The 140-GHz 1-MW CW Gyrotron for the Stellarator W7-X

G.Dammertz[1], S.Alberti[2], A.Arnold[1,3], E.Borie[1], V.Erckmann[4], G. Gantenbein[5], E.Giguet[6], R. Heidinger[1a], J.P. Hogge[2], S.Illy[1], W.Kasparek[5], K.Koppenburg[1], M.Kuntze[1], H.P.Laqua[4], G. LeCloare[6], F. Legrand[6], W.Leonhardt[1], C.Liévin[6], R. Magne[7], G.Michel[4], G.Müller[5], G.Neffe[1], B.Piosczyk[1], M.Schmid[1], K. Schwoerer[5], M.Thumm[1,3], M.Q.Tran[2]

[1]Forschungszentrum Karlsruhe, [1]IHM, [1a] IMF I, Association EURATOM-FZK, Postfach 3640, D-76021 Karlsruhe, Germany
[2]Centre de Recherche en Physique des Plasmas, Association Euratom-Confédération Suisse, EPFL Ecublens, CH-1015 Lausanne, Suisse
[3]Universität Karlsruhe, Institut für Höchstfrequenztechnik und Elektronik, Kaiserstr. 12, D-76128 Karlsruhe, Germany
[4]Max-Planck-Institut für Plasmaphysik, Teilinstitut Greifswald, Association EURATOM, Wendelsteinstr. 1, D-17491 Greifswald, Germany
[5]Institut für Plasmaforschung, Universität Stuttgart, Pfaffenwaldring 31, D-70569 Stuttgart, Germany
[6]Thales Electron Devices, 2 bis, Rue Latécoère, F-78941 Vélizy-Villacoublay, France
[7]Association Euratom-CEA, Départment de Recherches sur la Fusion Controlée, F-13108, Saint Paul Lez Durances, France

Abstract

The development of high power gyrotrons in continuous wave (CW) operation for heating of plasmas used in nuclear fusion research has been in progress for several years in a joint collaboration between different European research institutes and industrial partners. A recent R&D program aims at the development of 140 GHz gyrotrons with an output power of 1 MW in CW operation for the 10 MW ECRH system of the new stellarator plasma physics experiment Wendelstein 7-X at IPP Greifswald, Germany. The work is performed under responsibility of FZK Karlsruhe in collaboration with CRPP Lausanne, IPF Stuttgart, IPP Garching and Greifswald, CEA Cadarache and TED Vélizy. The gyrotron operates in the $TE_{28,8}$ mode and is equipped with a diode type magnetron injection electron gun, an improved beam tunnel, a high-mode purity low-ohmic loss cavity, an optimized non-linear up-taper, a highly efficient internal quasi-optical mode converter, a single-stage depressed collector and an edge-cooled, single disk CVD-diamond window. RF measurements with a pre-prototype tube “Maquette” at pulse duration of a few milliseconds yielded an RF output power of 1.15 MW at a beam current of 40 A and a beam voltage of 84 kV. Depressed collector operation has been possible up to decelerating voltages of 33 kV without any reduction of the output power, and an efficiency of 49% has been achieved. A second version of the tube - the prototype - with improved cooling mainly at the mirror box, yielded an output power of 970 kW for 11.7 s at a beam current of 41 A with an efficiency of about 44% with a depression voltage of 26.3 kV. At these power levels, the HV power supply is limited to 180s - a pulse length which could be achieved at an output power of 890 kW. Longer pulse lengths are possible at reduced power levels, and a pulse length of 938 s was possible at an output power of 539 kW. The pulse length was limited due to the pressure increase inside the tube.

1 Introduction

Electron-Cyclotron-Resonance-Heating (ECRH) and Electron-Cyclotron-Current-Drive (ECCD) require gyrotrons operating at a frequency of 110-170 GHz with an output power in the Megawatt range and an efficiency of about 50%. These gyrotrons have been subject of intense investigation worldwide for a number of years. Powers of 2 MW and more have been achieved in short pulse operation and great progress has been made in the development of 1 MW long pulse gyrotrons [1-3].

