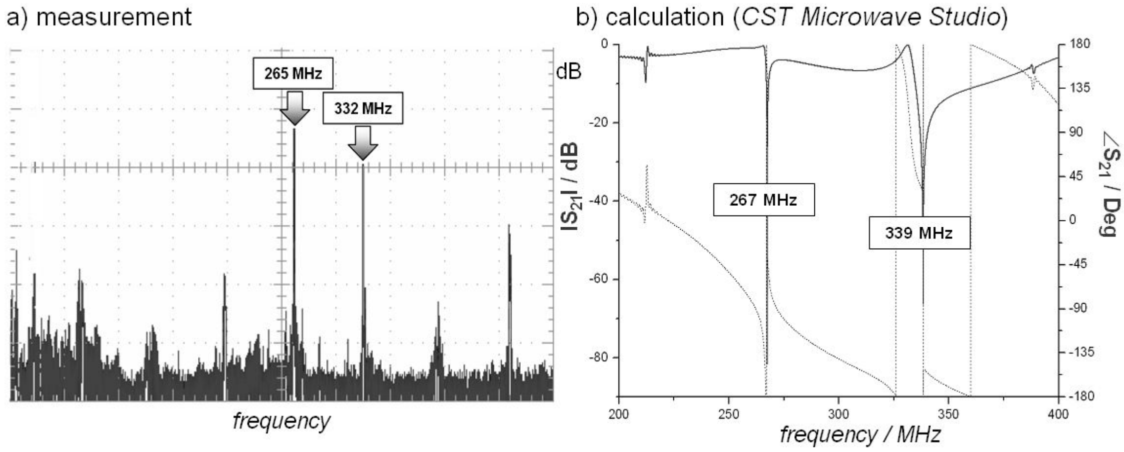

FIG. 1. Measured (LF) parasitic oscillations (a) and calculated with CST (b) frequency spectrum of the inner geometry of the pre-prototype gyrotron.

To study the mechanism of the parasitic LF oscillations the geometry of the whole gyrotron as installed in the superconducting magnet was simulated using the code *CST Microwave Studio.* As a result of the simulations two resonance frequencies at 267 MHz and 339 MHz, in very good agreement with the experimental observations, have been obtained (*FIG. 1b*). The calculated field distribution shows that in both cases a strong concentration of the electric LF field near the cathode exists. The *FIG. 2* shows as an example the field distribution of the LF oscillation at 267 MHz. The interaction of the emitted electrons with the LF field near the cathode results in a velocity modulation of the electrons which causes a longitudinal bunching of the electron beam. Taking into account the transit time of the electrons and the calculated distribution of the LF fields, in principle two regions of interaction, in which an energy transfer between the axially bunched electron beam and the LF field is possible, have been identified, namely (1) on the cathode side of the resonator and (2) at the end of the coaxial insert. A detailed analysis has shown that the oscillations at both frequencies are excited on the cathode side of resonator. At this position due to a radial step in the geometry an axial component of the LF field occurred, which interacted with the bunched electron beam. There is no energy transfer from the electron beam to the LF field at the end of the coaxial insert because of phase condition between the bunched beam and the LF field.

