2 MW, CW, 170 GHz Coaxial Cavity Gyrotron

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Abstract

Gyrotrons with coaxial cavities have the potential to generate millimetre wave power in the multi megawatt range. The development of a 2 MW, CW, 170 GHz coaxial cavity gyrotron is in progress. The basis for the work are results obtained recently with a coaxial gyrotron operated at 165 GHz in short (~ms) pulses. The design of critical components as electron gun, cavity and quasi optical RF output system will be verified under realistic conditions. For that the existing 165 GHz tube is under modification for operation at 170 GHz in the selected mode.

1 Introduction

Millimetre waves can be used with great advantage for heating as well as for controlling of instabilities of magnetically confined plasmas of thermonuclear fusion devices. For fusion experiments of the next generation as the International Thermonuclear Experimental Reactor (ITER) a microwave power of at least 25 MW, CW at 170 GHz will be needed [1]. To reduce the costs of the installations of the electron cyclotron wave (ECW) system at ITER and to allow a compact system for launching the microwave power into the plasma an increase of the output power from 1 to 2 MW per gyrotron is desirable. Coaxial cavity gyrotrons have the potential to fulfil the requirement since very high-order volume modes can be used. This is because in coaxial arrangements the presence of the coaxial insert practically eliminates the restrictions of voltage depression and limiting current and in addition, the problem of mode competition can be reduced by a selective influence of the diffractive quality factor of competing modes [2].

The feasibility of manufacturing a 2 MW coaxial gyrotron operated in CW at a frequency around 170 GHz has been studied experimentally and theoretically during the last years at the Forschungszentrum Karlsruhe (FZK). The investigations have been performed on a coaxial gyrotron operated at 165 GHz in the $TE_{31,17}$ mode which is described in detail in [3,4]. The gyrotron was demountable and enabled an easy replacement of the components. Its cooling performance allowed only operation at short pulses (~ms) limited by the temperature rise of the collector wall due to the large peak wall loading. The problems specific to the coaxial arrangement have been studied. In particular, the mechanical stability and the required alignment accuracy of the insert with respect to the electron beam has been investigated. The losses at the insert have been measured calorimetrically. Further on, the dependence of the leakage current on operating conditions has been studied. A limitation of the high voltage performance due to build up of a Penning discharge has been successfully suppressed by modifying the gun geometry such that electron trapping is avoided. A maximum RF output power of 2.2 MW has been obtained in single-mode operation and efficient microwave generation has been demonstrated (up to 48 %). The conversion of the high-order cavity mode into a free space Gaussian mode has been performed in a quasi-optical (q.o.) RF output system consisting of a smooth launcher with a cut and two mirrors. The microwave stray losses captured inside the tube body have been investigated and the amount of the losses has been measured. The suitability of the major gyrotron components for a 2 MW, CW gyrotron has been examined. A first draft integral design of a 2 MW, CW coaxial gyrotron has been performed and no technical constraints have been found.

Based on these results the development of a coaxial cavity gyrotron with an RF output power of 2 MW, CW at 170 GHz as could be used for ITER is in progress in cooperation between European Euratom Associations (CRPP Lausanne, FZK Karlsruhe and HUT Helsinki) together with European tube industry (Thales Electron Devices, Velizy, France). An engineering design of such a gyrotron is in progress and will be finished soon. This includes as well a technical design of critical components, integration of the tube and design and specification of auxiliary components as superconducting magnet and power supplies. The manufacturing of a first industrial prototype is expected to start soon. For testing the gyrotron a high power test facility is under preparation at CRPP Lausanne.

In parallel to the work on the industrial prototype the experimental short pulse gyrotron at FZK operated in the $TE_{31,17}$ mode at 165 GHz is under modification for operation at 170 GHz in the $TE_{34,19}$ mode. This modified tube will be used to verify the design of the most critical components as electron gun, cavity and the quasi-optical RF output system under realistic conditions. The cavity dimensions and the geometry of the RF output system are foreseen to be the same in the prototype and in the experimental tube. The geometry of the electron gun, mainly of the anode, differs slightly from the gun of the industrial prototype because of the different magnetic field distribution and different anode voltage. However, the main features are same.

