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A 2 MW, 170 GHz coaxial cavity gyrotron - experimental verification of the design of main components

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Abstract. A 2 MW, CW, 170 GHz coaxial cavity gyrotron is under development in cooperation between European Research Institutions (FZK Karlsruhe, CRPP Lausanne, HUT Helsinki) and the European tube industry (TED, Velizy, France). The design of critical components has recently been examined experimentally at FZK Karlsruhe with a short pulse (~ few ms) coaxial cavity gyrotron. This gyrotron uses the same cavity and the same quasi-optical (q.o.) RF-output system as designed for the industrial prototype and a very similar electron gun.

1. Introduction

Coaxial cavity gyrotrons have the potential to generate microwave power in the multi-megawatt range in continuous wave (CW) operation at frequencies around 170 GHz since very high-order volume modes can be used. The use of very high-order volume modes is possible because the presence of the coaxial insert practically eliminates the restrictions related to voltage depression and, in addition, the problem of mode competition is reduced by a selective influence on the diffractive quality factor of the competing modes [1]. The increase of the RF output power per unit would result in a reduction of the installation costs of the electron cyclotron wave (ECW) system at ITER and it would allow, if necessary, to enhance the total amount of microwave power injected into the plasma.

In development work performed at FZK Karlsruhe during the last years the feasibility of manufacturing a 2 MW, CW coaxial cavity gyrotron at 170 GHz has been demonstrated and information necessary for a technical design has been obtained [2,3]. Based on these results the fabrication of a first industrial prototype of a 2 MW, CW, 170 GHz coaxial cavity gyrotron for ITER has started in cooperation between European research centers (FZK Karlsruhe, CRPP Lausanne, HUT Helsinki) and a European industrial partner (Thales ED, Velizy, France) [4].

In parallel to the work on the industrial prototype tube, the experimental 165 GHz coaxial cavity gyrotron used previously at FZK, has been modified for operation at 170 GHz. This short pulse (≤ 5 ms) experimental gyrotron ("pre-prototype") operates in the same $TE_{34,19}$ mode and uses the same cavity with uptaper, launcher and mirrors as designed for the industrial prototype and in addition, a very similar electron gun. Therefore the pre-prototype tube has been used to verify the design of the main components of the industrial long pulse tube under relevant conditions. Experimental investigations on the pre-prototype have been performed recently. In the following the main gyrotron components are described and results of the experimental verification are presented and discussed.

2. Pre-prototype of the 170 GHz, 2 MW, CW coaxial cavity gyrotron

In table 1 the main nominal design parameters are summarized both for the 2 MW, CW prototype gyrotron and for the short pulse pre-prototype tube. The SC-magnet available at FZK for experiments with the pre-prototype delivers only a magnetic field up to about 6.7 T. Due to this the beam voltage had to be reduced to values below 80 kV in order to be able to excite the $TE_{34,19}$ mode at 170 GHz. According to simulations, operation at a lower voltage results in an RF output power reduced to about 1.5 MW, depending on the finally obtained magnetic field.

Table 1. Design parameters of the prototype and short pulse 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	~ 75
cavity magnetic field, B_{cav} / T	6.87	~ 6.7
velocity ratio, α	~ 1.3	

2.1. Experimental setup

A coaxial magnetron injection gun (CMIG), similar as used in the 165 GHz gyrotron [5], has been designed and fabricated. A schematic view of the gun is shown in figure 1. At I_b = 75 A the emitting current density is about 4.2 A/cm^2. The inner part of the coaxial insert is water cooled and its position can be adjusted under operating conditions. Special care has been taken in designing the geometry of the bottom part of the cathode body and of the insert in order to avoid regions in which electrons can be trapped. In such regions a Penning discharge could be built up and limit the high voltage performance, as observed in earlier experiments [4].

In order to keep the Ohmic losses at the cavity wall below 1 kW/cm² (ideal copper at 273 K) for 2 MW RF output power the $TE_{34,19}$ mode has been selected as the operating mode [6] instead of the $TE_{31,17}$ mode which was used in the experiments at 165 GHz. The corresponding peak losses at the insert are expected to be less than 0.1 kW/cm². The geometry of the 170 GHz, $TE_{34,19}$ cavity is shown in figure 2. The problem of mode competition has been investigated with a time dependent, self consistent multimode code considering up to 13 competing modes. The main competition has been found to occur between the two mode triplets, $\{TE_{-33,19}$, $TE_{-34,19}$, $TE_{-35,19}\}$ and $\{TE_{+32,20}$, $TE_{+33,20}$, $TE_{+34,20}\}$. According to the calculations, single-mode oscillation of the $TE_{34,19}$ mode is expected for accelerating voltages between about 65 and 75 kV for B_{cav} = 6.68 T (Fig. 3). This voltage range shifts to higher values with increasing magnetic field.

