Development of Advanced High Power Gyrotrons for EC H&CD Applications in Fusion Plasmas

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At Forschungszentrum Karlsruhe (FZK) R&D investigations are performed both on a 2 MW, 170 GHz coaxial cavity gyrotron and on stepwise frequency tunable 1 MW gyrotrons. In case of the coaxial gyrotron the previously used experimental tube has been modified for operation at 170 GHz in order to verify the design of the main components (electron gun, cavity and RF output system) of a corresponding industrial prototype which is under development in cooperation between EURATOM Associations together with European tube industry. For the stepwise tunable gyrotron, work has been done on optimization of the quasi-optical RF output system and on a broadband output Brewster window.

Introduction

The feasibility of manufacturing a 2 MW coaxial cavity gyrotron operated in continuous wave operation (CW) has been studied experimentally and theoretically during the last years at the FZK. The investigations have been performed on a coaxial gyrotron operated in the $TE_{31,17}$ mode at 165 GHz. The results are described in detail in [1]. The gyrotron was demountable and enabled an easy replacement of the components. Its cooling performance allowed only operation at short pulses (up to several 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. 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 microwave tube industry (Thales Electron Devices, Velizy, France) [2].

In parallel to the work on the industrial prototype, the experimental $TE_{31,17}$ short pulse gyrotron at FZK has been modified for operation at 170 GHz in the $TE_{34,19}$ mode. The modified tube will be used to verify the design of the electron gun, cavity and the quasi-optical RF output system under relevant conditions. The cavity dimensions and the geometry of the RF output system are the same in the prototype and in the short pulse (up to about 10 ms) 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 the same.

For plasma stabilization in nuclear fusion devices such as the ASDEX-Upgrade tokamak, there is an interest in step-tunable gyrotrons operating at frequencies between 105 GHz and 140 GHz. For this purpose a multi-frequency gyrotron for operation between 105 and 140 GHz is under investigation at FZK in a cooperative development with the Institute of Applied Physics in Nizhny Novgorod, Russia. The main key issues investigated at FZK are the development of a broadband quasi-optical (QO) output system and a broadband chemical vapor deposited (CVD) diamond Brewster window.

170 GHz Coaxial Cavity Gyrotron

The design parameters are given in Table 1 both of the 2 MW, CW prototype and for the experimental tube. The existing SC-magnet used for the short pulse experiments delivers a maximum magnetic field of about 6.68 T. Therefore, in order to be able to excite the $TE_{34,19}$ mode at 170 GHz it is necessary to reduce the beam 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	
electron beam radius in cavity, R_b/mm	10.0	

Electron gun

A coaxial magnetron injection gun (CMIG), similar as used in the previous short pulse experiments [3], has been designed and fabricated. The emitting cur-

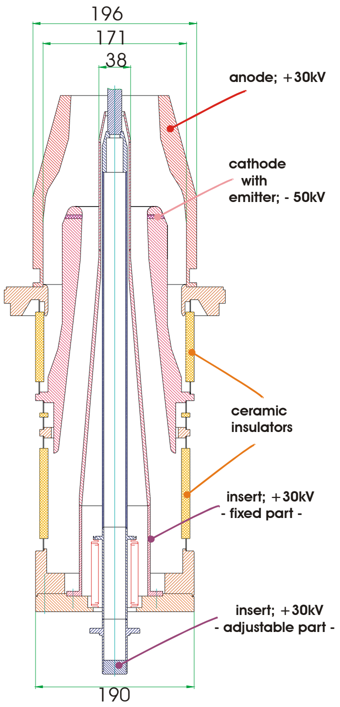

Fig. 1: CMIG gun (dimensions in mm).

rent density is about 4.2 A/cm^2 at I_b = 75 A. Fig. 1 shows the layout of the 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 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.

Coaxial cavity

The $TE_{34,19}$ mode has been selected [6] as operating mode for the 170 GHz prototype tube. The geometry of the cavity is same as foreseen for the 2 MW, CW prototype. The Ohmic losses at the outer cavity wall have been calculated to be within 1 kW/cm² (ideal copper at 273 K) at the nominal RF power. The corresponding peak losses at the insert are expected to be less than 0.1 kW/cm².

In simulations of the start up behaviour with a time dependent, self consistent multimode code it has been found that a single-mode operation in the $TE_{34,19}$ mode can be obtained at the reduced B-field with a beam voltage of about 80 kV. Due to the reduced voltage the generated microwave power is expected to be less than in the prototype gyrotron (see Tab.1). However, the short pulse experiments will allow to verify the design of the cavity under relevant conditions both with respect to the efficiency of the microwave generation and mode competition.

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. 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 due to the diffraction losses at the launcher cut. In order to reduce the diffraction losses 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 [5]. 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. Nevertheless a significant reduction of diffraction losses is expected compared with the smooth launcher used previously.

The RF output system consists of a dimpled-wall launcher and three mirrors - a quasi-elliptical mirror followed by a toroidal and a phase correcting mirror with a non-quadratic surface. The RF beam 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 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 lost inside the tube. According to the calculations it is expected that the total amount of stray losses should not exceed a value between 5 % and 6 % of P_{out}. The geometry of the QO output system is the same as foreseen for the 2 MW prototype gyrotron. Thus the short pulse experiment will allow to verify the design performance of the system. Further on, ways to absorb the microwave losses in the tube can be investigated under relevant conditions.