In the following the design of the critical components will be presented and then the status of the modifications will be described and the main goals of the experimental verification will be discussed.

2 Coaxial cavity gyrotron

The design parameters of the coaxial cavity gyrotron are given in Table 1, both of the 2 MW, CW prototype and the experimental short pulse tube (up to ~ 10 ms). The maximum magnetic field obtainable with the superconducting magnet used for operation of the short pulse gyrotron is only about 6.68 T. Therefore, in order to be able to excite the nominal operating mode at 170 GHz it is necessary to reduce the operating voltage to about 80 kV. Consequently the expected microwave power is less than 2 MW.

Tab. 1: Nominal design parameters of the prototype and the corresponding experimental short pulse tube.

	prototype	short pulse
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
retarding voltage, U_{coll} / kV	≅ - 34	~ - 30
output efficiency, η_{out}	≥ 45 %	
cavity magnetic field, B_{cav} / T	6.87	~ 6.68
velocity ratio, α	~ 1.3	
beam radius in cavity, R_b/mm	10.0	

All components have been designed and are already manufactured or near delivery. In the following the design of the components is given.

2.1 Electron gun

A coaxial magnetron injection gun (CMIG) similar as used in the previous short pulse experiments [5] has been designed. At the nominal beam current the emitting current density is about 4.2 A/cm^2. The nominal value of the ratio α (= transverse to axial velocity) has been taken to ~1.3. Fig. 1 shows schematically the geometry of the electron gun. The inner part of the coaxial insert is cooled with water and it can be adjusted under operating conditions. Special care has been taken in designing the geometry of the cathode and the insert in the technical (rear) part of the electron gun in order to avoid regions in which electrons can be trapped. This is necessary for suppressing the build up of a Penning discharge in that region which might result in a limitation of the high voltage performance.

The fabrication of the electron gun is nearly finished. The delivery is expected within the next weeks.