ECRH has proven to be important tools for plasma devices especially for stellarators, as it provides both net current free plasma start up from the neutral filling gas and efficient heating of the plasma [4].

The development of ECRH is closely linked to the development of stellarators, and one of the key issues for stellarators is the development and demonstration of high power gyrotrons with the capability of continuous wave (CW) operation. For the stellarator Wendelstein 7-X now under construction at IPP Greifswald, Germany, a 10 MW ECRH system is foreseen. The Forschungszentrum Karlsruhe has signed a contract to build up the 10 MW ECRH system at Greifswald, and a European collaboration has been established between Forschungszentrum Karlsruhe, CRPP Lausanne, IPF Stuttgart, CEA Cadarache and Thales Electron Devices (TED), Vélizy, to develop the gyrotrons with an output power of 1 MW for CW operation (30 min).

The major problems of high power, high frequency gyrotrons are given by the ohmic heating of the cavity surface, by the stray radiation due to non-perfect quasi-optical mode conversion, by the dielectric losses in the output window and by the power capability of the collector. The technical limit of the power density at the resonator surface is assumed to be 2 kW/cm^2 for CW operation. For this reason high power gyrotrons are operated in high order volume modes with a large cavity and thus reduced ohmic losses.

A major break through for a CW source is the use of a diamond window fabricated by microwave plasma assisted chemical vapour deposition (MPACVD) [5], which allows the design and the operation of a CW tube at the 1 MW power level. The single-stage depressed collector brings the overall efficiency of the gyrotron in the 50% range and at the same time significantly decreases the thermal loading inside the gyrotron.

2 Gyrotron Design

Output power	1 MW
Accelerating voltage	80 kV
Beam current	40 A
Cavity mode	$TE_{28,8}$
Frequency (stabilized)	139.8 GHz
Cavity magnetic field	5.56 T
Quality factor (self-cons.)	1100
Cathode half angle	21.8°
Cathode-cavity distance	350 mm
Beam radius	10.1 mm
Cavity radius	20.48 mm
Cavity length	14.5 mm
Launcher length	207 mm
Launcher taper	0.23°
Window material (300K)	Diamond

Table 1: Design parameters

The design values are summarized in Table 1. Fig. 1 shows the prototype gyrotron inside the teststand at Forschungszentrum.

The gyrotron uses a diode-type magnetron injection gun with a thermionic annular emitter consisting of an impregnated tungsten matrix.

The conical beam tunnel between gun and resonator is equipped with alternating rings of copper and absorbing ceramics in order to suppress spurious oscillations in that region.

The cylindrical cavity is designed for operating in the $TE_{28,8}$ mode. It is a standard tapered cavity with linear input downtaper of 2.5° and a non-linear output uptaper with the initial angle of 3°. The length of the cylindrical part is 14.5 mm, its diameter 40.96 mm. In order to avoid mode conversion, the transition from the tapers to the straight section is smoothly rounded