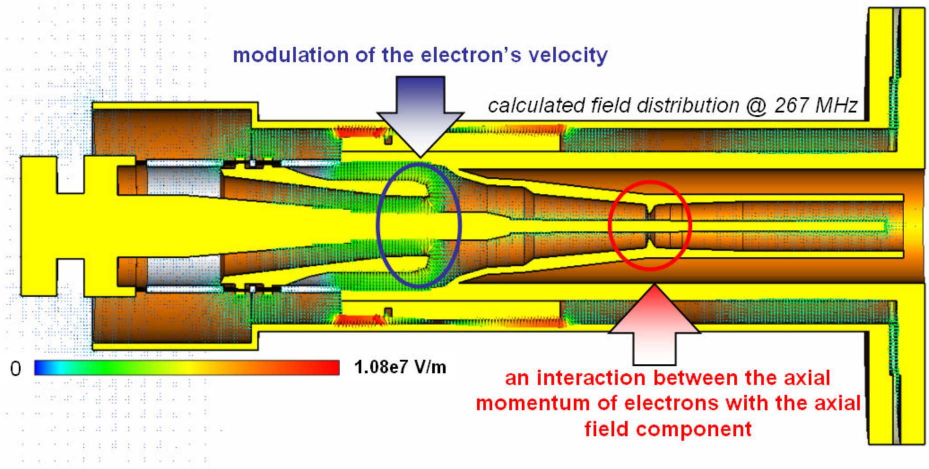

FIG. 2. Calculated field distributions at 267 MHz – regions responsible for the excitation of the parasitic oscillation are indicated.

Based on this model the geometry of the coaxial insert on the cathode side of the gyrotron cavity has been smoothed in order to reduce the axial components of the LF field. Experimentally it has been confirmed that the performed modification resulted in a significant reduction of the amplitude of the LF oscillations. In particular, the corresponding starting currents increased by a factor of more than 3. However, at higher beam current (above ~ 40 A) still some LF oscillations have been present. By external damping a stable operation of the gyrotron at nominal parameters was possible. Recently, measurements have been performed with an electron gun ("old gun") previously used in the coaxial gyrotron at 165 GHz [4]. For this the anode has been adjusted for operation at 170 GHz in the $TE_{34,19}$ mode. In agreement with the previous observations with the 165 GHz gyrotron, no LF oscillations have been observed in the 170 GHz gyrotron up to the nominal values. Since the geometry of both used gun is not very much different, the observed behavior indicates a great sensibility for occurring of such parasitic LF oscillations from the overall inner gyrotron geometry.

3. RF power generation

As just mentioned, for performing RF measurements the anode of the "old gun" has been adjusted for 170 GHz operation to: $\alpha = 1.3$ at $U_c = 80$ kV, $I_b = 75$ A, $B_{cav} = 6.72$ T for a beam radius $R_b = 10$ mm. In absence of the parasitic LF oscillations a maximum RF output power $P_{out} \approx 1.3$ MW with an efficiency of ~23 % has been obtained in non-depressed operation. *FIG. 3* shows the measured microwave output power in dependence of the cathode voltage. The also shown calculated values have been obtained with a self consistent single and multi mode, time dependent code. As input data either experimental parameters or best known values have been taken. The measured RF output power is in reasonable good agreement with simulations for $U_c < 73$ kV. With increasing U_c the experimental value of P_{out} is rising slower in comparison to the values expected from the calculations. Measurements with a broad-band Brewster-window out of SiN have been performed in order to study the influence of the stray radiation, mainly in the neighbored modes, on the gyrotron performance (mode sequence, operating range and efficiency). However, no significant difference has been found in comparison to results with the disc window out of fused silica ($15\lambda/2$ thick at 170 GHz). During the experiments it has been observed that at $U_c > 74$ kV and $I_b > 57$ A another oscillation around 160 GHz was excited simultaneously with the nominal $TE_{34,19}$-mode at 170 GHz. Further on, above U_c ~78 kV a strong "multi-moding" has been occurred. There are some indications that the oscillations around 160 GHz are generated inside the beam tunnel near the cavity. The original beam tunnel consists of cooper rings stacked together with lossy ceramic parts (*FIG. 4a*). To influence this parasitic beam tunnel oscillations the beam tunnel has been replaced by a simple conical full metallic structure (*FIG. 4b*). In measurements it turned out, that the situation becomes significantly worse with the conical full metal tunnel. The parasitic beam tunnel oscillations are under study. New different designs of beam tunnels are under consideration: (1) a structure consisting of copper rings with irregular slots and lossy material in between, (2) a full metal conical structure with corrugated inner wall and (3) a conical beam tunnel out of SiC. Experimental tests with the pre-prototype tube are foreseen.