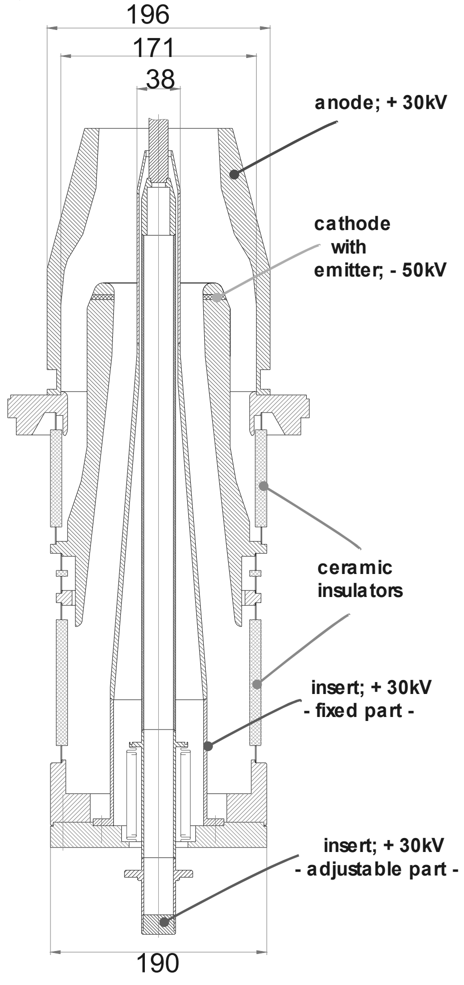


Fig. 1: Schematic arrangement of the CMIG gun. Dimensions in mm

2.2 Coaxial cavity

In order to keep the wall loading p_{peak} inside the cavity at 2 MW microwave output power within technically accepted limits the $TE_{34,19}$ mode has been selected [6] as operating mode instead of the $TE_{31,17}$ mode which has been used in the experiments at 165 GHz. The geometry of the cavity is shown in Fig. 2. The geometry is the same as foreseen for the 2 MW, CW prototype gyrotron. The Ohmic losses at the outer cavity wall have been calculated to be within 1 kW/cm² (ideal copper at 273^0K) at the nominal RF power. The corresponding peak losses at the insert are expected to be less than 0.1 kW/cm².
Because the maximum magnetic field of the existing SC-magnet at FZK is limited to a value between 6.66 and 6.70 T, a reduction of the beam voltage to about 80 kV becomes necessary in order to be able to excite the $TE_{34,19}$ mode at 170 GHz as already indicated in table 1. The start up behaviour of the experimental tube has been simulated with a time dependent, self consistent multimode code considering up to 13 competing modes. The main mode competition occurs between two mode triplets, $\{TE_{-33,19}, TE_{-34,19}, TE_{-35,19}\}$ and $\{TE_{+32,20}, TE_{+33,20}, TE_{+34,20}\}$. The results of the simulations are shown in Fig. 3.

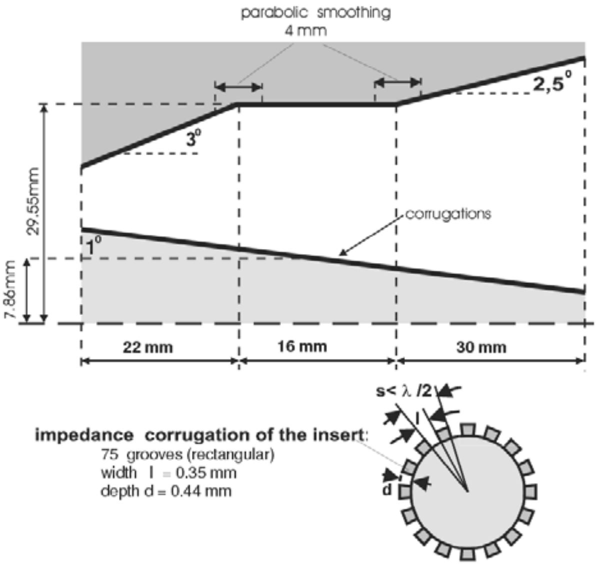


Fig. 2: Geometry of the $TE_{34,19}$ coaxial cavity.

The calculations have been done for two different values of the magnetic field with a velocity ratio $\alpha = 1.3$, a beam current $I_b = 70$ A at an accelerating voltage $U_c = 80$ kV. As relative transverse velocity spread $\delta\beta_{\perp rms}$ a value of 5 % has been assumed. The voltage range for excitation of the $TE_{34,19}$ mode depends on the value of the magnetic field. For the values assumed in Fig. 3 single-mode oscillation of the nominal $TE_{34,19}$ mode occurs between $U_c \cong 63$ and 77 kV. Due to the reduced beam voltage the calculated value of the generated microwave power is lower then expected in the 2 MW prototype gyrotron as indicated in Tab.1. However, the short pulse experiments will allow to verify under relevant conditions the efficiency of the microwave generation in the designed cavity and to investigate the problems of mode competition.

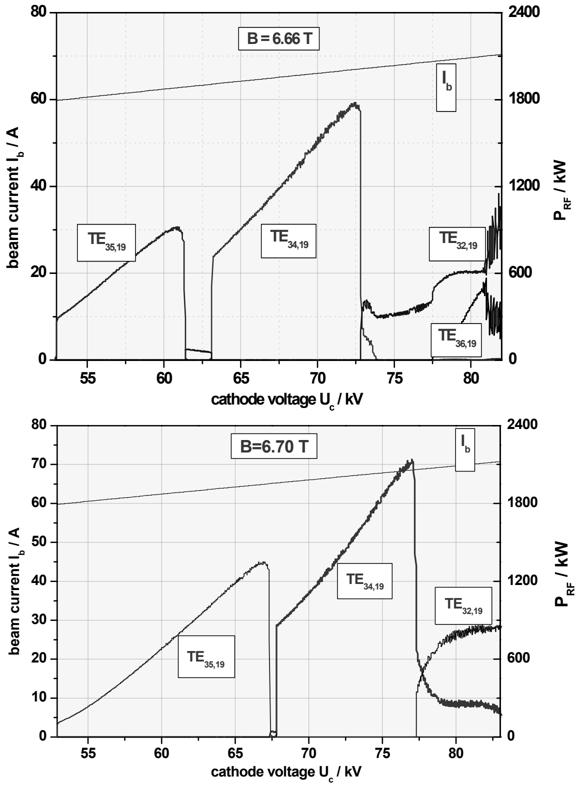


Fig. 3: Start-up scenario: beam current I_b and generated RF power P_{RF} versus the increasing cathode voltage U_c. The parameters α and I_b vary as in a diode gun with $\alpha = 1.3$ and $I_b = 70$ A at $U_c = 80$ kV.