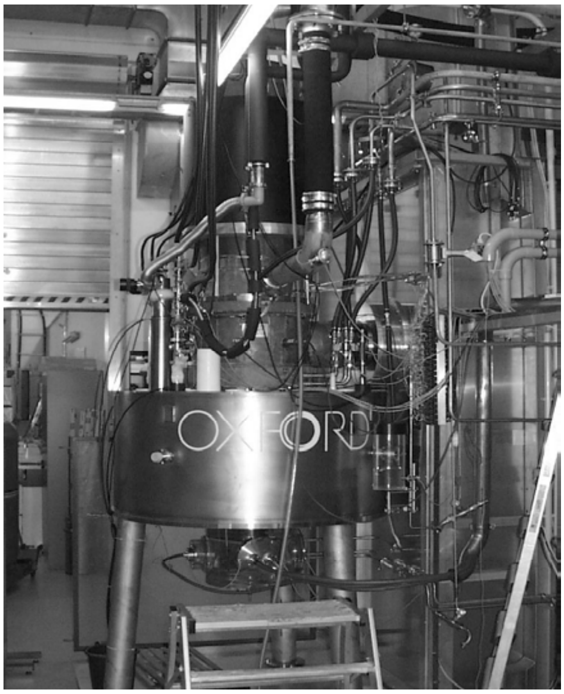

Fig. 1: The gyrotron at the teststand with a view to the microwave chamber

over a length of 4 mm and 6mm at the input-taper and the output-taper, respectively. The mode purity was calculated to 99.9%. The Q-value was calculated by self-consistent computations to Q = 1100, in cold cavity calculations to 855. The frequency was chosen to be 140.3 GHz in short pulse operation, and a frequency shift to 139.8 GHz is connected to the thermal expansion.

The RF beam is separated from the electron beam through a highly-efficient quasi-optical mode converter consisting of a rippled-wall waveguide launcher followed by a mirror of quasi-elliptical shape and two toroidal mirrors which match the beam to the window size. Coupled mode theory was used in the design and analysis of the launcher, and the reflectors are designed with Gaussian optics and diffraction theory. The launcher profits from an improved perturbation leading to optimum phasing of the mode mixture (optimum bunching) and suppression of spurious oscillation.

The output vacuum window unit uses a single, edge cooled CVD-diamond disk with an outer diameter of 106 mm, a window aperture of 88 mm and a thickness of 1.80 mm corresponding to 4 half wavelengths. Thermal finite element computations show that for a power of 1 MW at 140 GHz, a loss tangent of $4\cdot10^{-5}$, a dielectric permittivity of 5.67, a