Multi - Frequency Gyrotron

An existing conventional experimental gyrotron is under modification for operation as short pulse prototype of a multi-frequency step-tunable 1MW gyrotron. Major parts of the existing gyrotron as beam tunnel, collector and the housing will be re-used. The cavity, the dimpled-wall launcher with three beam-forming mirrors have been newly designed. A low power mode generator for the various modes has been constructed in order to perform low power measure-

Tab. 2: Cavity modes with resonant frequency, quality factor, beam radius and magnetic field in the cavity.

mode	f / GHz	Q - factor	R_b / mm	B_{cav} / T
$TE_{17,6}$	105.0	551	8.21	4.17
$TE_{18,6}$	108.4	586	8.42	4.31
$TE_{19,6}$	111.6	620	8.62	4.43
$TE_{19,7}$	120.9	714	7.96	4.80
$TE_{20,7}$	124.2	744	8.15	4.93
$TE_{21,7}$	127.4	773	8.32	5.06
$TE_{21,8}$	136.7	851	7.76	5.43
$TE_{22,8}$	140.0	881	7.93	5.56
$TE_{23,8}$	143.4	915	8.09	5.70

ments of the QO output system. A Brewster window of CVD diamond fulfils all requirements for a broadband transmission. A new electron gun of diode type has been ordered and is expected to be delivered soon.

Cavity design

The cavity has been optimized for the modes given in Tab. 2. In the optimisation process the variation of the beam parameters (diode-type electron gun) with the varying magnetic field B_{cav} and slightly varying beam radius R_b as needed for excitation of the different modes has been taken into account. The cavity has a radius of 17.96 mm and a length of 14 mm [6].

The RF-output system

The QO output system consisting of a dimpled-wall launcher and three mirrors have been optimised for 9 modes from $TE_{17,6}$ to $TE_{23,8}$. For these modes the dimpled wall launcher shows a well focused beam with low diffraction losses. The first mirror is a large quasi-elliptical one, the second and third are phase correcting mirrors with a non-quadratic surface contour. To verify the design of the QO system a low power mode generator has been manufactured which enables to generate the various modes with high mode purity [7]. First low power tests have been performed recently. For the $TE_{22,8}$ mode the calculated and the measured field pattern have been found to be in good agreement.

CVD-diamond Brewster window

A Brewster window with a CVD diamond disc would fulfil all requirements for a high power frequency tunable gyrotron operated in long pulses up to CW. Therefore, such a window is under design for a CVD diamond disc of 140 mm diameter which is under fabrication at Element Six (former DeBeers). CVD-diamond has a permittivity as large as ε_r=5.67 resulting in a Brewster angle Θ_B = 67,22°. Because of that the Brewster window made out of the 140 mm disc has only an aperture of 50 mm diameter as shown in Fig. 2. The total technical length of the window unit is approximately as long as 150 mm. The parameters (beam waist) of the RF output beam which is expected to be nearly Gaussian has to be such that not more then a few per mill of beam power is reflected from the window aperture. In particular, it has to be considered that due to the variation of the caustic radius in the single modes the position of the RF beam shifts radial up to about ± 6 mm at the window position. Taking the shift into account, results of calculations show that a Gaussian beam with a waist of 7 mm in the centre of the window unit is needed in order to limit the reflections at the window aperture to a few per mill. A Brewster window with a fused silica disc which will have the same dimensions (aperture radius and length) as the envisaged Brewster window with the CVD diamond disc has been designed and will be manufactured. This will be used to proof the new design of the QO output system under relevant conditions [8].

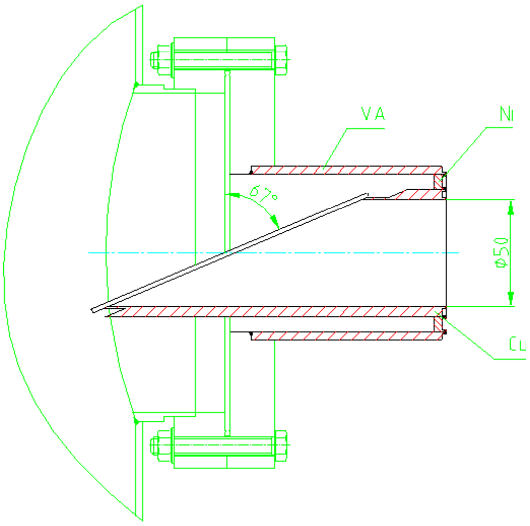

Fig. 2: Draft design of the Brewster window with the 140 mm CVD diamond disc. Dimensions are in mm.

Present status and outlook

The experimental 170 GHz coaxial cavity gyrotron has been assembled and installed in the SC-magnet. The operation started in May 04 with performing the alignment and conditioning of the tube. The main goal of the experiments is to verify the design of components for a 2 MW, CW industrial prototype.

Cold measurements on the QO system of the multi-frequency gyrotron started and a design of a Brewster window for a CVD diamond disc has been done. An existing gyrotron is under modifications in order to perform multi-frequency operation at short pulses.

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