A 2 MW, CW, 170 GHz Gyrotron for ITER

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Abstract

A 140 GHz gyrotron for CW operation is under development for the stellarator W7-X. With a prototype tube a microwave output power of about 0.9 MW has been obtained in pulses up to 180 s, limited by the capability of the high voltage power supply. The development work on coaxial cavity gyrotrons has demonstrated the feasibility of manufacturing of a 2 MW, CW 170 GHz tube that could be used for ITER. The problems specific to the coaxial arrangement have been investigated and all relevant information needed for an industrial realization of a coaxial gyrotron have been obtained in short pulse experiments (up to 17 ms). The suitability of critical components for a 2 MW, CW coaxial gyrotron has been studied and a first integrated design has been done.

1. Introduction

Millimeter waves can be used with great advantages for heating of magnetically confined plasmas of thermonuclear fusion devices and for controlling instabilities as has been demonstrated with great success in different fusion experiments. In a close collaboration between Euratom associations and European industry the development of a 1 MW, CW, 140 GHz gyrotron for the W7-X stellarator at Greifswald/Germany is progressing well [1].
For fusion experiments of the next generation such as the international thermonuclear experimental reactor (ITER), a microwave power of above 20 MW at 170 GHz operated almost in CW will be needed. To reduce the costs of the installations of the electron cyclotron wave (ECW) system and to make the launcher inside the torus more compact an increase of the output power per unit to about 2 MW is desirable. Coaxial cavity gyrotrons have the potential to fulfill this requirement because of the possibility to use high-order volume modes. This is because the presence of the coaxial insert practically eliminates the restrictions of voltage depression and limiting current and in addition, the problem of mode competition is reduced by a selective influence of the diffractive quality factor of the competing modes.
Within a development program performed as an ITER task at Forschungszentrum Karlsruhe (FZK) the feasibility of manufacturing a 2 MW, CW coaxial gyrotron operated at 170 GHz

has been demonstrated and all information necessary for a technical design and industrial manufacturing has been obtained [2,3]. Based on the experimental results a draft integral design of a 170 GHz coaxial gyrotron for 2 MW, CW output power has been done. The usability of the components for CW operation and their compatibility with technical restrictions has been investigated. In collaboration between Euratom Associations with the European Tube industry a technical design of a 2 MW coaxial gyrotron is under preparation.
In this paper both the status of the development work of the conventional 140 GHz gyrotron and of the coaxial 170 GHz tube is described and recent results are given.

TABLE 1: GYROTRON DESIGN PARAMETERS

type of the gyrotron	conventional	coaxial
operating mode	$TE_{28,8}$	$TE_{34,19}$
frequency: f/ GHz	140	170
RF-output power: P_{out} / MW	1	2
magnetic field: B_{cav} / T	5.5	6.87
accelerating voltage: U_{acc} / kV	82	90
beam current: I_b / A	40	75
velocity ratio: α	1.3	1.3
mean emitter radius: R_{cath} / mm	50	≅ 60
emitter current density: j_e/A/cm²	2.5	≅ 4.3
beam radius: R_b / mm	10.1	10.2
cavity radius: R_{cav} / mm	20.48	29.55
peak wall losses at P_{out} (ideal copper, 20^0C): p_Ω /kW/cm²	1	0.96

2. The 1 MW, 140 GHz, CW Gyrotron for W7-X

The gyrotron has been designed for an RF output power of 1 MW, CW operation. The main design parameters are given in table 1. As electron gun a MIG gun of diode type is used. The real peak wall losses in the cavity, which is made out of Glidcop, are calculated to be about 2 kW/cm² at P_{out} = 1 MW assuming a wall temperature of 270°C and a factor of 1.3 for surface roughness. The conical beam tunnel between the electron gun and the cavity is equipped with alternating rings of copper and strongly absorbing ceramics. The $TE_{28,8}$ cavity mode is transformed to a Gaussian distribution by a quasi-optical mode converter consisting of a rippled-wall waveguide launcher with tapered diameter followed by one mirror of quasi-elliptical shape and two toroidal focusing mirrors. The output window consists of an edge cooled CVD-diamond disk with an outer diameter of 106 mm, a window aperture of 88 mm and a thickness of 1.8 mm. At the window plane the radius of the RF beam is 23.3 mm. A single-stage depressed collector is used in order to raise the overall efficiency. The walls of the mirror box which are made of stainless steel are well cooled.

