

170 GHz, 2 MW, CW Coaxial Cavity Gyrotron for ITER - status and experimental results -

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Abstract. A first industrial prototype of a 2 MW, CW, 170 GHz coaxial cavity gyrotron has been fabricated and will soon be delivered next. A suitable superconducting magnet is expected to be available in January 2007. Therefore experimental operation of the gyrotron experiments could start in February 2007. In parallel to the fabrication phase, extensive investigations have been performed on a short pulse 170 GHz coaxial gyrotron equipped with the same main components as the prototype tube. In general, the obtained results confirm the design calculations, although some discrepancies exist with respect to results of numerical simulations. In particular, the observed mode spectrum is more dense than predicted by calculations. This results in a reduced range of excitation of the nominal mode. Possible reasons for the observed discrepancy are under investigation. The performance of the quasi optical RF-output system is in agreement with the design, however, the Gaussian content of the RF output beam is unsatisfactorily low. The design of an improved RF-output system is in progress.

1. Introduction

Microwave power in the frequency range above 100 GHz has successfully been used in magnetically confined fusion devices for plasma heating at the electron cyclotron resonance frequency (ECRH) and for electron cyclotron current drive (ECCD). In order to reduce the costs of the EC microwave system at ITER and to decrease the space requirements for injection of the microwave power into the plasma, the use of gyrotrons with 2 MW output power would be an advantage. Therefore the development of a 170 GHz coaxial cavity gyrotron with 2 MW output power in continuous wave (CW) operation has been started. In proof of principle experiments carried out at FZK Karlsruhe on a 165 GHz coaxial cavity gyrotron during the last years, the feasibility of manufacturing a 2 MW, CW coaxial gyrotron at 170 GHz has been demonstrated and information necessary for a technical design has been obtained [1]. Based on these results and on the experience acquired during the development of the 1MW, CW, 140 GHz gyrotron [2] for W7-X, the technical feasibility of a 2 MW, CW, 170 GHz coaxial cavity gyrotron has been studied by the Associations and by means of an industrial study contract. Further to the positive results of those studies, EFDA have placed a

contract with Thales Electron Devices (TED) for procurement of a first industrial prototype of such a coaxial gyrotron tube [3]. The development work is done in cooperation between European research centers together with TED, under EFDA coordination. Within this cooperation the physical specifications and the design of gyrotron components have been done by the research institutions whereas TED is responsible for the technological aspects and manufacturing of the tube. At present the fabrication of the prototype gyrotron has been finished and the tube will be delivered to CRPP Lausanne where the tests will be performed. To support the work on the industrial prototype gyrotron, experimental studies with a short pulse ($< \sim 5$ 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. Thus the pre-prototype gyrotron offers the possibility to study the performance of the main gyrotron components under relevant conditions. In particular, experimental investigations have been carried out, (1) to prove the behavior of the electron gun and electron beam, (2) to verify the microwave generation and (3) to measure the performance of the quasi optical (q.o.) RF output system, the properties of the RF output beam and the amount of microwave stray losses inside the tube. In addition, the operation of the pre-prototype tube made it possible to discover unexpected operating problems, as e.g. the excitation of parasitic low frequency (LF) oscillations, sufficiently in advance. As a result some small modifications in the design of the industrial prototype tube have been introduced in order to suppress the excitation of the parasitic LF oscillations. In addition to the experiments with the pre-prototype gyrotron, a low power test facility has been developed at FZK, which allows to perform microwave measurements on the components of the q.o. RF output system (launcher and mirrors) prior to installation on the prototype tube. In this report first the main design characteristic and the status of the industrial prototype will be given. Then results obtained with the pre-prototype gyrotron and also those of low power measurements will be presented and discussed.