The aim of the q.o. RF output system is, as indicated in figure 4, to convert the RF-power generated in the $TE_{34,19}$ mode inside the cavity into a free-space beam with high content of the fundamental Gaussian mode. The conversion of the very high order gyrotron mode into a free space Gaussian mode is a very complex task. The designed q.o. system (figure 4) 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. To keep the microwave losses inside the gyrotron tube within technically acceptable limits, a dimpled-wall launcher with reduced diffraction losses at the edge of the launcher cut is used [7]. However, because of limitations in the accuracy of mechanical fabrication of the surface structure of the non-quadratic mirror a compromise had to be made between the Gaussian content of the RF output beam and the amount of microwave losses inside the tube. According to calculations the total amount of stray losses is expected not to exceed a value of 5 % to 6 % of P_{out}.

For this gyrotron, the RF output window a disc made of fused silica with an optical thickness of

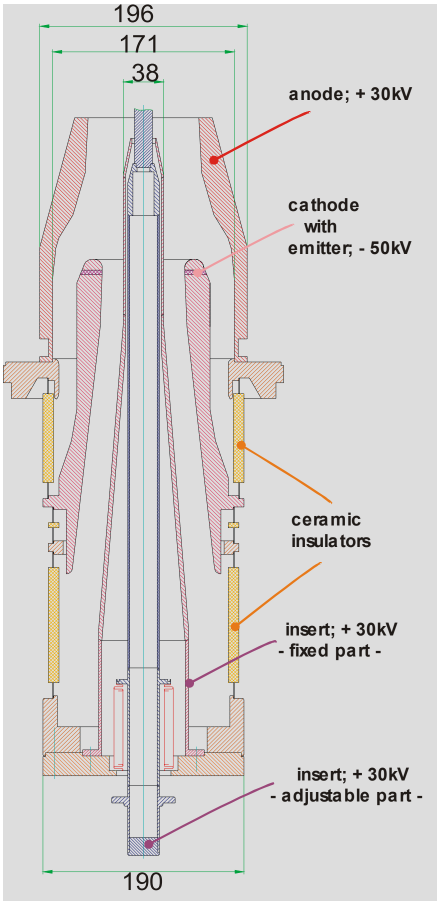

Figure 1. Schematic view of the CMIG gun.

15λ/2 at 170 GHz, whereas for the 2 MW prototype a 5λ/2 disc made of CVD diamond is foreseen.

A schematic view of the whole pre-prototype coaxial gyrotron and a photograph of the assembled tube are shown in figure 5. The presence of three relief windows with diameter of 100 mm allows one to measure the amount of microwave stray losses inside the tube.

2.2. Experimental operation and results

When starting the gyrotron operation strong parasitic low frequency (LF) oscillations at frequencies of around 259, 328 and 68 MHz have been observed at beam currents $I_b \geq 10$ A and accelerating voltages $U_c \geq 40$ kV. The amplitude of these LF oscillations could become very large, completely preventing a stable gyrotron operation. The most severe LF oscillation appeared at ~259 MHz. The appearance of those LF oscillations was unexpected, in particular, because no such oscillations have been observed in the previous 165 GHz coaxial gyrotron with very similar geometrical dimensions (in comparison to the wavelength of the LF frequencies). Finally it was found that the whole coaxial insert (total length ~ 1.2 m) acts as a full wavelength coaxial resonant circuit with open ends on both sides [8]. The capacitance at the bottom side between the insert and ground dominates the termination at the LF frequencies. Therefore, in agreement with observations, practically no influence of the external cabling on the oscillating frequency has been observed. Finally the oscillations were completely suppressed by placing absorbing material ("eccosorb") around the bottom end of the insert. The corresponding reduction of the quality factor of the coaxial LF resonator formed by the whole insert resulted in an increase of the starting current for exciting the LF oscillations to beam currents $I_b > 80$ A.

