Status of development of high power coaxial-cavity gyrotrons at FZK

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Abstract

The development of high power gyrotrons at Forschungszentrum Karlsruhe (FZK), in cooperation with several European research institutions, is in progress. Gyrotrons are foreseen for heating, current drive and stabilization of plasmas in experimental fusion reactors. At FZK a high power 2 MW, 170 GHz pre-prototype gyrotron with coaxial cavity for ITER is being developed and experimentally tested at short pulse (a few ms) operation, a similar industrial prototype gyrotron has been tested at the Centre de Recherches en Physique des Plasmas (CRPP), Lausanne. Recent activities at FZK included the verification of its critical components, especially the electron gun, cavity and quasi-optical RF-output system. Low frequency oscillations at 265 MHz have been successfully suppressed due to a small modification of the geometry of the gyrotron components, increasing the measured power of the gyrotron up to 1.4 MW with an efficiency of 26% (non-depressed operation). However, additional parasitic oscillations around 152 - 160 GHz appear simultaneously with the desired gyrotron working mode. New beam tunnel prototypes which should avoid the excitation of parasitic oscillations in the GHz frequency range are fabricated and first tests have been performed. To increase the output power of the coaxial-cavity gyrotron up to 2 MW it is necessary to operate the tube at the nominal magnetic field, namely at 6.87 T. This has been realised with an additional normal conducting coil directly wounded on the gyrotron body in the cavity region. In first experiments at nominal operating parameters for the coaxial-cavity gyrotron a output power of 1.8 MW and a efficiency of 27% has been achieved. Further optimization of the quasi optical (q.o.) output system has been developed and according to the calculations an efficiency of the launcher with Gaussian mode content of about 96 % is expected. The new launcher antenna together with a suitable mirror system has been fabricated and will be verified.

Introduction

A 170 GHz coaxial cavity gyrotron with an output power of 2 MW in continuous wave (CW) operation is under development in cooperation between European research centers (FZK Karlsruhe, CRPP Lausanne, HUT Helsinki) and a European industrial partner (Thales Electron Devices (TED), Velizy, France). The increase of the RF output power to 2 MW per unit would have economical advantages of the electron cyclotron wave system at ITER and it would allow, if necessary, to enhance the total amount of microwave power injected into the plasma. Based on proof of principle experiments and on the experience acquired during the development of the 1 MW, CW, 140 GHz gyrotron for W7-X [1,2], the technical feasibility of a 2 MW, CW, 170 GHz coaxial cavity gyrotron has been studied first before EFDA (European Fusion Development Agreement) has placed a contract with TED for procurement of a first industrial prototype [3].

To support the work on the industrial prototype, experimental studies with a short pulse (up to ~ 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 experiments with the pre-prototype allow to study the performance of the main gyrotron components under relevant conditions and to discover and to investigate unforeseen problems of the prototype tube sufficiently in advance. In addition, a low power test facility is used to perform microwave measurements on the components of the q.o. RF output system (launcher and mirrors) prior to installation into the gyrotron tubes.

Experimental Set-up of the Coaxial Cavity Gyrotron

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

Pre-Prototype Coaxial Cavity Gyrotron	
Operating Cavity Mode	$TE_{34,19}$
Frequency [GHz]	170
RF output Power [MW]	~1.5
Beam Current [A]	75
Accel. Voltage [kV]	75 – 80
Cavity Magnetic Field [T]	6.7
Electron Velocity ratio α	1.3

Table 1: Design parameters of the short pulse coaxial cavity gyrotron.

The electron gun is a coaxial magnetron injection gun (CMIG) of diode type similar as has been used in the experiments at 165 GHz [4]. Although the gun is used at short pulses, it has the capability to be operated up to CW. The main features of this gun have been taken as reference for the gun of the industrial prototype. Special care has been devoted to the design of the technical part of the electron 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. At a beam current of 75 A the current density at the emitter surface 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.

The geometry of the coaxial cavity designed for operation in the TE-$_{34,19}$ mode at 170 GHz is the same as used in the prototype tube. Due to the reduced value of the magnetic field (see below) the excitation of the nominal $TE_{34,19}$ mode is expected for accelerating voltages below about 80 kV (Table 1).

The aim of the q.o. RF output system is (1) 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 and (2) to keep the microwave losses inside the gyrotron tube low. The q.o. system consists of a dimpled-wall launcher with a helical cut and three mirrors.

As the 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 uses a CVD diamond disc with a thickness of $5\lambda/2$. The transmission characteristic of the windows is similar.