2. Main design features of the prototype gyrotron and specifications

The main nominal design parameters of the prototype coaxial cavity gyrotron are summarized in Table I together with the corresponding parameters of the short pulse pre-prototype tube. The SC-magnet at FZK which is used for operation of the pre-prototype gyrotron, is able to generate a maximum magnetic field of about 6.7 T only. Therefore, in order to be able to excite the $TE_{34,19}$ mode at 170 GHz at the reduced magnetic field, the beam voltage had to be reduced to values below 80 kV. Consequently somewhat reduced RF output power is expected from the pre-prototype tube [4]. The coaxial magnetron injection gun (CMIG) designed for the pre-prototype tube, has been taken as reference for the gun of the prototype gyrotron [5]. The $TE_{34,19}$ mode has been selected as operating mode [6]. A new mode had to be chosen since the $TE_{31,17}$ mode, previously used in the 165 GHz coaxial gyrotron [7], would have at 170 GHz peak wall losses about 20% above the technically accepted value of 2 kW/cm^2 . In calculations with two independent self-consistent, time-dependent, multimode codes, the $TE_{34,19}$ mode have shown a wide parameter range for single mode operation. The cavity has an outer diameter of 59.1 mm and a length of 16 mm. The coaxial insert has a diameter of 15.72 mm in the centre of the cavity and is corrugated and tapered by an angle of 1 degree. The cavity is made of glidcop (dispersion strengthened copper). Taking into account the resistivity of glidcop and the effect of surface roughness a peak ohmic loading at the outer cavity wall of 1.7 kW/cm^2 has been estimated (compared to 1 kW/cm^2 for ideal copper) corresponding to a total dissipated power of 45 kW. The peak losses at the insert are expected to be less than 0.1 kW/cm^2 .

TABLE I. Design parameters of the prototype and the pre-prototype tube.

	Prototype	pre-prototype
operating cavity mode	TE _{34,19}	
frequency, f / GHz	170	
RF output power, P_{out} / MW	2	~ 1.5
beam current, I_b / A	75	
accelerating voltage, U_c / kV	90	80
RF output efficiency (with SDC) η_{out}	> 45 %	-
velocity ratio, α	1.3	1.3
electron beam radius, R_b / mm	10	
cavity magnetic field, B_{cav} / T	6.87	~ 6.7
pulse length τ_{pulse} / s	> 1	~ 0.005