2.2.1 Electron gun and electron beam. The performance of the electron gun has been found to be in agreement with the design objective as far as the properties have been observable during the gyrotron operation. No limitations on high voltage performance due to build up of a Penning discharge have been observed. An extension of the pulse length up to 100 ms / 40 ms at $I_b \approx 1$A / 17 A did not show any indications of occurrence of a Penning discharge inside the gun. Stable operation up to $I_b \approx 80$ A and $U_c \approx 80$ kV has been observed without any beam instabilities. The current to the insert was measured to be below 0.1% of the beam current, in agreement with the results of previous experiments.

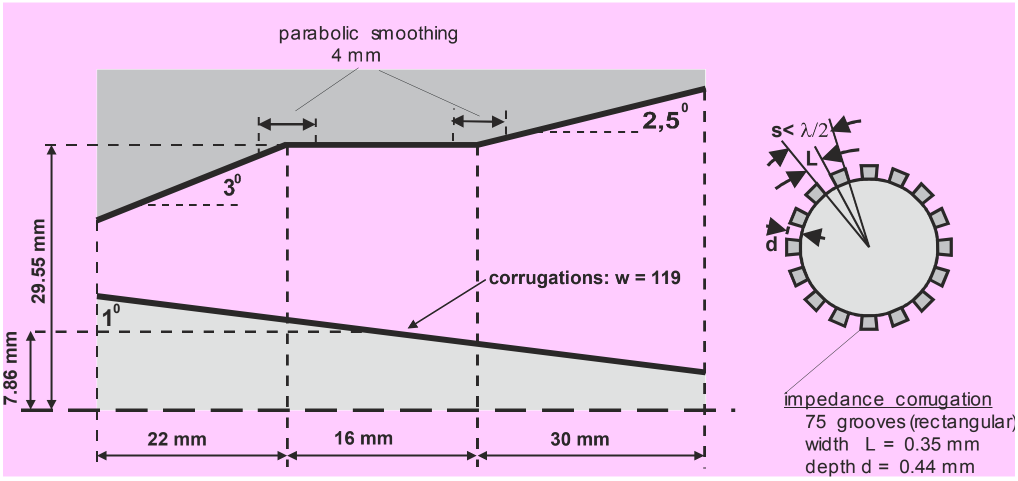

Figure 2. Geometry of the 170 GHz, $TE_{34,19}$ coaxial cavity.

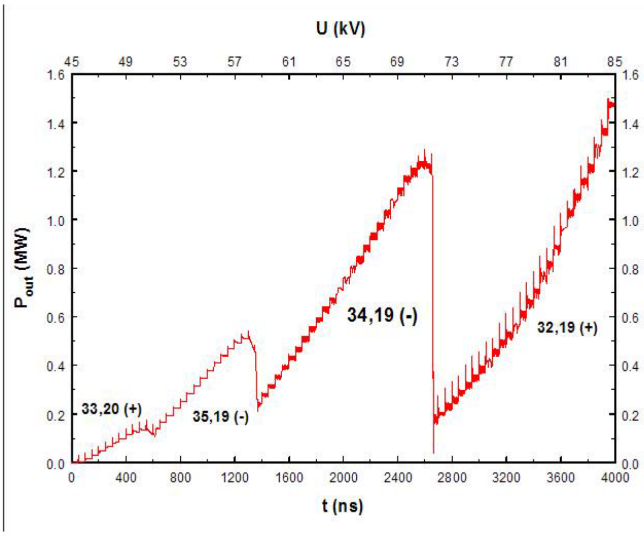

Figure 3. Simulated start-up behavior of the gyrotron (RF output power versus beam voltage) as obtained with a self consistent, time dependent multi mode code for $B_{cav} = 6.68$ T. A diode behavior of the gun has been assumed with $I_b = 50$ A and $\alpha = 1.3$ at $U_c = 80$ kV has been assumed [6]. The given voltage U corresponds to the beam energy (without voltage depression).