Experimental Results

Parasitic oscillations

When starting the experiments the gyrotron operation was strongly limited to low beam current and low accelerating voltage (I_b~ 15A, U_C~40 kV) due to the excitation of parasitic LF oscillations with very high amplitude mainly around 265 MHz. The reason of the LF oscillations has been studied and a mechanism has been proposed [5]. Based on the suggested hypothesis the geometry of the coaxial insert on the cathode side of the gyrotron cavity has been modified. Due to these modifications, a significant reduction of the level of the LF oscillations has been found in measurements. In particular, the corresponding starting currents increased by a factor of about 3. Recent measurements have been performed with the electron gun previously used in the coaxial gyrotron at 165 GHz. The anode has been modified for operation at 170 GHz in the $TE_{34,19}$ mode. During the operation with this gun, no LF oscillations have been observed. This confirms the observations in the 165 GHz gyrotron and indicates a great sensitivity of such parasitic oscillations to the overall geometry. In order to be able to perform experiments in the $TE_{34,19}$ mode at 170 GHz a electronic velocity ratio, α, of 1.3 at U_C= 80 kV and I_b = 75 A and a beam radius R_b = 10 mm, was chosen.

The magnetic field in the cavity is limited to 6.72 T by the sc magnet. As maximum output power, P_{out}, a value around 1.3 MW with an efficiency of ~23 % has been obtained in non-depressed collector operation. Fig.1 shows the measured microwave power in the different modes as well as the microwave power calculated with a single and a multi-mode self-consistent code. The experimental values are in reasonably good agreement with results of simulations for U_C<73 kV. During the experiments it has been found 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. This coincides with reduction of the generated power in comparison with calculations in this region (Fig. 1). There are some indications that the oscillation around 160 GHz could be generated inside the beam tunnel between cathode and cavity. Above U_C~78 kV severe “multimode”-operation has been observed.

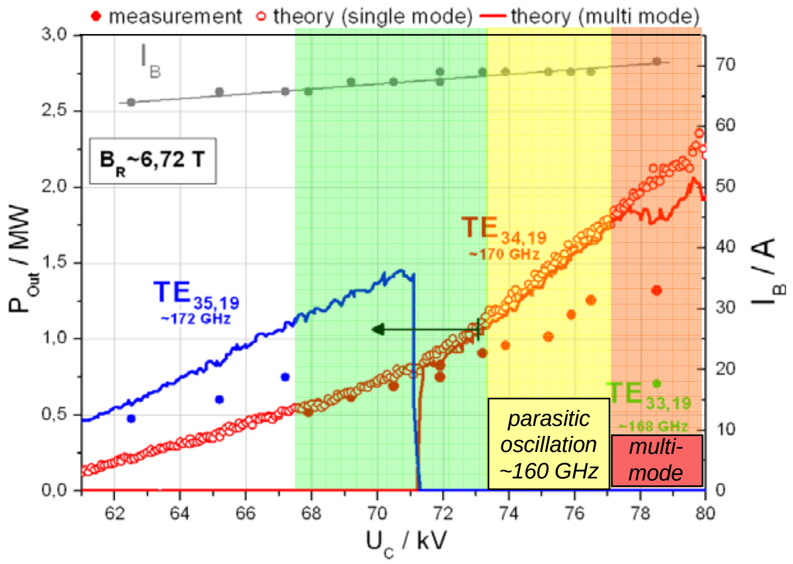

Figure 1: Measured and calculated output power of the coaxial cavity gyrotron.

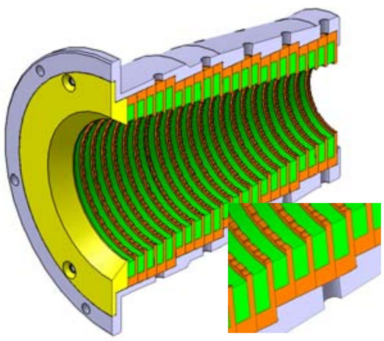

Figure 2: Modified beam tunnel with corrugated Cu rings.

Investigations concerning parasitic oscillations in the beam tunnel are in progress. In particular the beam tunnel has been modified to complicate the excitation of parasitic TE modes by introducing irregular corrugations in the copper ring structure (see Fig. 2). Results are reported in the next chapter.

Operation at full magnetic field

The sc magnet available at FZK delivers a maximum field of about 6.7 T in the cavity. However, the design value for the gyrotron is 6.87 T. Thus the optimized parameters could not be achieved and the performance of the gyrotron is somewhat less. Recently this situation has been improved by winding a normal conducting coil directly onto the body of the gyrotron. This coil, placed at the cavity region, increases the magnetic field up to the design value. Figure 3 shows the influence of the coil current I_{CC} on different parameters. The α-value is varying only slightly with I_{CC} and the beam radius R_b increases only by ~ 0.1 mm if the current I_{CC} is changing from 0 A to 55 A and the magnetic field in the cavity B_{cav} is increasing linearly from 6.72 T up to 6.87 T.

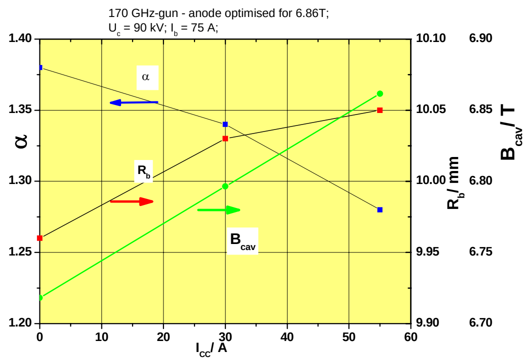

Figure 3: Influence of the current I_{CC} in the normal conducting coil on α, R_b and B_{cav}.