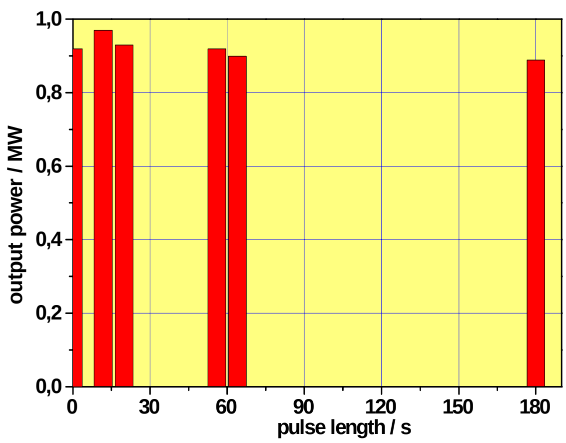

Fig. 1: Output power at different pulse lengths

2.1 Experimental Results

The reported results have been obtained with the first prototype tube. Compared to the pre-prototype called maquette some small technical modifications have been made [1]. Fig. 1 shows the dependence of the RF-output power P_{out} on the pulse length. At a pulse length of 180 s, limited by the performance of the high voltage power supply, P_{out} of about 0.9 MW has been obtained with a mode purity of 98 %. At pulses of 12 s $P_{out} \approx 1$ MW with an efficiency of 44 % has been measured. The depression voltage of the collector was 26 kV. The frequency decreases due to thermal expansion by about 0.4 GHz from 140.2 GHz at short pulse operation to a stationary value of 139.8 GHz. The microwave stray radiation inside the mirror box was measured to be only about $0.015\times P_{out}$. The losses in the output window were found to be $0.0005\times P_{out}$ in reasonable agreement with the value expected from the loss tangent of the CVD disk. Up to the longest pulse length the vacuum conditions stayed well within the tolerable values.

3. A 2 MW, 170 GHz, CW Coaxial Cavity Gyrotron for ITER

The experimental investigations have been performed on a gyrotron operated in the $TE_{31,17}$ mode at 165 GHz and optimized for an RF output power of 1.5 MW. The frequency has been limited by the maximum magnetic field obtainable with a superconducting (SC) magnet existing at FZK. The gyrotron is of modular type and permits an easy replacement of the components. Its cooling performance allows only operation at short pulses (up to about 50 - 100 ms) with a low duty factor. The experimental set up is described in [2,3].

3.1 Experimental Results

The RF-measurements were performed with a pulse length of typically 1 ms and a repetition rate of 1 Hz. Single-mode oscillation has been found over a reasonably large parameter range. A maximum RF output power as high as $P_{out} = 2.2$ MW was achieved at a beam current $I_b = 84$ A with an efficiency $\eta_{out} = 28$ %. A maximum output efficiency of 30 % (without depressed collector) was measured at the nominal RF output power $P_{out} = 1.5$ MW. In operation with a single-stage depressed collector the overall efficiency has been increased from 30 % up to 48 % by applying a negative retarding voltage $U_{coll} = -34$ kV. The experimental values are in good agreement with numerical results obtained with a self-consistent, multi-mode code [4]. The pulse length has been extended up to about 17 ms, limited by a strong sudden rise of the current I_{ins} to the coaxial insert. Experimental investigations and numerical simulations indicated that the observed phenomenon is caused by a Penning type discharge in the region between the cathode and the coaxial insert. The electric and magnetic fields in that region provide an efficient trap for electrons which cause the build up of the Penning discharge. By a modification of the geometry the trapping condition for electrons can be avoided and thus a degradation of the high voltage performance due to the occurrence of the Penning discharge can be excluded. The mechanical properties of the coaxial insert have been investigated under operating conditions. The flow of the cooling water has been identified as a main source of mechanical vibrations. Under representative operating conditions the amplitude of the mechanical vibrations around the cavity has been measured to be less than 0.03 mm. This value is compatible with requirements for a stable long pulse operation.

The calorimetrically measured losses P_{ins} at the coaxial insert have been found to be about twice the theoretically calculated values for ideal copper at room temperature. This means that

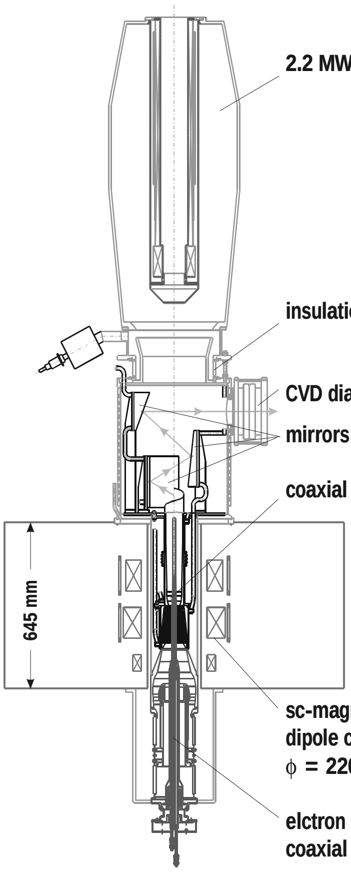

Fig. 2: A draft integrated draft design of the 2 MW, CW, 170 GHz coaxial gyrotron.

the total losses at the insert are expected to be less than 0.1 % of the RF output power, $P_{ins} \le 0.001 \times P_{out}$, even if some increase of the RF losses due to an enhanced temperature of the insert under CW conditions is taken into account. Thus the power dissipated at the insert should not cause any technical problems even for CW operation with P_{out} = 2 MW.