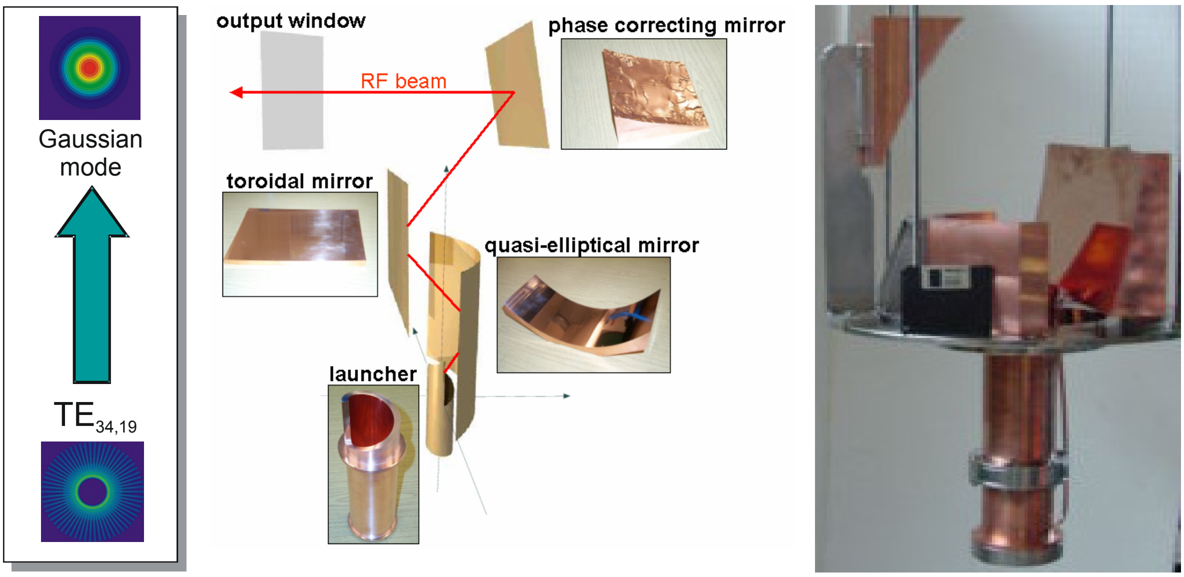

Figure 4. The q.o. RF-output system, schematic arrangement and photograph.