2.3 RF output system

The RF output system used in the experimental $TE_{31,17}$ gyrotron at 165 GHz consisted of a smooth wall launcher with a helical cut and two mirrors, one quasi-elliptical mirror and one phase correcting mirror with a non-quadratic surface. For this system the microwave losses P_{stray} inside the tube have been measured to be as high as about 9% of the microwave output power P_{out}. A main contribution to P_{stray} is assumed to come from diffraction losses at the launcher cut.
In order to reduce this contribution and consequently to lower the total amount of P_{stray}, a dimpled-wall launcher has been designed for use in the 170 GHz gyrotron as utilized successfully in the 140 GHz gyrotron for the W7-X stellarator [7]. Unfortunately due to the ratio of the cavity to caustic radius of ~3 for the $TE_{34,19}$ mode, the transformation of this mode into a nearly Gaussian distribution at the launcher cut cannot be done as good as with the $TE_{28,8}$ mode of the 140 GHz gyrotron with a ratio of cavity to caustic radius of ~2. The microwave field distribution at the inner surface of the dimpled-wall launcher is shown in Fig. 4. The edge of the cut is marked in the figure.

Since the field amplitude at the cut edge is reduced in comparison to the smooth wall launcher, lower diffraction losses and thus a decrease of the total stray radiation is expected. The microwave power radiated from the cut is collected by a quasi-elliptical mirror and then shaped by two non-quadratic phase correcting mirrors. Fig. 5 shows a schematic arrangement of the q.o. RF output system.

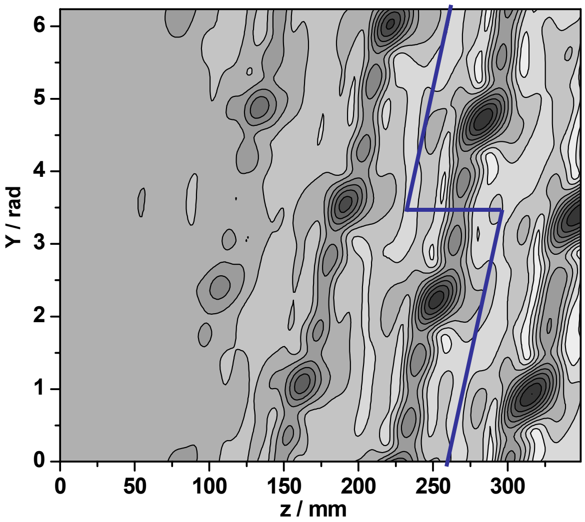


Fig.4.: Field distribution at the launcher surface. The edges of the launcher cut are indicated.