A radial misalignment δR_{ins} of the insert results both in an increase of the insert losses and in enhanced problem of mode competition which leads to a reduction of the parameter range for single-mode operation. In order to avoid these unfavorable effects an alignment accuracy of the insert within $\delta R_{ins} \le 0.15$ mm is needed. This accuracy was easily achieved in the experimental coaxial gyrotron.

The microwave stray radiation P_{stray} captured inside the mirror box has been found to be distributed approximately uniformly inside the box. The total amount of stray radiation P_{stray} was measured to be as large as: $P_{stray} = (0.09 \pm 0.01) \times P_{out}$. The relatively large value of P_{stray} is assumed to be related to the use of a smooth-wall launcher with a single cut which has relatively large diffraction losses [5]. However, the uniform distribution of P_{stray} inside the mirror box keeps the technical problems related to dissipation of P_{stray} inside the tube in acceptable limits, even for a 2 MW gyrotron. A reduction of P_{stray} by using an improved rippled wall launcher is under investigation.

3.2 Design of 2 MW, CW 170 GHz Coaxial Cavity Gyrotrons

A draft integrated design of a 2 MW, CW, 170 GHz coaxial cavity gyrotron has been performed as shown in Fig. 2. The overall dimensions are comparable with the dimensions of a conventional 1 MW, CW gyrotron. The collector is at ground potential, insulated from the body with a ceramic ring placed at the top of the mirror box. The main design specifications and parameters are summarised in table 1. The individual components have been checked for their suitability for a use in a 2 MW coaxial gyrotron.

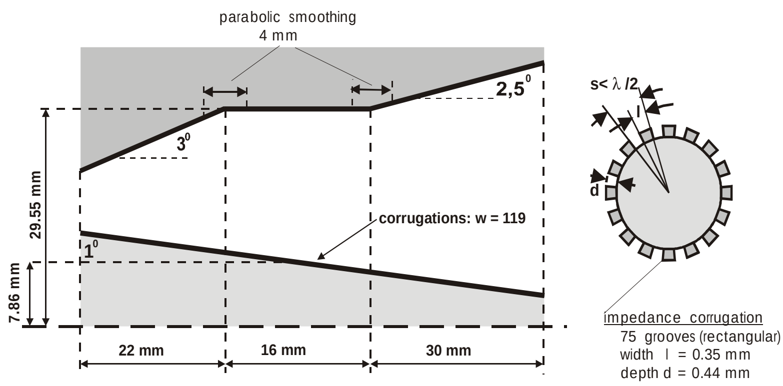

Fig. 3: Geometry of the $TE_{34,19}$ coaxial cavity

The CMIG gun [6] used in the short pulse experiments is suitable for CW operation. In the design of the technical parts of the gun care has to be taken in order to avoid trapping

regions for electrons which may cause a build-up of a Penning discharge. The radial dimension of the gun is compatible with a bore hole of 220 mm diameter for the SC-magnet.
The $TE_{34,19}$ mode has been selected as cavi-ty mode [7]. The geometry of the cavity is shown in Fig. 3. The Ohmic losses at the cavity wall are within technically accepted limits. The peak loading at the insert has been calculated to be less than 10 % of the cavity wall loading.
In order to reduce the amount of stray losses an improved q.o. output system with a rippled wall launcher as used in the 140 GHz gyrotron for W7-X has been designed. Experimental tests at short pulses are foreseen.
A single-disk CVD-diamond window with a thickness of 1.85 mm can be used for transmission of 2 MW microwave power at 170 GHz. About 0.6 kW power is expected to be absorbed in the disk for a loss tangent of 2×10^{-5} (state of the art).

For dissipation of the remaining beam power of about 2.4 MW a new collector with improved power distribution along the collector surface has been designed [8]. The feasibility for manufacturing of the collector has been examined and an industrial design has been done.

A SC-magnet with a warm bore hole of ≥ 220 mm diameter as used e.g. for the W7-X gyrotron is required. NbTi-technology can be used for the SC-coils. In addition to the solenoidal coils, the SC-magnet has to be equipped with a set of dipole coils, which are needed to perform in particular the alignment of the coaxial insert under operating conditions.

4. Summary

Gyrotrons with an output power of 1 MW, CW are close to becoming state of the art. The physical feasibility for fabrication of a 2 MW, CW 170 GHz coaxial cavity gyrotron has been demonstrated and all necessary data for an industrial realization of a 2 MW, CW 170 GHz coaxial cavity gyrotron are available. A draft integrated design does not show any principle limitations for a technical realization of such a gyrotron.

Acknowledgments

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