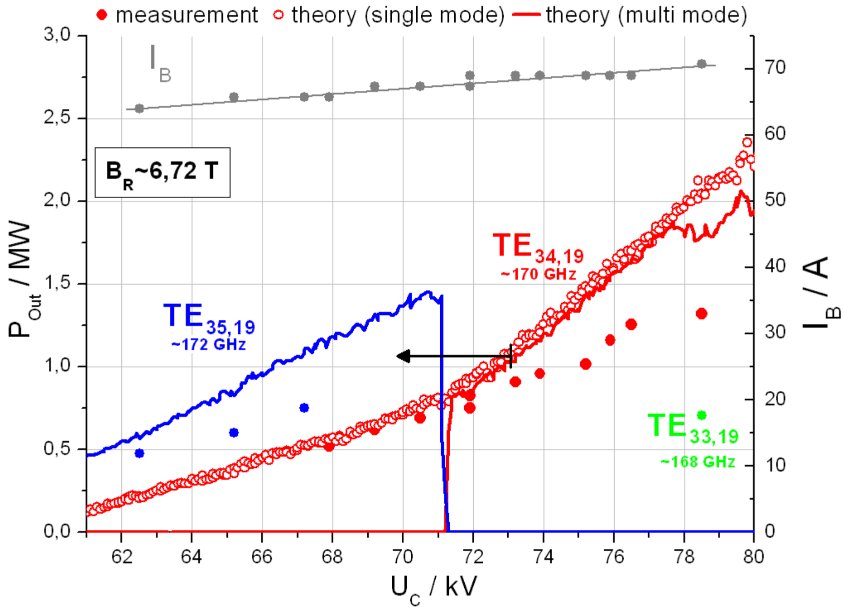

FIG. 3. RF output power vs. cathode voltage. The experimental values are compared with self consistent calculations (single and multi-mode).

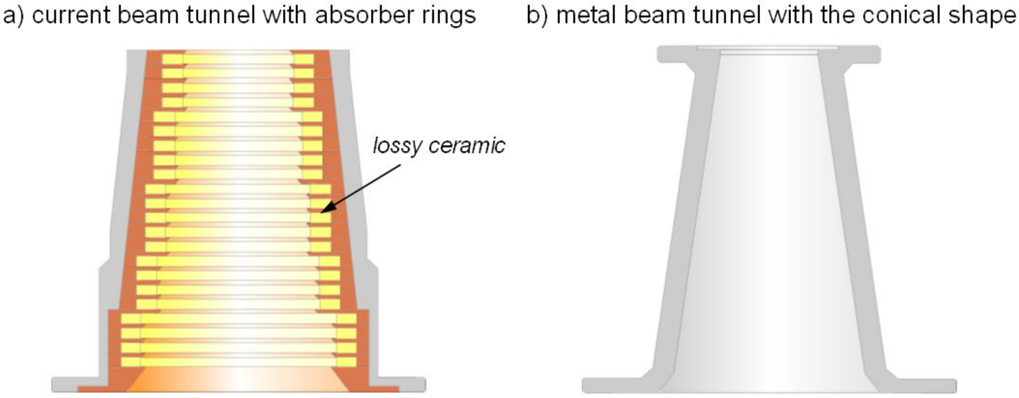

FIG. 4. Beam tunnels used in the experiments with pre-prototype gyrotron.

4. Improvement of the RF output system

The general task of the q.o. system is to convert the RF-power generated in the $TE_{34,19}$-cavity mode into a free-space beam with a high content of the fundamental Gaussian mode. The q.o. RF output system has already been described in detail in [5]. It consists of a launcher antenna and three mirrors: a quasi-elliptic, a toroidal and a phase-correcting mirror (*FIG. 5*).

