Gyrotron Research at Forschungszentrum Karlsruhe

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***Short Abstract*— One of the important heating schemes for fusion plasma devices is given by the electron-cyclotron-resonance-heating. This application, however, is limited to the lack of powerful sources operated at the appropriate frequency. At the Forschungszentrum Karlsruhe, a 1 MW, 140 GHz gyrotron for continuous wave operation has been developed for the ECRH system built up at the new stellarator facility in Greifswald / Germany. Due to the successful results with the prototype, seven 140 GHz CW gyrotrons were ordered. The first series tube was operated at the Forschungszentrum Karlsruhe. A power of 920 kW at an efficiency of 45 % (with energy recovery) could be obtained for pulse lengths of 180 s (limited by the available high-voltage power supply). A 30 minute pulse was performed with an output power of 570 kW. For the next fusion plasma device ITER, gyrotrons with higher output power of about 2 MW are desirable. In short-pulse experiments, the feasibility of coaxial-cavity gyrotrons with an output power up to 2 MW in continuous wave operation has been demonstrated and the information for a technical design has been obtained.**

Keywords-components; gyrotron, coaxial cavity, quasi-optical system, diamond window, mode converter, depressed collector

I. INTRODUCTION

In next step thermonuclear fusion experiments, electron cyclotron wave (ECW) systems will be used for plasma heating and current drive. This strategy relies on millimeter-wave sources, that generate output powers in the Megawatt level in continuous wave (CW) operation.

For the stellarator W7-X now under construction at the Max-Planck-Institute for Plasma Physics in Greifswald (IPP), a power of 10 MW is needed for the electron-cyclotron-resonance-heating (ECRH) in CW operation. In a European collaboration between European research laboratories and European industry Thales Electron Device (TED) in France, conventional gyrotrons designed for an output power of 1 MW at 140 GHz have been developed. They are equipped with a single-stage depressed collector for increasing the efficiency and reducing the power loading, an advanced quasi-optical mode converter with minimized stray radiation inside the gyrotron, and a single-disk diamond window made by chemical vapor deposition (CVD-diamond) [1].

For the next fusion plasma device ITER, about 24 MW of ECRH (and electron-cyclotron-current-drive) at 170 GHz CW will be needed. Units with higher output power of about 2 MW will considerably reduce the cost for the ECRH.

An output power of 1-1.5 MW seems to be the limit for stable operation of conventional gyrotrons. Whereas those with coaxial cavities have the potential to fulfill the requirements for 2 MW output power. At the Forschungszentrum Karlsruhe, investigations on a short-pulse gyrotron with a coaxial cavity have been performed with the goal to demonstrate the feasibility and to provide all necessary information for a technical realization of a 2 MW, CW gyrotron at 170 GHz. Based on these results, an industrial prototype of a 2 MW, CW coaxial cavity gyrotron is under fabrication and a suitable test facility is under construction at CRPP Lausanne, Switzerland.

Fig. 1 shows a scheme of the 170 GHz pre-prototype gyrotron.