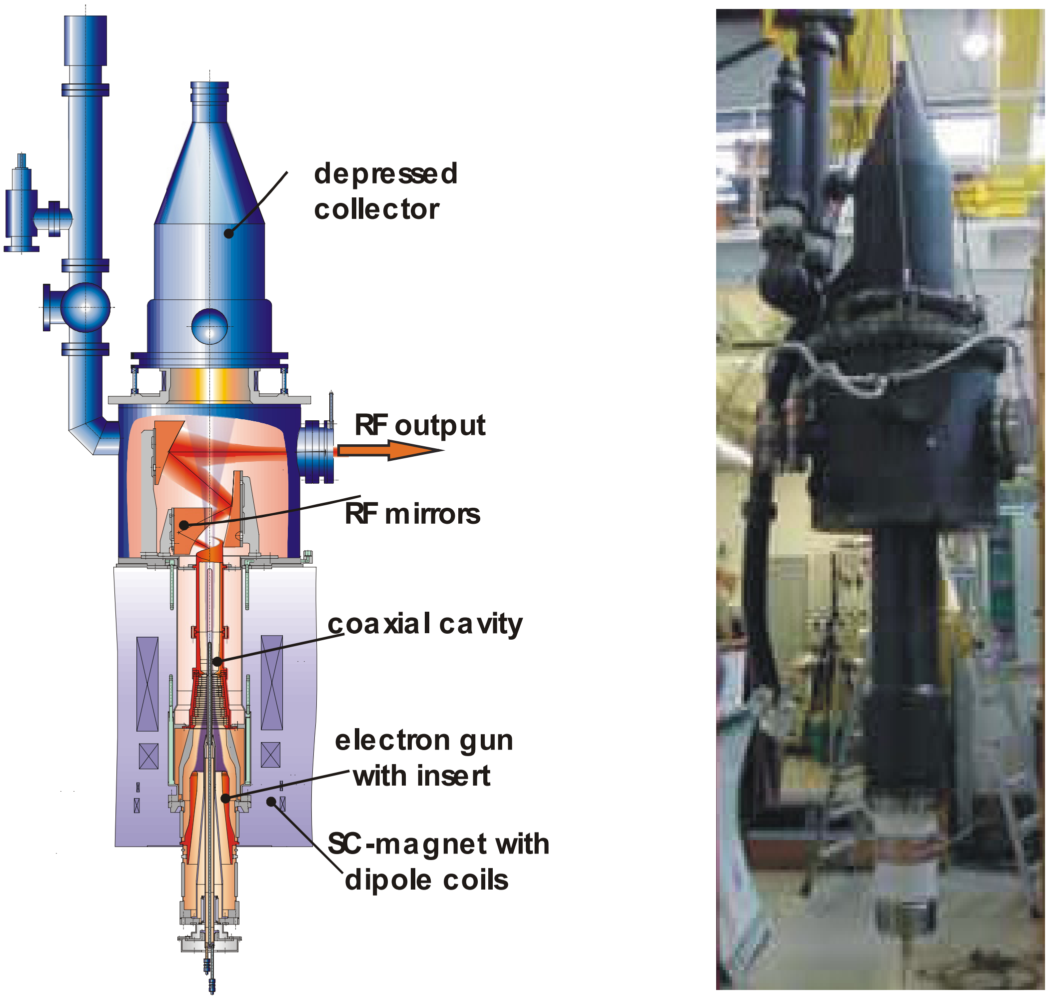

Figure 5. Pre-prototype of the 170 GHz coaxial gyrotron, left side: schematic arrangement, right side: photo of the assembled tube.

2.2.2. Cavity and RF-interaction. After suppressing the excitation of the parasitic low frequency oscillations, measurements in the gyrotron mode have been performed. The inner conductor has been radially aligned with respect to the electron beam within ± 0.1 mm and the concentricity between the electron beam and the cavity wall has been verified. In general the results obtained can be summarized as follows:

The nominal $TE_{34,19}$ mode at 170 GHz has been excited stably in single-mode operation over a wide parameter range. Figures 6a and 6b show typical behaviour of the RF output power measured as a function of the applied accelerating voltage U_c for beam currents between 50 and 75 A. The magnetic field B_{cav} has been increased up to $B_{cav} = 6.718$ T and the beam radius has been optimized for maximum output power in the nominal mode by varying the magnetic compression ratio. In the measurements shown the magnetic field and the heating power of the cathode have been kept constant. In all cases the $TE_{33,19}$ mode at 167.85 GHz occurred as the main competitor with increasing U_c followed by the $TE_{32,19}$ mode at 165.74 GHz. This experimentally observed mode sequence with increasing beam voltage is not in agreement with the expected results of numerical simulations (Fig,3), namely:

experiment: ---- **$TE_{-34,19}$** $\rightarrow$ $TE_{-33,19}$ $\rightarrow$ $TE_{-32,19}$

theory: $TE_{+32,20}$, $TE_{-35,19}$ $\rightarrow$ **$TE_{-34,19}$** $\rightarrow$ $TE_{-32,19}$

In the experiment the nominal $TE_{-34,19}$ mode was practically always followed by the $TE_{-33,19}$ mode before the $TE_{-32,19}$ mode started to oscillate. Probably as a consequence of the occurrence of the $TE_{-33,19}$ mode as an additional competitor the oscillation range of the nominal $TE_{34,19}$ mode ends at lower beam energies than expected from simulations.

Another result of the reduced range of oscillation is the fact that the maximum measured RF output power ($P_{out} \cong 1.15$ MW) and corresponding efficiency of about 20 % are relatively low. At the lower voltages ($U_c \leq 73$ kV) the velocity ratio is fairly low ($\alpha \leq 1.1$). However, the reasons for the discrepancy between theory and experiment is unclear and needs further investigations.

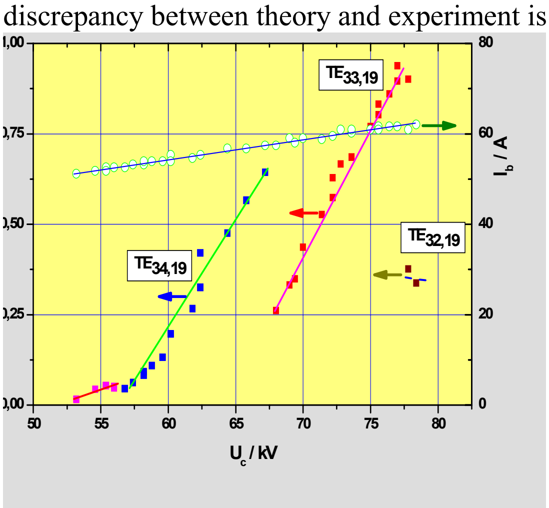

Figure 6a. RF output power and beam current versus cathode voltage at $B_{cav} = 6.668$ T.