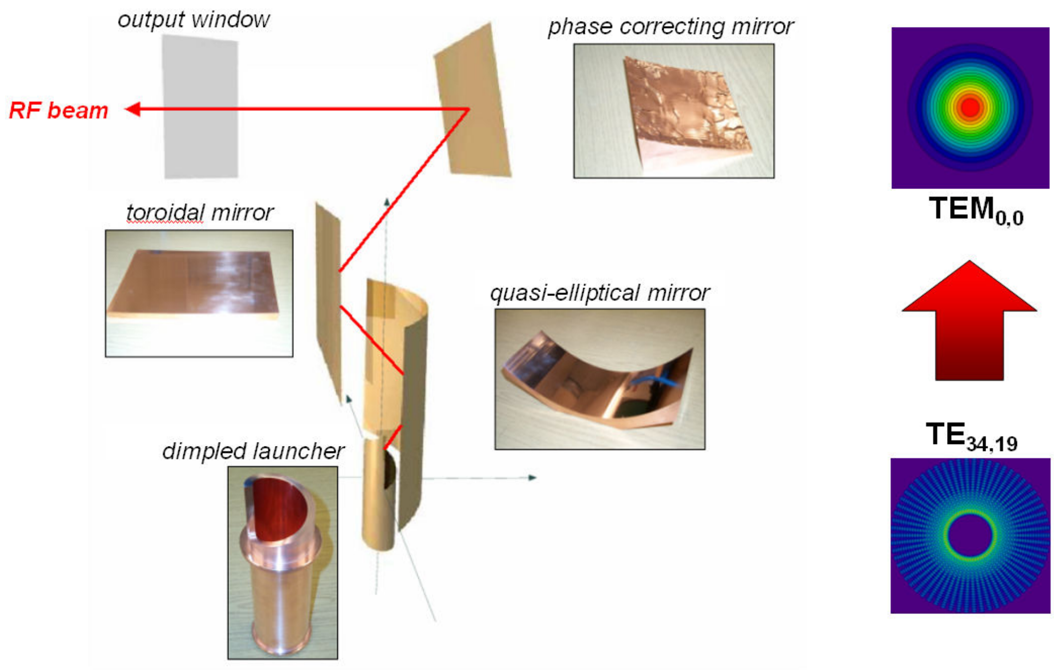

FIG. 5. Arrangement of the q.o. RF output system.

To realize a better coupling of the $TE_{34,19}$ mode to the free space beam, a launcher with a dimpled 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 surface. In addition, the decreased amplitude of the microwave field at the cut of the launcher reduces the diffraction losses and results thus in a reduction of the microwave stray losses inside the gyrotron tube. Theoretically a conversion of a field pattern with low Gaussian mode content into the fundamental Gaussian free space mode can be performed with two mirrors with especially adapted phase correcting surfaces. The calculated surface contours of the phase correcting mirrors can only be realized in approximate way. This causes some additional microwave stray losses inside the tube. Therefore, as a compromise between low stray radiation losses and large Gaussian mode content in the output beam only one phase correcting mirror (3^{rd}) has been chosen. In that case only the amplitude distribution of the RF-beam has been optimized to be approximately Gaussian at the position of the gyrotron output window, without considering the phase distribution. The phase front has to be corrected with an additional mirror outside the gyrotron. At the beginning the launcher ("old") inner wall perturbation was describe by a combination of 1^{st}, 2^{nd} and 3^{rd} orders. However, further calculations have shown that the launcher ("new") with only an 1^{st} and 3^{rd} perturbation produce a higher Gaussian content in the launcher radiated pattern. In addition, the phase distribution is not so strongly distorted and makes the conversion easier. The “new” launcher was installed with the mirror system optimized for the "old" launcher. Although the phase correcting mirror was not optimized for the “new” launcher, the expected Gaussian beam content at the window position was about 86% as calculated with the OSSI code, which is currently used at FZK. The "new" launcher has been fabricated and tested at low power (“cold”) [3]. First measurements at the window position have shown relatively strong disagreement with theory. The analysis of the “cold” measurements in the window plane resulted only in 77 % Gaussian mode content. To prove the OSSI code and to find the reason for the disagreement, calculations with the most sophisticated code in this field, the Surf3D code [7] have been performed. The results obtained using Surf3D were in very good agreement with calculations with OSSI code as is shown in *FIG. 6*.