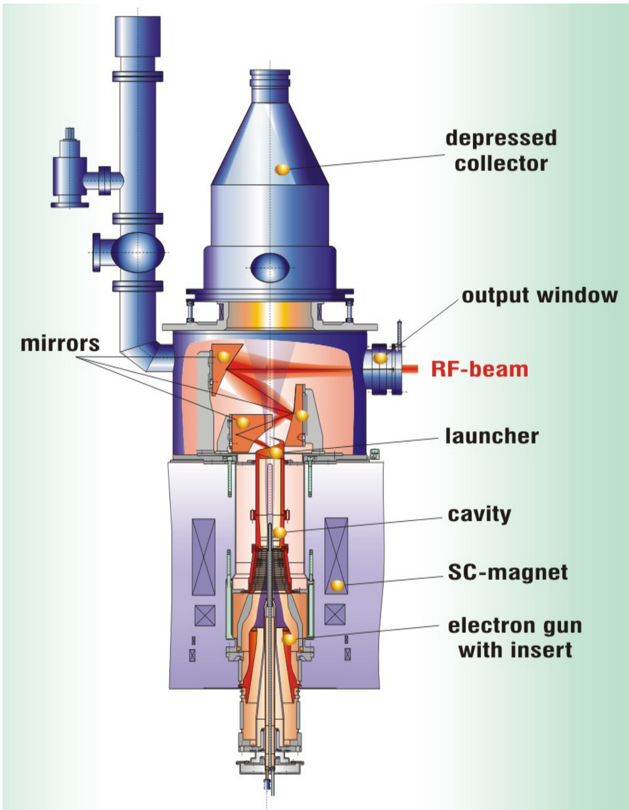

Figure 1. View of the 170 GHz pre-prototype gyrotron.

II. CONVENTIONAL GYROTRON

A. Design

The RF-cavity operates in the $TE_{28,8}$ mode. It is a standard cylindrical cavity with a linear input taper and a non-linear output taper. Special care has been taken for the design of the quasi-optical mode converter [2] to have very little amount of stray radiation. The radius of the antenna waveguide launcher is slightly uptapered towards the output by an angle of 4 mrad in order to avoid parasitic oscillation in this region. Due to the low fields along the edge of the helical cut, this advanced dimpled-wall launcher generates a well focused Gaussian-like field pattern with low diffraction. In combination with a three mirror system the desired Gaussian output beam pattern can be obtained.

TABLE I. PARAMETERS OF THE CONVENTIONAL GYROTRON

RF output power	1 MW
Accelerating voltage	81 kV
Beam current	40 A
Cavity mode	$TE_{28,8}$
Efficiency	45 %
Cavity radius	20.48 mm
Self consistent quality factor	1100
Cavity magnetic field	5.56 T
Launcher taper	0.004 rad
Launcher efficiency	98 %
Window aperture	88 mm

B. Experimental results: short pulse operation

The long-pulse results of the measurements on the pre-prototype and the prototype tube were reported in earlier publications [3]. With the prototype, two problems were faced. The specified output power of 1 MW has not completely achieved and the pulse length was limited to about 15 minutes even at reduced power of 534 kW. The reason for the limit in power is seen in a poor electron emitter quality (cathode) which leads to an inhomogeneous electron emission and thus to a poor beam quality. The limitation in pulse length was due to a pressure increase during the pulse which was caused by a temperature increase of the internal ion getter pumps. This temperature increase was proven by an infrared measurement after a long pulse [4].

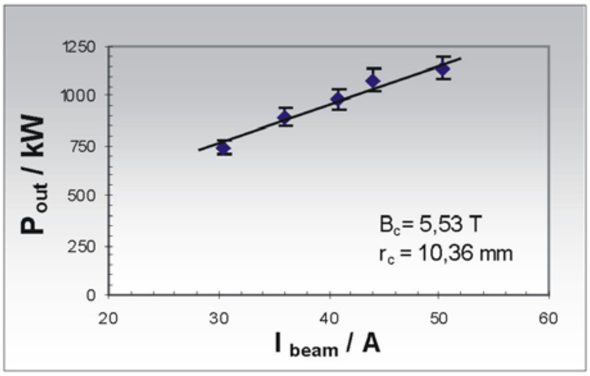

Figure 2. Dependence of output power on electron.

To eliminate the limitation in output power for the series tubes, a better quality assurance of the emitter ring has to be performed before installing it into the gyrotron. To avoid the pulse length limitation it was decided to use external ion getter pumps with better shielding against RF stray radiation.

Knowing the reasons for the limitation in power and pulse length, the development phase for the gyrotrons was finished and seven series tubes were ordered. The first series tube had been delivered to FZK and tested in short and long pulse operation.