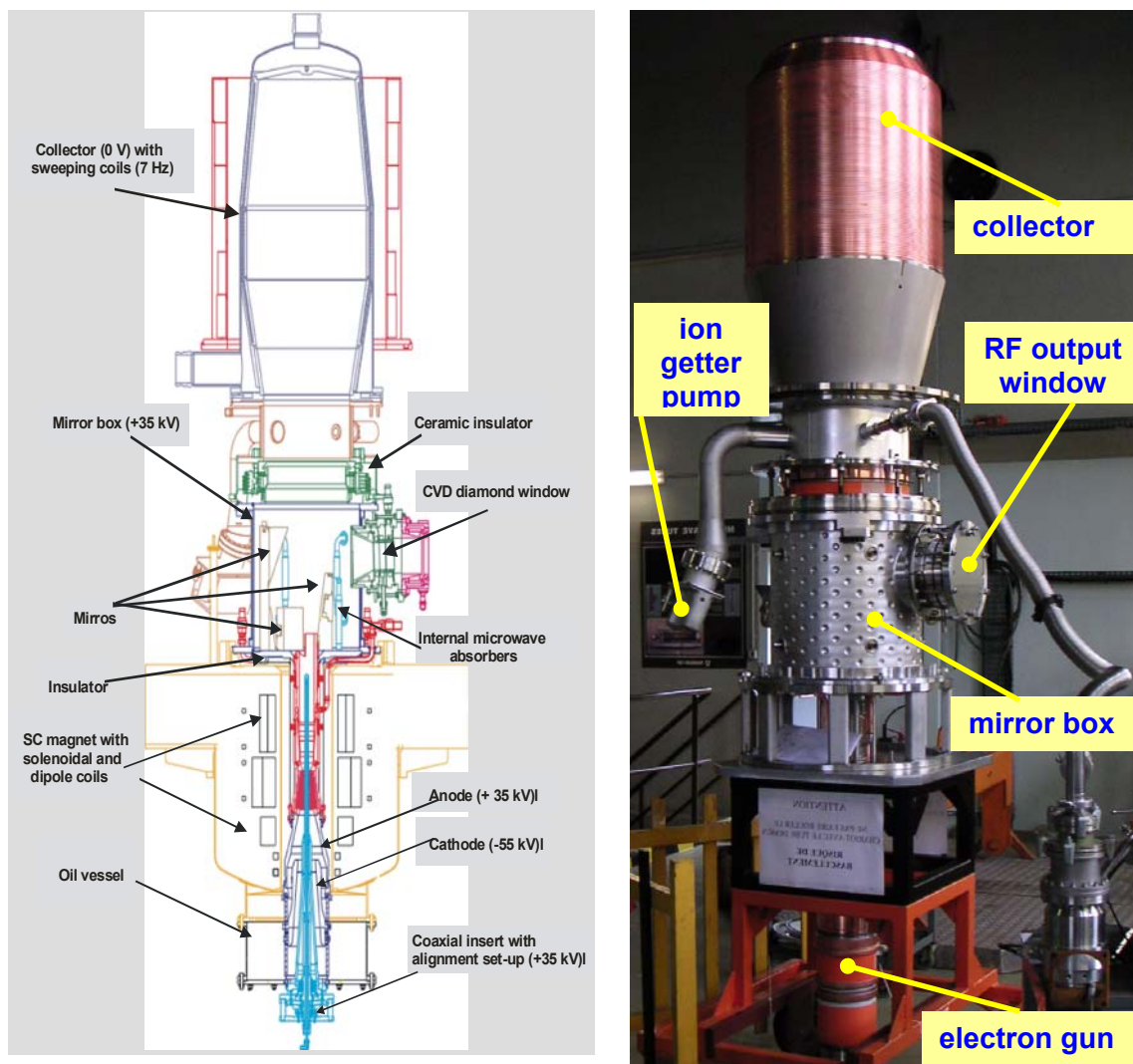


Fig. 1. Schematic view and a photograph of the completed prototype gyrotron

Special care has been devoted to the handling of the microwave stray losses inside the gyrotron. To dissipate the stray radiation in a well defined way and to keep the level of the microwave stray power in the gyrotron tube low, internal microwave absorbers consisting of six water cooled Al_2O_3 tubes are installed inside the mirror box. According to extrapolation of results obtained with the pre-prototype gyrotron it is expected that around 2/3 of the total stray radiation, which has been measured to be about 8% of the RF output power, will be

absorbed by the internal absorbers. The output window has an aperture of 96 mm and uses a 1.852 mm thick disc made of CVD diamond, which allows transmission of a 2 MW RF-beam in CW operation with large safety margin. The gyrotron will be operated with a single stage depressed collector (SDC). The nominal value of the retarding voltage is around 35 kV. The collector will be at ground potential and the gyrotron body including the mirror box and RF output window will be at +35 kV. A ceramic ring placed at the top of the mirror box is used for electrical insulation. The collector has a maximum inner diameter of 600 mm. At nominal conditions the collector has to dissipate a total power of about 2.4 MW of the spent electron beam. A collector sweep-coil system with a sweeping frequency of 7 Hz has been optimized to distribute the spent electron beam along the collector wall approximately uniformly. As a result of the optimizations, in which the influence of the eddy currents in the collector wall have been considered, a time averaged power loading below 500 W/cm² has been obtained at the collector wall [8]. However, the simulations have shown great sensitivity of the calculated power distribution to the value of the electrical conductivity of the collector wall, which is dependent by the temperature of the wall. The average power dissipated on the collector may increase to about 3.4 MW during modulation of the RF output power with 50% duty factor. An improved design of the collector is therefore under study.

3. Status of the industrial prototype gyrotron

Fig. 1 shows a schematic view and a photo of the completed first prototype of the coaxial cavity gyrotron. After bake-out and factory acceptance tests the gyrotron is expected to be delivered to CRPP, Lausanne in October 2006. At CRPP Lausanne a facility for testing the coaxial gyrotron up to CW has been constructed and is ready for operation [9]. The fabrication of a suitable superconducting (SC) magnet, which has been ordered for operation of the gyrotron, is delayed. Presently the delivery is expected in January 2007. Therefore, the gyrotron experiments with generation of RF power will not start before February 2007. Nine months are foreseen for the experimental investigations.