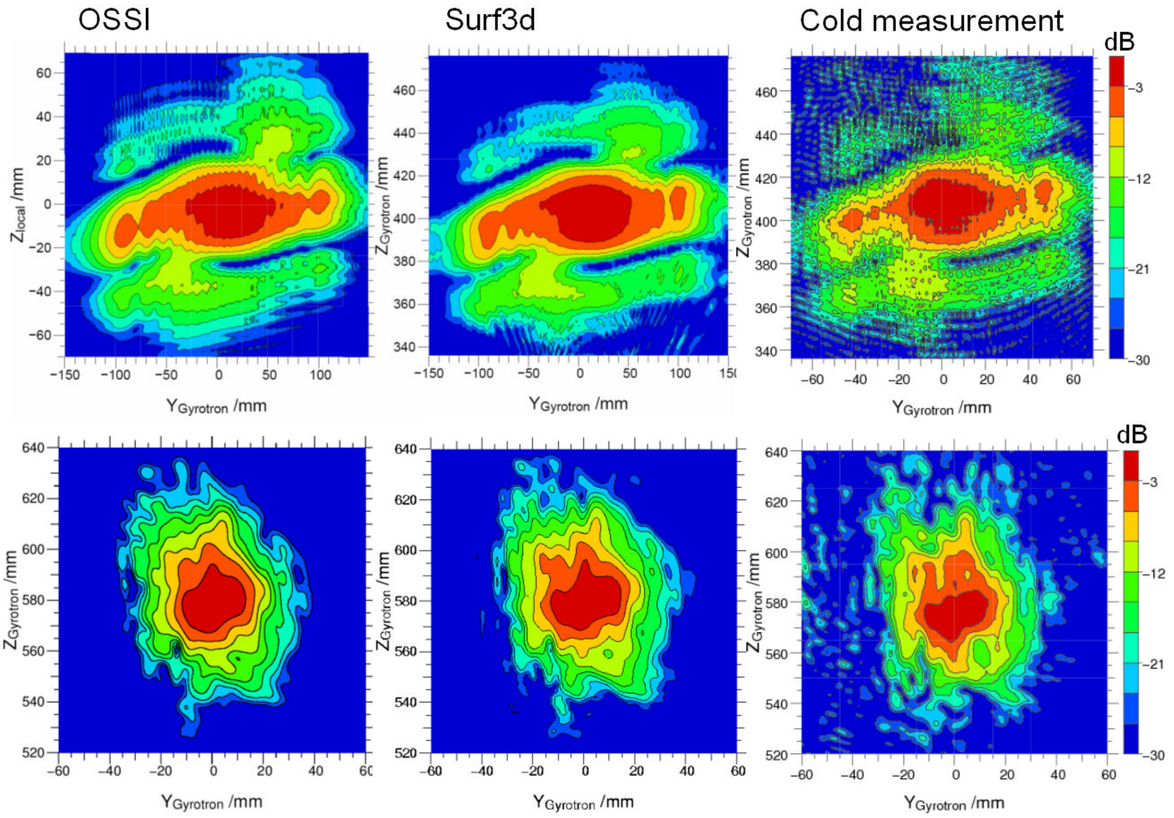

FIG. 6. Comparison of the measured fields patterns (right) with calculations: OSSI (left) and Surf3d (middle), at the 2nd mirror position (upper row) and on the gyrotron window (bottom row).

To find the reasons for the discrepancy between experiment and theory the influence of the alignment of the components of the output system has been studied thoroughly. It has been found that a small misalignment of about 0.3 mm of the 2nd mirror with respect to the theoretical position causes a shift of the beam of about 5 mm at the phase correcting mirror. As a consequence, the phase correction of the 3rd non-quadratic mirror does not work properly. After a new adjustment of the mirrors, measurements at low power were repeated and results were in a good agreement with calculations (*FIG. 6*). However, the Gaussian content evaluated from the low power measurements is still about 5 % below the theoretically expected value. The reason for this is probably related to the algorithm of the code used for evaluation of the Gaussian content out of the experimental values. In particular, the code is quite sensitive to parasitic effects observed usually in the measurements. Such effects may result from interferences with stray radiation. Further studies are going on.