Fig. 2 shows the output power of the series tube versus beam current at constant magnetic field. The saturation in power as seen in the prototype could not be found indicating the good emission of the cathode. An output power of 1 MW at 40 A and 1.15 MW at 50 A was measured in short pulse operation (ms). The corresponding efficiencies without depressed collector were 31 % and 30%, respectively.

RF-field distribution measurements (perpendicular to the output RF-beam direction) were performed at different positions with respect to the window. The Gaussian content was calculated to be 97.5 %.

C. Experimental results: long pulse operation

The optimisation procedure for finding the operating parameters at high output power in long pulse operation was performed in 1s-pulses assuming that the instantaneous power is well described by the frequency difference between the initial frequency and the instantaneous frequency (after one second). In a range between 5.52 –5.56 T of the magnetic field at the cavity, no maximum for the output power was found. The power increased slightly with increasing magnetic field. In order to achieve the maximum output power, the accelerating voltage (this corresponds to the energy of the electrons inside the cavity) was adjusted and followed nicely the law that the ratio between magnetic field and the relativistc factor γ has to be constant. Increasing the voltage beyond this value leads to an excitation of neighbouring modes. The measurements were performed at a constant beam current of 40 A, but with optimising the electron beam radius inside the cavity.

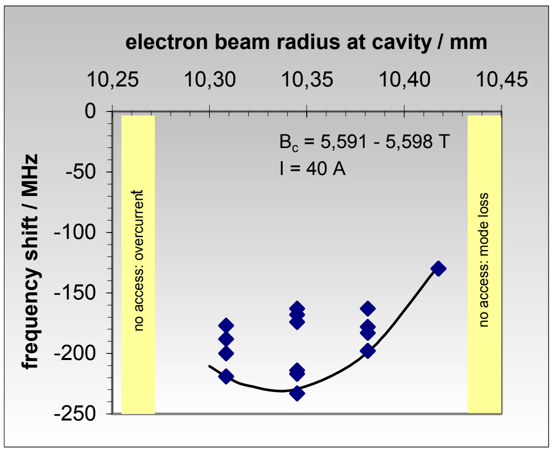

Figure 3. Dependence of output power on electron beam radius in cavity for optimum output power. The allowed range for excitation of the desired mode is only 10.27 to 10.43 mm.

A strong dependence of the output power has been found for different electron beam radii inside the cavity (Fig. 3). The desired mode can only be excited in a narrow range between 10.25 mm and 10.43 mm. At lower beam radii, arcing occurs, at higher radii a wrong mode (or the counter-rotating mode) is excited. The optimum value of the beam radius decreases slightly with decreasing cavity field and beam current.

In long pulse operation, the power was measured calorimetrically by the temperature increase of the cooling water of the RF-load. This load is placed about 6m away from the gyrotron window. The RF beam is focused and directed by two matching mirrors into the load. In order to reduce the power loading on the surface, a set of polarizers are installed to produce a circularly polarized beam. The first matching mirror owns a corrugated surface. A small amount of the RF beam is focused on a horn antenna with a diode detector to get a signal proportional to the output power. This signal, however, is not used for power measurements as the calibration is complicated and can vary easily.

In long pulse operation, the gyrotron was operated with depressed collector. The electrons are decelerated after the RF interaction by a negative voltage U_{body} which usually is chosen to a value between 25 and 30 kV.

Fig. 4 (top) shows the gyrotron operating parameters for a pulse length of three minutes. Shown are the beam current I_{beam}, the body voltage U_{body}, the accelerating voltage U_{acc}, the diode signal U_{diode} and the pressure inside the tube measured as the current of the ion getter pumps. It is increasing very smoothly and stays well in the allowed operating range. The increase of pressure is less than a factor of two.

The highest output power inside the load for a three minute pulse was measured to 922 kW. Including the external stray radiation determined by the calorimetric measurement performed inside the microwave chamber, the total power was 920 kW with an efficiency of 45%. The directed power was measured t0 906 kW and thus the specified value of 900 kW for the Gaussian content has been achieved.