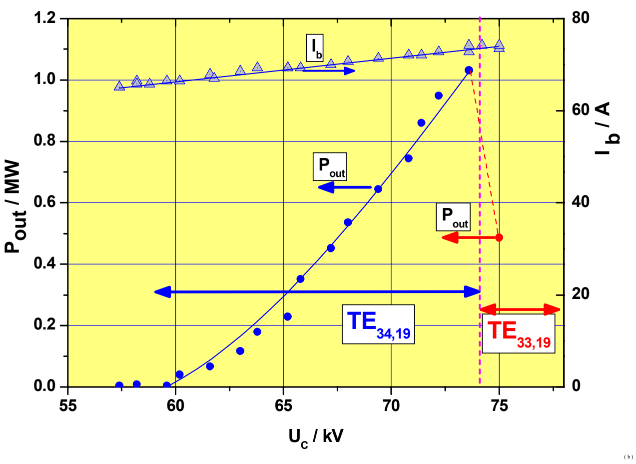

Figure 6b. RF output power and beam current versus cathode voltage at $B_{cav} = 6.718$ T.

2.2.3. Quasi-optical (q.o.) RF-output system. The performance of the q.o. RF output system has been studied both at low power levels ("cold") and at high power ("hot") with the gyrotron. Figures 7 show the power distribution of the RF output beam in the window plane placed 350 mm from the gyrotron axis. The distribution according to the original design (figure 7, upper left) is not in agreement with results of either the "cold" (figure 7, lower left) or "hot" (figure 7, lower right) measurements. However, there is a reasonably good agreement between the "cold" and "hot" measurements. The reason for the disagreement between the design calculations and the experimental observations has been found to be a design error. By mistake the optimization of the mirrors was performed with a wrong launcher field distribution. Good agreement with the experimental results was obtained when the calculations were redone with the correct launcher field distribution (figure 7, upper right). This agreement strengthens the confidence in the reliability of the design code. As a consequence of the error, the two last mirrors have been redesigned and are under fabrication. The expected microwave field pattern is similar to the distribution of the original design (figure 7, upper right).