A possible way to improve the efficiency of the current mode converter is to design of a new phase correcting mirror for the RF pattern of the launcher with only 3rd order azimuthal perturbation. First results of optimization obtained with the OSSI code have shown that with an optimized non-quadratic mirror a Gaussian beam content of about 88 % can be obtained. The optimization results have been verified with the Surf3d code. The field distributions at the window plane calculated with both codes (OSSI and Surf3d) are in good agreement as shown in *FIG. 7*.

To achieve a conversion of the $TE_{34,19}$ mode into the Gaussian beam with a content of around 95 %, the design tools of the launcher antenna have to be improved. 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 launcher length by using the coupled mode equation theory. Therefore another optimization method based on the quasi-optical propagation theory of the modes inside waveguides has been used. Recently a new optimization code has been developed [8]. The new code performs a numerical optimization of the launcher surface in order 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. Recent results which have been verified with the Surf3d code are very promising as is shown in *FIG. 8*. According to the calculated complex correlation factor between the field radiated from the launcher and an ideal Gaussian field distribution, a Gaussian content of about 96 % is expected. Next the launcher will be manufactured and measurements at low power will be performed for verification [6].

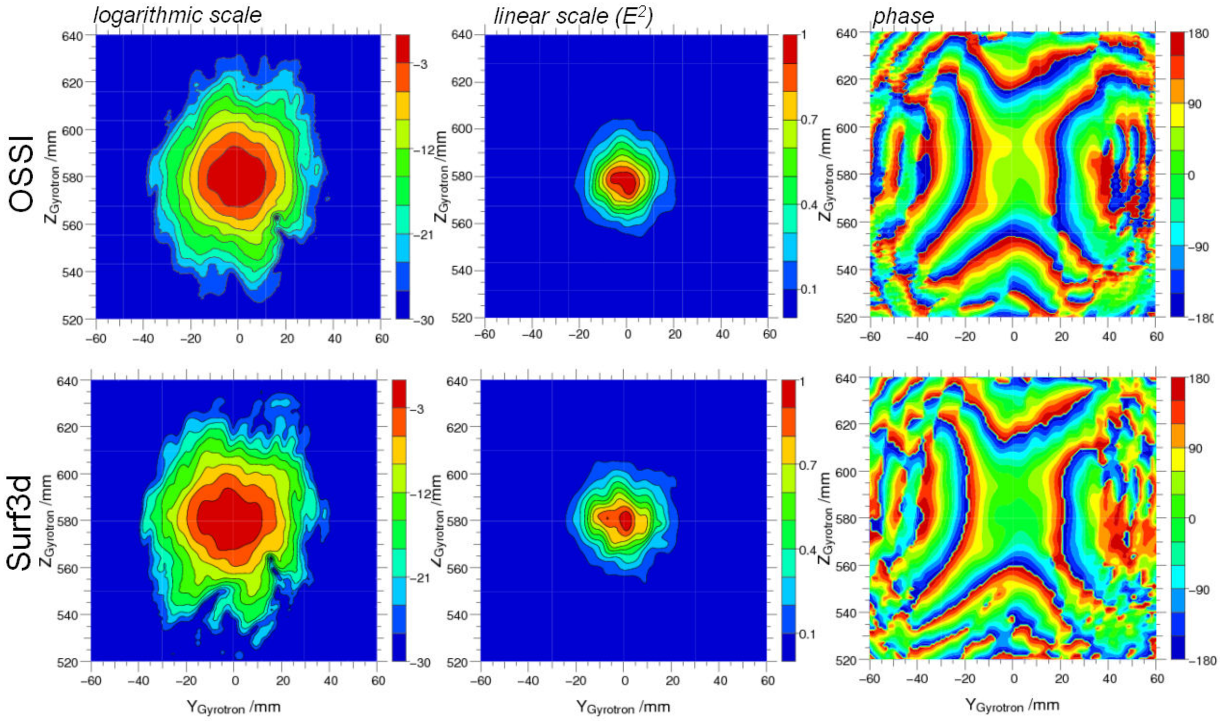

FIG. 7. Results of the optimization of the 3rd phase correcting mirror – field distribution at gyrotron window calculated with OSSI (upper row) and results of verification with Surf3d (bottom row).