4. Experimental 170 GHz pre-prototype coaxial cavity gyrotron

4.1 Experimental setup

The pre-prototype coaxial cavity gyrotron is an experimental tube of demountable type which can be operated at pulses up to a few ms limited mainly by the power loading at the collector surface since no beam sweeping is applied.

The electron gun is a coaxial magnetron injection gun (CMIG) of diode type similar to the one which has been used in the previous experiments at 165 GHz [4]. Although the gun is used at short pulses, it has a performance as required for CW operation. The inner part of the coaxial insert is water cooled and its position can be adjusted under operating conditions. Special care has been devoted to the design of the lower part of the gun in order to avoid trapping of electrons, which may result in a limitation of the high voltage performance due to built-up of a Penning discharge [9]. At $I_b = 75$ A the emitting current density is about 4.2 A/cm².

The geometry of the coaxial cavity designed for operation in the TE_{-34,19} mode at 170 GHz [6] is the same as foreseen for the prototype tube. Due to the reduced value of the magnetic field the excitation of the nominal TE_{34,19} mode at 170 GHz is expected for accelerating voltages below about 80 kV (Table I).

The aim of the q.o. RF output system is (1) to convert the RF-power generated in the cavity in the TE_{34,19} mode into a free-space beam with high content of the fundamental Gaussian mode

and (2) to keep the microwave losses inside the gyrotron low. The q.o. system consists of a dimpled-wall launcher with a helical cut and three mirrors - one quasi-elliptical mirror followed by a toroidal mirror and a phase correcting mirror with an adapted, non-quadratic surface contour function [10]. The q.o. system has the same geometry as designed for the prototype tube.

As RF output window a disc made of fused silica with an optical thickness of $15\lambda/2$ at 170 GHz is taken in the pre-prototype tube, whereas the 2 MW prototype gyrotron will use a CVD diamond disc with a thickness of $5\lambda/2$. Both windows have an aperture of 96 mm. Due to the larger electrical thickness the frequency bandwidth of the fused silica window is smaller than the bandwidth of the diamond window.

4.2 Results

Extensive measurements have been performed to prove the design of critical components. The results obtained with the pre-prototype gyrotron are relevant for the prototype tube since both gyrotrons have a similar geometry and field distribution.

When first starting the operation, strong parasitic low frequency (LF) oscillations have been excited at frequencies around 259 and 328 MHz at beam currents $I_b \geq 10$ A and accelerating voltages $U_c \geq 40$ kV. The amplitude of these LF oscillations could become large enough to prevent stable gyrotron operation. Ultimately, the oscillations have been suppressed by placing microwave absorbing material ("Eccosorb") around the bottom end of the coaxial insert. To understand the mechanism of the LF oscillations, numerical simulations have been performed with the commercial software "CST microwave studio" using the detailed geometry of the whole gyrotron including the bore hole of the SC-Magnet as input. The calculated resonance characteristic has been found to be in good agreement with the observed frequencies. In addition, the simulations resulted in the resonance field distribution of the LF oscillations. The results clearly show that the observed parasitic LF oscillations are related to the coaxial geometry of the gyrotron. Based on this a mechanism for excitation of the LF oscillations has been developed. As a consequence of the proposed excitation mechanism, it has been suggested, to modify in the prototype gyrotron the contour of the insert on the gun side of the cavity, in order to increase the starting current of the LF oscillations and thus to suppress an appearance of the parasitic oscillations.

Electron gun and electron beam:

The behavior of the electron gun has been found to be in agreement with the design. No limitations of the high voltage performance due to build up of a Penning discharge inside the gun occurred. Stable operation up to $I_b \approx 80$ A and $U_c \approx 80$ kV has been obtained without any observable beam instabilities.