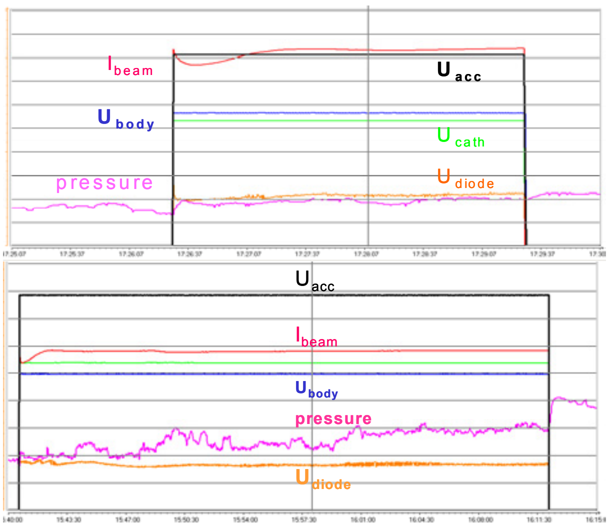

Figure 4. Operation parameters for the 180 s, 950 kW. (top) and the 1893 s, 540 kW pulse (bottom).

At Forschungszentrum Karlsruhe, the available HV power supply is only able to operate up to three minutes at full power, but at reduced electron beam current at less than 30 A longer pulses can be achieved. Fig. 4 (bottom) shows the operating parameters for a pulse of about 31 minutes (1893 s) with an output power of 540 kW. It can be seen by the diode signal that the output power is very stable. The scale for the pressure is logarithmic with a factor of 1.8 per division. The pressure increase is lower than a factor of 2 ending up at about $6{\cdot}10^{-9}$ mbar.

After the successful tests at the Forschungszentrum Karlsruhe, the tube was delivered to IPP Greifswald for tests at highest output power and a pulse length of 30 minutes. A directed output power of 865 kW was measured inside the load, and a total output power of about 910 kW was estimated taking the losses in the transmission line into account (world record in energy content).

III. Coaxial Cavity 170 GHz Gyrotron

A. Design of the pre-prototype tube

Table II summarizes the parameters of the pre-prototype gyrotron. It operates in the $TE_{34,19}$-mode [5]. It is in most respect identical to the long-pulse prototype [6,7] which is under construction. However, the field of the superconducting magnet available at Forschungszentrum Karlsruhe is limited to 6.7 T. Thus the accelerating voltage has to be reduced to values below 80 kV in order to enable operation at 170 GHz. (The industrial prototype will be operated at 90 kV with a cavity magnetic field of 6.87 T). The reduction in accelerating voltage for the short-pulse tube also reduces the available output power to 1.5 MW. The electron gun is a coaxial magnetron injection gun. Special care has been taken to avoid regions of trapped electrons which may cause a Penning discharge. The water cooled coaxial insert can be aligned with high accuracy with respect to the electron beam in the cavity under operating conditions. The geometry of the cavity is shown in Fig. 5.

TABLE II. Parameters of Coaxial Cavity Gyrotron (Pre-Prototype)

RF output power	1.5 MW
Accelerating voltage	80 kV
Beam current	75 A
Cavity mode	$TE_{34,19}$
Cavity radius	29.55 mm
Launcher taper	0.002 rad
Window aperture	100 mm

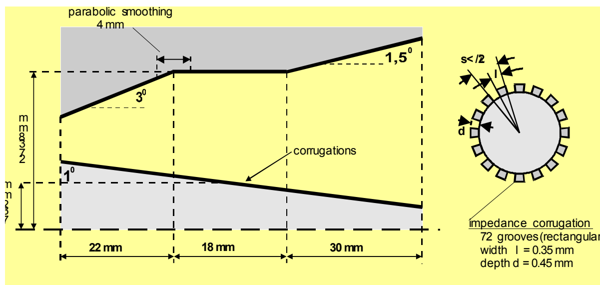

Figure 5. Geometry of the $TE_{34,19}$ coaxial cavity.