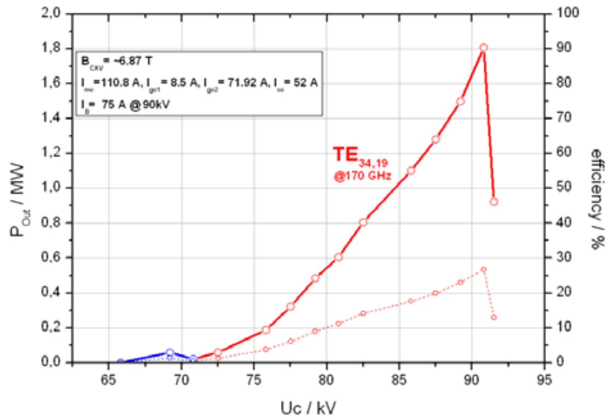

Figure 4:. Output power and efficiency in dependance of accelerating voltage.

In the experiments an output power of up to 1.8 MW has been achied with a maximum efficiency of 27 %. The abrupt decrease of the output power at Uc= 91 kV is due to the excitation of a competing cavity mode. Due to the nominal magnetic field in the cavity the tube could be operated at the design mode in excess of 90 kV. During operation in this high power regime practically no parasitic oscillations excited in the beam tunnel were observed.

Improvement of the quasi-optical RF system

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 had 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 [6]. 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 complicated surface contour is obtained, which cannot be described by analytic functions. Recent results, verified with the Surf3d code are very promising as is shown in Fig. 5. According to the calculated complex correlation factor between the field radiated from the

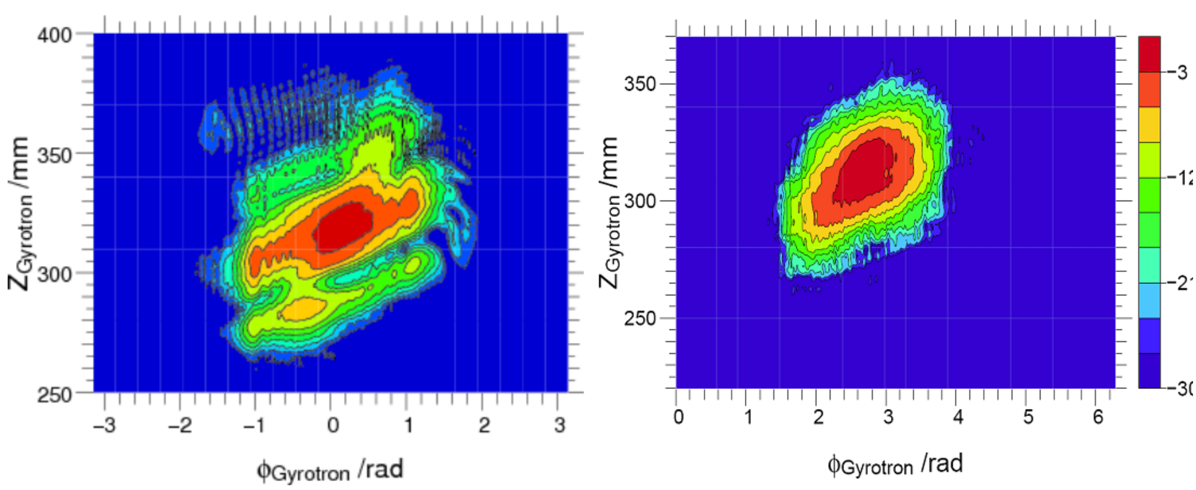

Fig. 5:. Surf3d calculation of the radiated field of the: previous launcher with 1st, 3rd perturbation orders at the inner wall (left) and improved launcher with arbitrary deformations (right).

launcher and an ideal Gaussian field distribution, a Gaussian content of about 96 % is expected. This is a significant improvement over to the previous design (Gaussian beam content 76 %). The launcher has been manufactured and measurements at low power are being performed.

Conclusions

Investigations on the pre-prototype gyrotron have been continued. The mechanism of excitation of parasitic LF oscillations inside a coaxial gyrotron has been successfully studied and eliminated. 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 these experiments 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. A modified beam tunnel has been realised. First experiments show a significantly reduced danger of parasitic oscillations. Together with an additional normal-conducting coil the pre-prototype gyrotron has been operated at full magnetic field yielding an out put power of 1.8 MW with an efficiency of 27% (non-depressed collector).

Concepts for the improvement of the q.o. RF output system have been investigated. A launcher designed with a newly developed code and verified with the Surf3d code is radiating a field distribution with ~ 96 % Gaussian content.

Acknowledgements

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