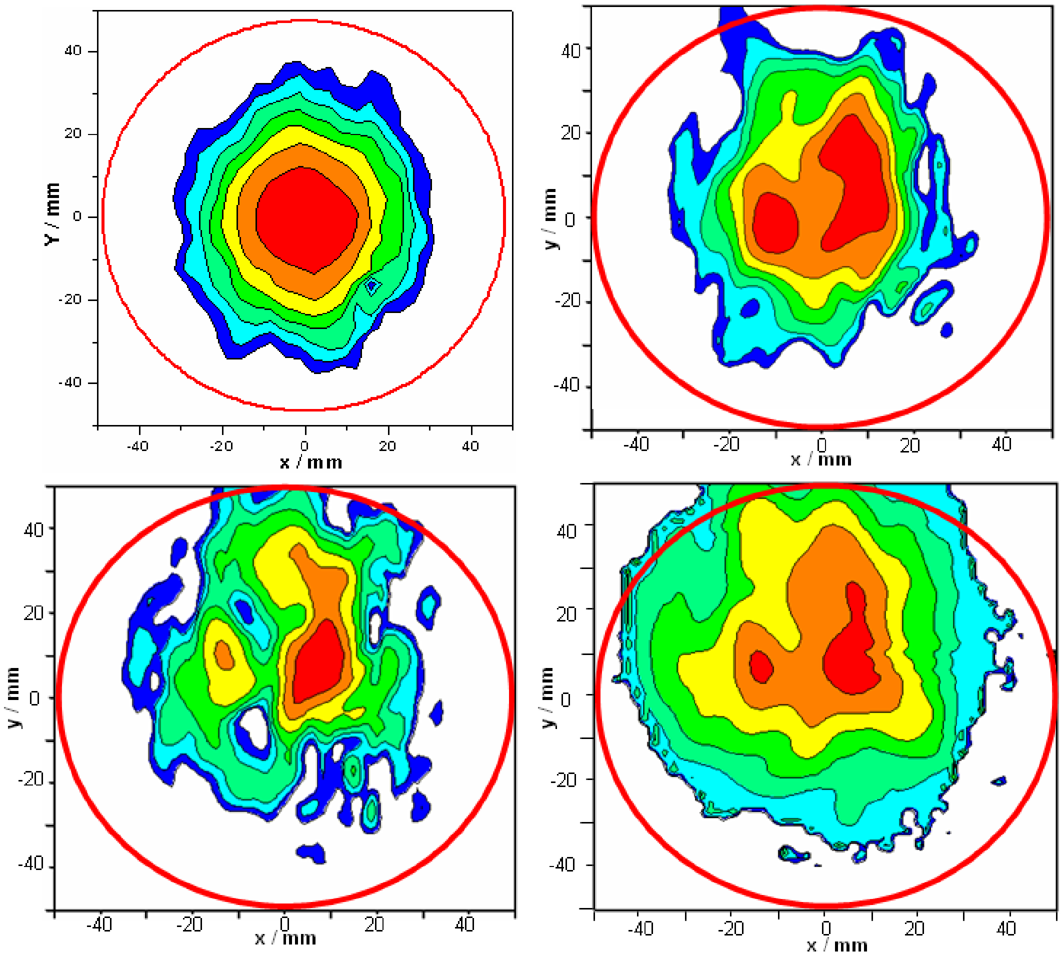

Figure 7. Distribution of the power of the RF output beam in the window plane; upper left = original design; lower left = "cold" measurements; lower right = "hot" measurements; upper right = calculation with correct launcher field.

2.2.4. Microwave stray losses inside the tube. The mirror box has a total of three relief windows in addition to the main RF output window. All the windows have a diameter of 100 mm. The amount of stray losses inside the tube has been determined by measuring the power radiated through one relief window with a sensitive bolometer both for the case when the two other relief windows were covered either with a reflecting metal plate or with a good absorber. As summarized in table 2, stray losses of about 8% have been estimated for operation in the nominal $TE_{34,19}$ mode at 170 GHz. For the $TE_{33,19}$ mode at 167.85 GHz the stray losses have been approximately three times as high, namely about 22 %. The main reason for the increase of the losses at the $TE_{33,19}$ mode is due to the large power reflection at the RF output window of about 9%. The absolute value of power radiated through the relief window has been measured to be 0.74 % of P_{out} at 170 GHz and 1.9 % of P_{out} in the $TE_{33,19}$ mode. The power radiated through the relief windows was approximately the same in all windows, confirming the assumption of a nearly uniform distribution of the stray losses inside the mirror box.

Table 2. Microwave stray losses inside the gyrotron.

mode	$\mathbf{TE_{34,19}}$	$TE_{33,19}$
frequency / GHz	**169.9**	167.85
power reflection from window / dB	**-20**	-10.5
power reflection from window	**0.01**	0.09
microwave stray losses, P_{stray} / P_{out}	**0.08**	0.22
power through a relief window, P_{relief} / P_{out}	**0.0074**	0.019
power absorbed in the internal load, P_{load} / P_{out}	**0.022**	0.055

2.2.5. Operation with internal microwave absorbers. In order to reduce the amplitude of the captured stray radiation inside the gyrotron tube, effective internal microwave absorbers are proposed. To measure the absorption efficiency a test internal absorber consisting of an array of four water cooled Al_2O_3 tubes (diameter = 20 mm, length = 100 mm) has been installed inside the mirror box as shown in figure 8. The power absorbed in the tubes has been measured calorimetrically. As given in table 2 in the nominal mode 2.2 % of P_{out} has been found to be absorbed in the internal loads, approximately 3 times the power radiated through one relief window with 100 mm diameter. The position of the Al_2O_3 tubes inside the mirror box may have some influence on the absorption efficiency. The operation with the internal absorbing tubes did not show any significant influence on the microwave generation.