Cavity and RF-interaction:

The nominal co-rotating $TE_{34,19}$ mode has been excited stably in single-mode operation over a wide parameter range. Fig. 2 shows as example the RF output power and beam current in dependence of the beam voltage. At the maximum obtainable value of the magnetic field $B_{cav} = 6.718$ T, an RF output power up to 1.15 MW has been measured at $I_b \approx 77$ A and $U_c = 74.5$ kV in the nominal mode. Its frequency is very close to 170 GHz. With further increasing of U_c the $TE_{33,19}$ mode at 167.85 GHz occurred as the first competitor followed by the $TE_{32,19}$ mode at 165.74 GHz. According to numerical simulations the $TE_{34,19}$ mode at 170 GHz is expected to oscillate until $U_c \approx 80$ kV at the used value of B_{cav} , followed by the $TE_{32,19}$ mode [6]. The reason for the disagreement with the experimental observations is under investigation. In particular, the simulations are going to be improved by using more realistic input parameters. At present the influence of energy spread, and of microwave stray radiation

is not taken into account in the calculations. Experimentally the influence of a radial misalignment of the electron beam and the coaxial insert relative to the outer cavity wall has been investigated. It is observed that a radial displacement of the beam and insert relative to the cavity wall causes some reduction of the oscillating range. However, an alignment accuracy better than $\delta R = \sim 0.15$ mm seems to be sufficiently good not to influence the gyrotron behavior markedly. In the experiments an alignment accuracy of better than 0.1 mm has been obtained.

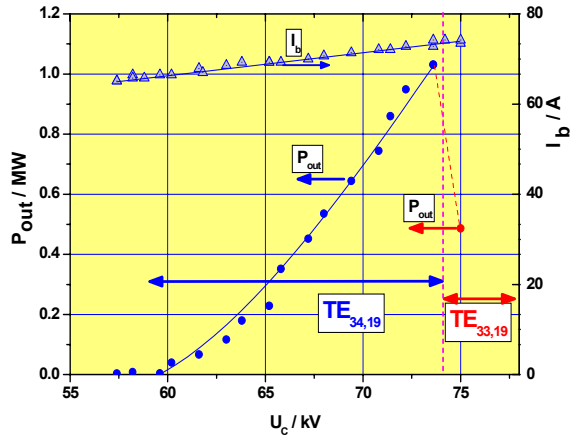


Fig. 2: Microwave output power P_{out} versus U_c . $B_{cav}=6.718$ T. $I_b \approx 65-75$ A is increasing with U_c due to the Schottky effect

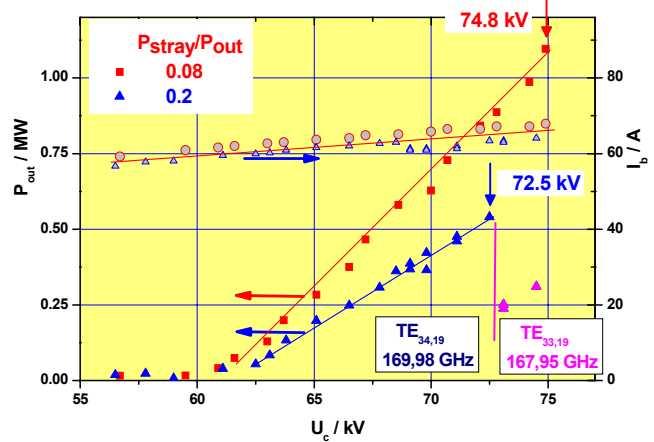


Fig. 3: P_{out} vs. U_c for two levels of stray radiation. $B_{cav} = 6.718$ T. I_b is approximately same in both cases.

The level of the stray radiation captured inside the gyrotron P_{stray} has been measured to be about 8% of the RF-output power, $P_{stray}=0.08 \times P_{out}$. To study the influence of the stray radiation on microwave generation, the amount of P_{stray} inside the gyrotron has been increased by undirected reflection of a part of P_{out} back into the gyrotron. It has been found that an increase of the level of stray radiation by only 2.5%, from $P_{stray}=0.08 \times P_{out}$ to $P_{stray}=0.105 \times P_{out}$, resulted in a reduction of P_{out} by about 15% while a further increase of the level of P_{stray} by 12%, from $P_{stray}=0.08 \times P_{out}$ to $P_{stray}=0.2 \times P_{out}$, has caused a reduction of P_{out} by $\sim 35\%$. In this latter case also a reduction of the oscillating range by about 2.5 kV has also been observed (Fig. 3). To prove the influence of the internal part of the stray radiation on the microwave generation, an efficient internal microwave absorber will be used to reduce the level of the captured stray radiation. In a previous experiment a reduction of the level of the stray radiation by using efficient internal absorbers resulted in improvement of the gyrotron performance [11]. It is planned to investigate on the pre-prototype tube, the influence of power reflection at the RF output window on the mode competition by using a broadband Brewster window.