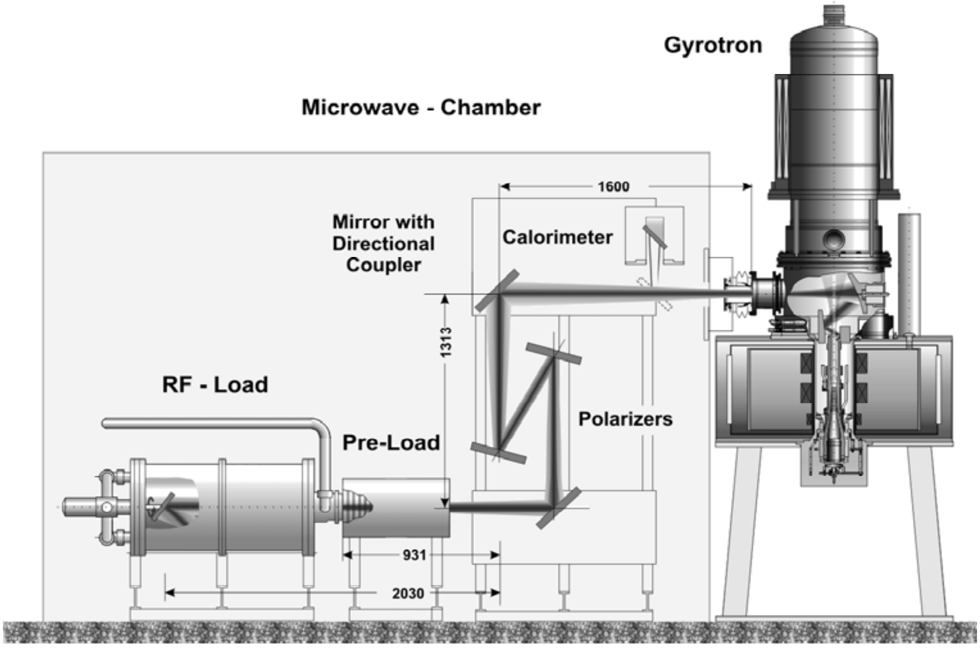

Fig. 2: Microwave chamber with RF-diagnostics

thermal conductivity of 1900 W/m·K at T~300 K, a cooling rim of 5 mm and for a heat transfer coefficient of 12 kW/m²·K to the cooling water of 20°C, the temperature of the window increases to 61°C in the center and to 15°C at the edge. The absorbed power is 705 W. The loss tangent has a potential option of $2\cdot10^{-5}$. This reduces the absorbed power and the temperature increase by a factor of 2, and the window losses are expected to 4 % (Table 3).
A depressed collector for energy recovery is used in order to increase the efficiency and to decrease the collector power density on the surface. A normal conducting axial magnet sweeps the electron beam sinusoidally along the collector surface.

3 Diagnostics

In order to have similar condition as for the operation at IPP Greifswald and to be able to test the mirrors at full power, the beam is transmitted quasi-optically into an RF-tight microwave box which is equipped with water-cooled mirrors and polarizers directing the beam towards the high power water load (Fig.2).
The mode purity of the Gaussian beam is determined by a thin dielectric target plate placed across the RF-beam. The temperature rise of the target, which is proportional to the absorbed RF-beam power, is measured by an infrared camera at different positions. From the temperature distribution the fundamental Gaussian contribution can be calculated.
The power can be measured in short pulse operation by inserting a mirror into the RF beam which reflects the beam into a calorimeter (Fig. 2).
During long pulse operation the power is measured by the RF-load. As there will be reflections from the main load, a pre-load is installed in front of the main load in order to measure the contribution of this power as well. The sum of the two contributions is called directed power.
The different components of the gyrotron (as for example the cavity, launcher, mirrorbox of the gyrotron etc.) as well as those inside the microwave chamber are equipped with calorimetric measurement devices. These allow a very accurate measurement of the power losses during a long pulse measurement.

4 Experiments

The pre-prototype gyrotron "Maquette" had been tested successfully at Forschungszentrum Karlsruhe [6]. The pulse-length limitations were mainly due to a pressure increase inside the tube. Another difficulty had arisen due to arcing inside the high-power RF-load, especially in the horizontal plane.
The next tube, the prototype gyrotron, had been built with some improvements concerning the water cooling of the mirror box and had also been tested successfully. The problems of arcing inside the RF-load were solved by inserting polarizers into the RF-beam which convert the linear horizontal polarization into a circular one. In short pulse operation an output power of 940 kW has been achieved. Fig. 3 shows the profile measurement of the RF-beam. The shape indicates a slight ellipticity.
Fig. 4 shows the output power as function of the beam current. The output power agrees very well to the theoretical value (straight line) at low beam currents, however the experimental output power starts saturating when increasing the beam current, whereas the theoretical output power does not. As this effect was not observed with the pre-prototype tube (for this tube 1.15 MW had been achieved in short pulse

Pulse length	Power (kW)	Current (A)	Efficiency	Energy (MJ)	limitation
3^{m}	890	41	0,41	160	power supply
$15^{m}38^{s}$	539	24	0,42	505	pressure
$21^{m}40^{s}$	257	26	0,21	350	pressure

Table 2: Pulse limitations for different output powers

operation), the effect is very unlikely caused by spurious mode oscillations. It is assumed that the saturation is related to an azimuthally inhomogeneous emission of the electrons from the cathode surface. Indeed, by a visual inspection of the emitter ring, the inhomogeneities on the surface could be verified.

The highest output power of 970 kW could be achieved for a pulse length of 11.7 s with an efficiency of 44% with single-stage depressed collector. The specified output power of 900 kW for a Gaussian beam content (directed power) could be obtained during 55s at a total output power of 922 kW.

Further long pulse results are summarized in Table 2. At high output power (MW level) the pulse-length are limited due to the existing HV power supply. At reduced output power, the limitations are caused by the pressure increase inside the gyrotron, though the radiation inside the mirror box is very low. Table 3 shows a calorimetric measurement of internal gyrotron components for two pulses: for the 890 kW pulse (180s) and for the 922 kW pulse mentioned above. The relative power losses (related to the generated output power) are the same for the two pulses. The electric and the calorimetric measurements of the power deviate by less than ± 5%.