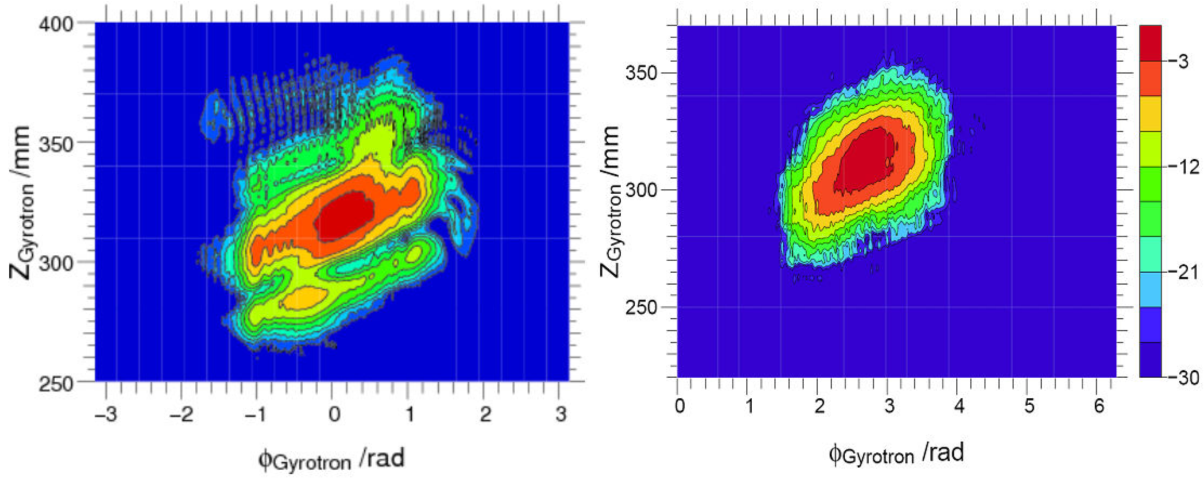

FIG. 8. Surf3d calculation of the radiated field of the: current launcher with 1st, 3rd perturbation orders at the inner wall (left) and improved launcher with arbitrary deformations (right).

5. Conclusion and Outlook

Investigations on the pre-prototype gyrotron have been continued. The mechanism of excitation of parasitic LF oscillations inside a coaxial gyrotron has been studied. By smoothing the coaxial insert the amplitude of the parasitic LF oscillations has been significantly reduced. Operation of the 170 GHz gyrotron with an "old" electron gun used previously in the 165 GHz gyrotron, has shown no parasitic LF oscillations. This indicates a strong sensibility for excitation of parasitic LF oscillation from the gyrotron geometry. In operation with the "old" gun without LF oscillations a reasonable good agreement between theory and experiment has been obtained with a maximum RF output power around 1.3 MW and corresponding efficiency of ~23 % in non-depressed collector operation. In these experiments at voltages > 74 kV high frequency parasitic oscillation around 160 GHz have been observed which is suspected to be responsible for a reduction of the RF output power. The parasitic high frequency oscillations are assumed to be excited in the beam tunnel. To verify this, measurements with modified beam tunnels are in preparation. Concepts for the improvement of the q.o. RF output system have been presented. A launcher designed with a newly developed code and verified with the Surf3d code is radiating a field distribution with ~ 95 % Gaussian content.

To improve the relevance of the measurements between the pre-prototype and the industrial prototype tube a normal conducting coil will be placed around the cavity in order to increase the magnetic field to the nominal value of ~6.86 T.

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