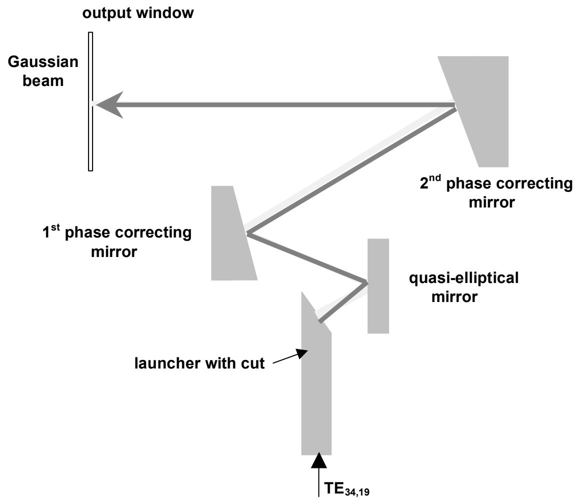
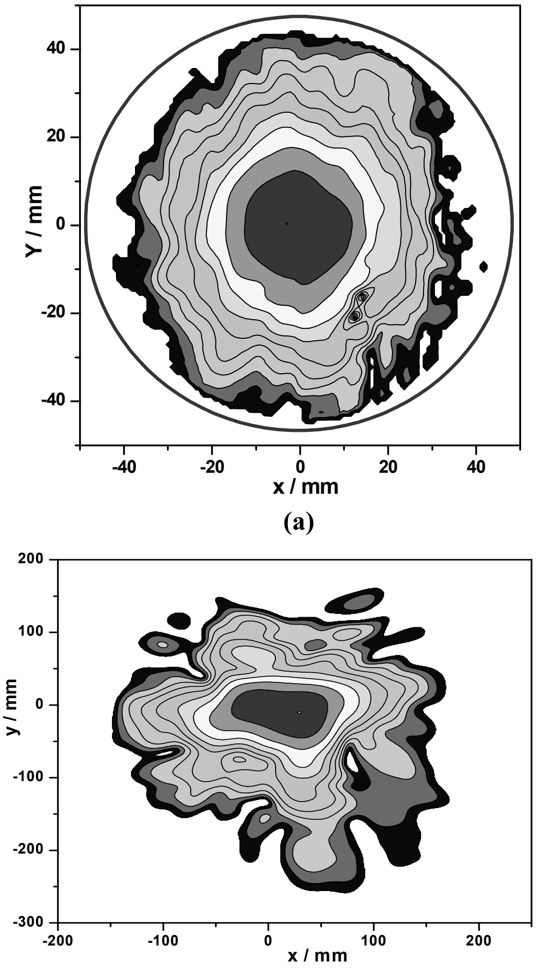


Fig. 5: Schematic view of the RF output system

The RF beam radiated out of the gyrotron has not an ideal Gaussian (TEM_{00}) distribution. Because of limitations in the accuracy of mechanical fabrication of the surface structure of the non-quadratic phase correcting mirrors a compromise has to be made between the Gaussian content in the distribution of the RF output beam and the amount of stray radiation captured inside the tube. Fig. 6 shows the calculated power distribution in the window plane and 1000 mm outside the window plane. According to the calculations it is expected that the total amount of stray losses will not exceed a value between 5 % and 6 % of P_{out}. Since as already pointed out the geometry of the q.o. RF output system is same as foreseen for the 2 MW, CW prototype gyrotron the short pulse experiment will allow to determine the power distribution of the RF output beam at different planes and to measure the amount of microwave stray radiation inside the tube. Further on, ways to absorb the microwave stray power can be investigated under realistic conditions.



(a)

(b)

Fig.6: RF power distribution (contour lines in 3dB steps). (a) the window plane and (b) 1000 mm outside the window plane.

2.4 Status of the short pulse gyrotron

The fabrication of the components of the quasi-optical RF output system - launcher and three mirrors - has just been finished. Before the q.o. system will be installed in the gyrotron tube measurements will be performed at low microwave level ("cold tests"). A mode generator needed for such measurements has already been tested successfully. The results of the cold measurements will be compared with the results of calculations in order to prove both the reliability of the used codes and the accuracy of fabrication.

All other needed parts and components are already available. As RF output window a disc out of fused silica (thickness = 6.8 mm = 15/2 λ) will be used.

The assembling of the tube is expected to be finished not later than April 2004. Experiments could start in Mai 2004.

3 Summary and outlook

The development of an industrial prototype of a 2 MW, CW coaxial cavity gyrotron at 170 GHz started in cooperation between European Euratom Associations (CRPP Lausanne, FZK Karlsruhe, HUT Helsinki) and European tube industry (Thales ED, Velizy, France). The final goal of the development work is to provide 2 MW, CW coaxial cavity gyrotrons for use at ITER. The engineering design of a first prototype tube is in progress and will be finished beginning of 2004. The fabrication is expected to start in the first half of 2004. Then the delivery of the first 2 MW, CW prototype gyrotron could be around the end of 2005.

In order verify the design of the most critical gyrotron components foreseen for the 2 MW, CW gyrotron under relevant conditions the experimental coaxial gyrotron at FZK is under modifications for operation in the $TE_{34,19}$ mode at 170 GHz. The modifications are nearly accomplished and investigations may start soon.

4 Literature

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