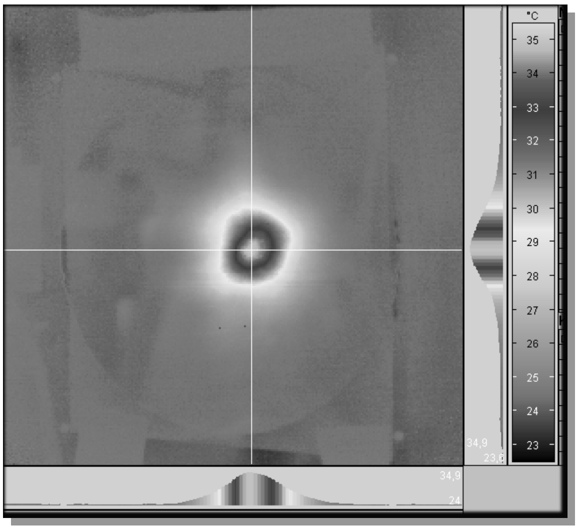

Fig.3: RF-beam profile measurements at a distance of 650 mm from window

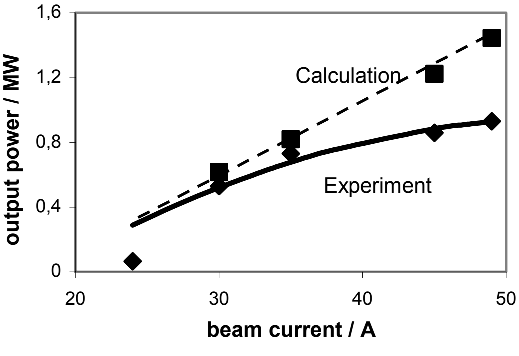

Fig. 4: Output power versus beam current

The internal stray radiation was measured to be only 1.2 to 1.3% of the generated power, the total stray radiation (sum of external and internal stray radiation) is only about 3%. Though the theoretical amount of total stray radiation is calculated to only 1.1 to 1.2 %, it is assumed that - due to fabrication tolerances - the experimental level of stray radiation cannot be reduced further.

The pressure increase is caused by the heating and outgassing of the ion getter pumps which are placed inside the gyrotron and are operated by the magnetic fields of the superconducting magnet. An infrared temperature measurement of the internal ion getter pumps (through the diamond window) immediately after the 938 s pulse indicated a strong temperature increase of some parts of the pumps up to 250°C. The measured temperature distribution only can be explained by assuming that internal parts of the ion getter pumps are heated. As these parts are seen by the infrared camera through the pumping grid, which reduces the intensity of the radiation, the real temperatures are much higher than measured. The internal parts are at HV-potential and have to be isolated, therefore it is rather difficult to introduce better cooling schemes. Due to the HV-connections, it is also rather difficult to improve the RF-shielding of the internal parts.

The prototype tube was sent back to the manufacturer TED for visual inspection of interior gyrotron components. No severe damage could be found. The tube was reassembled including two improvements. A new emitter ring was installed with a better homogeneity of emission and it was tried to have a better cooling for the external parts of the ion getter pumps.

Despite the fact, that the 1 MW level could not be achieved with this tube due to the saturation of output power with beam current and that the pulse length of 30 minutes has not been achieved, the development of the gyrotron had been stopped and the series tubes were ordered. They of course contain improvements in order to overcome the observed limitations.