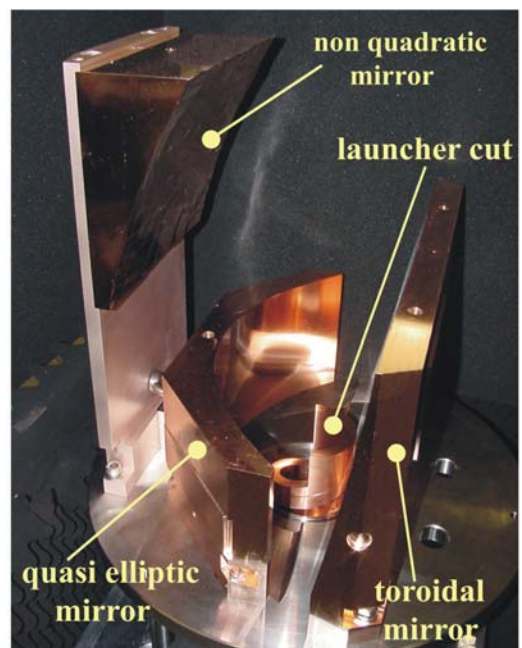


Fig. 4. Photography of the q.o. RF output system fabricated for the prototype gyrotron as installed for measurements at low power.

Quasi-optical (q.o.) RF-output system:

The performance of the q.o. RF output system has been investigated both at low power levels ("cold") [12] and at high power ("hot") with the pre-prototype gyrotron. The "cold" measurements allow to prove the integral performance of the whole q.o. RF output system before assembling inside the tube. Fig. 4 shows the launcher and the mirrors, as fabricated for the prototype tube, installed in the low power test facility. In Fig. 5 results of "cold" measurements in the plane of the RF output window are shown in comparison with calculations. The measurements have been performed with the q.o. system used in the pre-prototype tube as well as with the system manufactured for the prototype gyrotron. There is a reasonable agreement between the experiment and the design calculations. In particular, the microwave power is well coupled out through the output window. Fig. 6 shows the power distribution of the microwave output beam in a plane 500 mm outside the window. In that figure the calculated power distribution is compared with results of "cold" and "hot" measurements performed with the q.o. system used in the pre-prototype gyrotron. The agreement between the measurements and the calculation is good. The content of the fundamental Gaussian in the RF output beam has been analyzed and found to be only around 70 %. Enhancement of the Gaussian content to a value around 95% is, however, essential for efficient application in a tokamak installation. The design of a corresponding improved q.o. RF output system is in progress.