The built-in quasi-optical (q.o.) mode converter transforms the cavity mode into a free space beam. It consists of a launcher with smooth wall dimpling and a helical cut and three mirrors, a quasi-elliptical one and a toroidal one followed by a phase correcting mirror. The mirrors were optimized as a compromise between low stray radiation inside the tube and maximum Gaussian content of the RF output beam.

The window unit contains a single quartz-disk with a thickness of 15 half wavelengths at 170 GHz (the long-pulse gyrotron uses a single-disk CVD-diamond window with a thickness of 5 half wavelengths.) The collector can be operated as a single-stage depressed collector for reducing the power density and for increasing the overall efficiency.

B. Experimental Results

During the first measurements parasitic oscillations at low frequency of about 259 and 328 MHz occurred. They could be suppressed successfully by external RF-absorbing material. The LF resonances have also been found in numerical simulations using the code "CST Microwave Studio". The simulations now will be applied to the geometry of the industrial prototype tube.

The performance of the electron gun and electron beam has been found to be in agreement with the design objective as far as the properties have been observable during the gyrotron operation. Stable operation up to $I_b \approx 80$ A and $U_{acc} \approx 80$ kV has been obtained without any observable beam instabilities.

The nominal co-rotating $TE_{-34,19}$ mode at 170 GHz has been excited stably in single-mode operation over a wide parameter range. However, the experimental results are not fully in agreement with calculations. In particular, the observed mode sequence is more dense then predicted by simulations limiting the excitation range of the nominal mode to lower voltages than expected. At an accelerating voltage of 73 kV a microwave output power of 1.15 MW was obtained with 20 % efficiency (without depressed collector). The reasons for the discrepancy need further investigations.

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. A good agreement has been found between the "cold" and "hot" measurements and calculations. A mistake in the optimization of the mirrors has been discovered. The q.o. RF output system with the redesigned mirrors has been tested at low power. The experimental results are in good agreement with the design calculations confirming the reliability of calculations and the accuracy of fabrication. With the incorrect q.o. system which is installed in the pre-prototype the amount of stray microwave losses has been measured to be 8 % of the output power. It has been found that the internal microwave losses are efficiently absorbed by an array of water cooled Al_2O_3 tubes. Based on these results internal absorbers will be installed in the industrial prototype tube for absorbing of at least 50 % of the stray radiation.

IV. CONCLUSIONS AND PERSPECTIVES

The first of seven series gyrotrons for the stellarator W7-X has been tested up to three minutes at full power at FZK and up to 30 minutes at IPP Greifswald. It yielded an output power of 1 MW in short pulse operation with an efficiency of 30% (without depression) and about 950 kW in long pulse operation (180 s) with an efficiency of 45% (with depression). The output power in almost CW operation (30 minutes) was measured to 910 kW.

The second tube will arrive at Forschungszentrum Karlsruhe end of November 2005.

As a next step for the coaxial-cavity gyrotron, the operation with a new redesigned quasi-optical mode converter will be performed. To clarify the different behaviour of the tube with respect to theoretical predictions, a careful investigation of mode competition has to be performed.

REFERENCES

[1] R. Heidinger et al., IEEE Trans. Plasma Science **30** (2002) 800-807.

[2] M. Thumm et al., IEEE Trans Plasma Science **52** (2005) 818-824.

[3] G. Dammertz et al., IEEE Trans Plasma Science **30** (2002) 808-818.

[4] G. Dammertz et al., IEEE Trans Plasma Science **52** (2005) 808-817.

[5] O. Dumbrajs et al., 26th Int. Conf. on Infrared and Millimeter Waves, Toulouse (2001) 10-14.

[6] B. Piosczyk et al.,IEEE Trans. Plasma Science **32.2** (2004) 413-417.

[7] J. P. Hogge et al., Proc. 13th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Heating, Nizhny Novgorod, Russia, (2004) 393-397.