	922 kW; 55 s		892 kW; 180 s	
	efficiency (SDC)	42.2%	efficiency (SDC)	40.9%
	Power / kW	Power / %	Power / kW	Power / %
Generated Power	**972 ± 48**	100	**941 ± 47**	100
Ohmic losses	37 ± 5	3.8	37 ± 5	4.0
Int. Stray Radiation	13 ± 4	1.3	12 ± 4	1.2
Window Losses	0.4	0.04	0.4	0.04
Output Power	**922 ± 46**	95.2	**892 ± 45**	95.0
Ext. Stray Radiaton	16 ± 4	1.7	16 ± 4	1.6
Directed Power	**907 ± 45**	93.5	**876 ± 44**	93.3

Table 3: Power measurements for the prototype tube

5 Conclusions

With the prototype tube an output power of 970 kW could be achieved with a pulse length of 11.7 s, and 890 kW with a pulse length of 180 s. This was limited due to the HV power supply available at Forschungszentrum. The limitation of the output power to values somewhat lower than 1 MW is due to an azimuthal inhomogeneity of the emission from the electron gun. For reduced output power of 539 kW, the pulse length was limited to 938 s due to a pressure increase inside the tube. This effect was caused by insufficient RF-shielding of the internal parts of the ion getter pumps.

Acknowledgements

The 140 GHz gyrotron has been constructed in the frame work of a joint development between the Associations EURATOM-FZK, EURATOM-Swiss Confederation and Thales Electron Devices. The work performed at FZK is fully supported by the Project PMW within the Program FUSION and at the CRPP is partially supported by the Swiss National Science Foundation.

References

[1] V. E. Zapevalov, G.G. Denisov, V. A. Flyagin, A. Sh. Fix, A.N. Kuftin, A. G. Litvak, M. V Agapova, V. N. Iljin, V. A. Khmara, V. E. Myasnikov, V. O. Nichiporenko, L. G. Popov, S. V. Usachev, V. V. Alikaev, V. I. Iljin, "Development of a 170 GHz/1 MW Russian gyrotron for ITER", Fus. Eng. Design 53 (2001), pp. 377-385

[2] A. Kasugai, K. Sakamoto, K. Takahshi, K. Kajiwara, H. Shoyuma, Yu. Ikeda, M. Tsuneoka, Y. Ikeda, T. Fujii, T. Kariya, Y. Mitsunaka, T. Imai, "1 MW and long pulse operation of Gaussian beam output gyrotron with CVD diamond window for fusion devices", Fusion Eng. Design 53 (2001) 399-406

[3] M. Blank, K. Felch, P. Borchard, P. Calahan, S. Cauffmann, T. S. Chu, H. Jory, "Demonstration of High-Power, Long-Pulse, 140 GHz Gyrotron Oscillator", to be published in IEEE Trans. Plasma Sci.,

[4] V. Erckmann, G. Dammertz, D. Dorst, L. Empacher, W. Förster, G. Gantenbein, T. Geist, W. Kasparek, H.P. Laqua, G.A. Müller, M. Thumm, M. Weissgerber, H. Wobig: "ECRH and ECCD with high power gyrotrons at the stellarators W7-AS and W7-X", IEEE Trans. Plasma Sci., PS-27, pp. 538-546, 1999.

[5] R. Heidinger, G. Dammertz, A. Meier, M. Thumm, "CVD diamond windows studied with low and high power millimeter waves", IEEE Trans. Plasma Sci., vol. 30, 800-807 (June 2002)

[6] G. Dammertz, S. Alberti, A. Arnold, E. Borie, V. Erckmann, G. Gantenbein, E. Giguet, R. Heidinger, J.P. Hogge, S. Illy, W. Kasparek, K. Koppenburg, M. Kuntze, H. P. Laqua, G. LeCloarec, Y. LeGoff, W. Leonhardt, C. Liévin, R. Magne, G. Michel, G. Müller, G. Neffe, B. Piosczyk, M. Schmid, K. Schwörer and M. Thumm, "Development of a 140-GHz, 1-MW Continuous Wave Gyrotron for the W7-X Stellarator", IEEE Trans Plasma Sci., vol. 30,. 808-818, (June 2002)