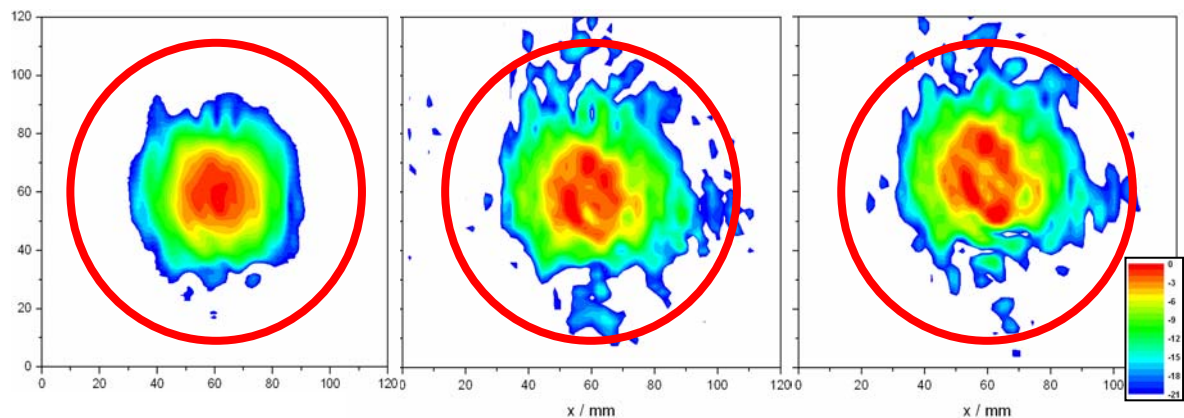


Fig. 5: Power distribution of the RF output beam (in steps of 3 dB) at the window plane obtained in low power ("cold") measurements: calculations (left), prototype (middle), pre-prototype (right). The aperture of the output window (96 mm) is indicated.

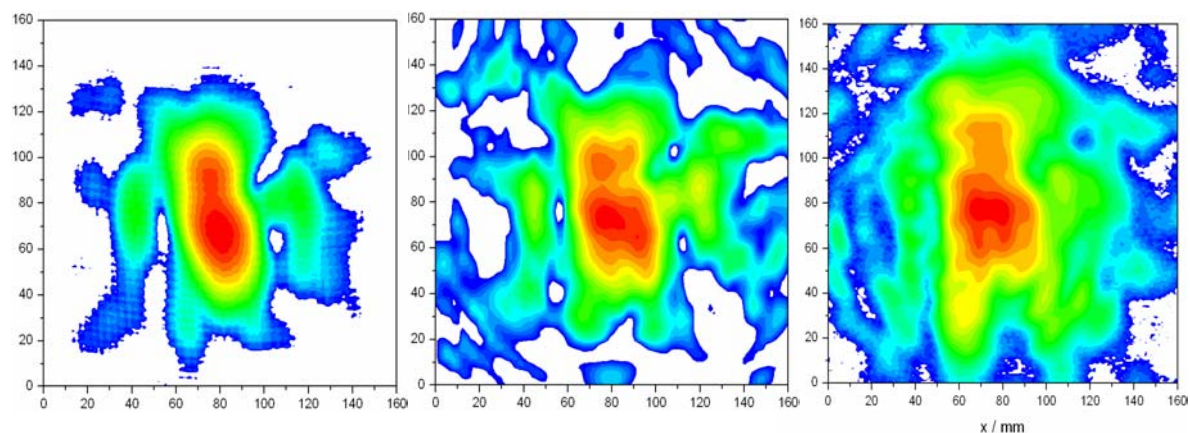


Fig. 6: Power distribution of the RF output beam (in steps of 3 dB as in Fig. 5) of the pre-prototype gyrotron in a plane 500 mm outside the window: calculations (left), "hot" measurements (middle), "cold" measurements (right). Edge lengths = 160 mm.

As mentioned above, the amount of stray losses inside the tube has been determined to be as high as about 8% of P_{out} . To keep the level of stray radiation inside the prototype gyrotron

low, the use of internal microwave absorbers installed inside the mirror box has been studied in the pre-prototype tube. Based on these results, internal absorbers consisting of water cooled Al_2O_3 tubes have been installed in the prototype gyrotron which are expected to reduce significantly the level of stray radiation in the prototype gyrotron.

5. Summary and outlook

The fabrication of the industrial prototype is completed. The tube will be delivered to CRPP, Lausanne within the next months. At CRPP Lausanne a facility for testing the 2 MW, CW gyrotron has been constructed and is now ready for operation. Due to manufacturing problems, the delivery of the SC magnet is delayed and is presently expected for January 2007. Thus, RF tests with the first prototype tube will not start before February 2007. The short pulse pre-prototype 170 GHz gyrotron has been used to validate the design of critical components of the first industrial prototype. In general, the obtained results are promising concerning the microwave generation at 170 GHz in the prototype gyrotron. However, further studies are needed to clarify the observed discrepancy in the microwave generation. The generated microwave power is coupled out of the gyrotron efficiently despite the low Gaussian content in the RF output beam. The design of a system with a Gaussian content around 95% is in progress.

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