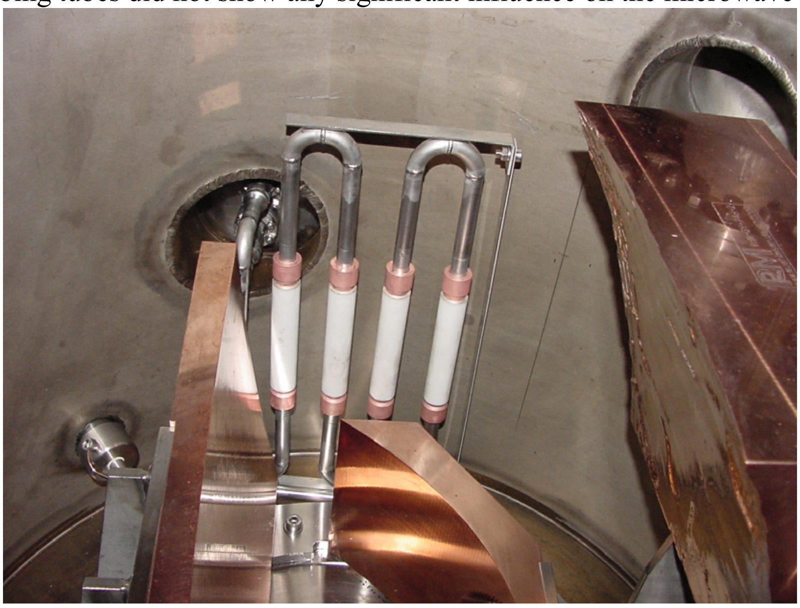

Figure 8. View of the internal absorbers inside the gyrotron mirror box.

3. Summary and outlook

The short pulse pre-prototype of the 170 GHz, 2 MW, CW gyrotron has been used to verify under relevant conditions the design of critical components as electron gun, cavity and RF output system of the 1st industrial prototype of the 2 MW, CW 170 GHz coaxial cavity gyrotron. The cavity and the quasi-optical RF output coupler are identical to those designed for the industrial tube. The electron gun is very similar to the gun designed for the prototype tube. The pulse length is limited to a few ms mainly by the peak power loading at the collector surface.

The performance of the electron gun is in agreement with the design. The gyrotron has been operated stably up to an electron beam current of 80 A.

The nominal $TE_{34,19}$ mode has been excited at 170 GHz over a reasonably wide parameter range. At a magnetic field of 6.716 T, limited by the available SC-magnet, a maximum RF output power of about 1.15 MW has been measured. The experimentally observed mode sequence with increasing beam voltage is not in agreement with theoretical predictions. In particular a more dense mode spectrum has

been excited in the experiment than expected from simulations. The reason for this is under investigation.
The q.o. system has been tested both at low power ("cold") and in the gyrotron ("hot"). A mistake made in optimization of the mirrors is responsible for the observed disagreement with the design calculations. A repeat of the optimization of the q.o. system with the correct launcher field has been performed. The last two mirrors have been redesigned and are under fabrication. Measurements of the stray losses have been performed. An internal load has been found to be an efficient absorber of the stray losses.
In conclusion it can be stated that the results confirm the main features of the design of the 2 MW, CW 170 GHz industrial prototype of the coaxial gyrotron.

References

[1] Iatrou C T, Kern S and Pavelyev A, 1996, Coaxial cavities with corrugated inner conductor for gyrotrons, *IEEE Microwave Theory Tech.* **41,1** 56-64
[2] Piosczyk B et al. 2004, 165 GHz Coaxial Cavity Gyrotron - last results, *IEEE Trans. Plasma Science* **32,3**, 853-60.
[3] Piosczyk B et al., 2004, A 2 MW, 170 GHz Coaxial Cavity Gyrotron, *IEEE Trans. Plasma Science* **32,3**, 413-7.
[4] Hogge J P et al., 2005, Development of a 2 MW, CW, Coaxial Cavity Gyrotron at 170 GHz and test facility for ITER, *Third IAEA Technical Meeting on "ECRH Physics and Technology for ITER ", 2 May – 4 May 2005, Como, Italy*.
[5] Piosczyk B, 2001, A novel 4.5 MW electron gun for a coaxial gyrotron, *IEEE Trans. Electron Devices*, **48,12** 2938-44
[6] Dumbrajs O et al., 2001, Mode selection for a 2 MW, CW 170 GHz coaxial cavity gyrotron, *26th Inter. Conf. on Infrared and Millimeter Waves, Toulouse, France,* pp.10-14
[7] Michel G, 2003, Synthesis of Yet-footprint-mirrors with low stray radiation, EC 13, May 17-20, Nizhny Novgorod, Russia.
[8] Piosczyk B et al., 2004, Progress in the development of the 170 GHz coaxial cavity gyrotron, *29th Inter. Conf. on Infrared and Millimeter Waves, Karlsruhe, Germany, pp.107-108*