Development of Steady-State 2 MW, 170 GHz Gyrotrons for ITER

B. Piosczyk 1), A. Arnold 1[a]), G. Dammertz 1), R. Heidinger 1), S. Illy 1), J. Jin 1), K. Koppenburg 1), W. Leonhardt 1), G. Neffe 1), T. Rzesnicki 1), M. Schmid 1), M. Thumm 1[a]), X. Yang 1),
S. Alberti 2), R. Chavan 2), D. Fasel 2), T. Goodman 2), M. Henderson 2), J.P. Hogge 2), M.Q. Tran 2), I. Yovchev 2),
V. Erckmann 3), H.P. Laqua 3), G. Michel 3),
G. Gantenbein 4), W. Kasparek 4), G. Müller 4), K. Schwörer 4),
D. Bariou 5), A. Beunas 5), E. Giguet 5), G. LeCloarec 5), F. Legrand 5), C. Liévin 5),
O. Dumbrajs 6)

1) Forschungszentrum Karlsruhe (FZK), Association EURATOM-FZK, Postfach 3640, D-76021 Karlsruhe, Germany, [(a)] also Universität Karlsruhe, D-76128 Karlsruhe, Germany
2) CRPP, Ass. EURATOM-Confédération Suisse, EPFL Ecublens, Lausanne, Suisse
3) MPI für Plasmaphysik, Association EURATOM, D-17491 Greifswald, Germany
4) Institut für Plasmaforschung, Universität Stuttgart, Pfaffenwaldring 31, Stuttgart, Germany
5) Thales Electron Devices, 2 bis, Rue Latécoère, F-78941 Vélizy-Villacoublay, France
6) Helsinki University of Technology, Association EURATOM-TEKES, FIN-02015 HUT, Finland

e-mail contact of main author: bernhard.piosczyk@ihm.fzk.de

Abstract. A prototype of a 1 MW, CW, 140 GHz conventional gyrotron for the W7-X stellarator in Greifswald/Germany has been tested successfully and the fabrication of series tubes started. In extended studies the feasibility for manufacturing a continuously operated high power coaxial cavity gyrotron has been demonstrated and all needed data for an industrial design has been obtained. Based on this results the fabrication of a first prototype of a 2 MW, CW, 170 GHz coaxial cavity gyrotron started recently in cooperation between European research institutions and European tube industry. The prototype tube is foreseen to be tested in 2006 at CRPP Lausanne where a suitable test facility is under construction.

1. Introduction

Gyrotron oscillators have proven to be the most powerful sources of coherent wave radiation in the millimeter wavelength range. Fusion experiments of the next generation such as the stellarator W7-X now under construction at Greifswald/Germany or the international thermonuclear experimental reactor (ITER) require gyrotrons with a microwave (RF) output power of one megawatt or more in continuous wave (CW) operation. At the W7-X stellarator plasma heating with EC waves will be the main heating method. In total an electron cyclotron wave (ECW) system capable to deliver up to 10 MW, CW microwave power at 140 GHz (10 gyrotrons a 1 MW) will be built up to meet the goals of this stellarator with inherent steady-state capability [1]. For ITER 24 MW, CW microwave power at 170 GHz is foreseen in the basic scenario for heating and for stabilization of NTM instabilities [2]. The development of such gyrotrons in the frequency range between 110-170 GHz is subject of investigation worldwide since a number of years. A great progress has been made in the development of conventional long pulse gyrotrons with 1 MW microwave output power during the last years [3-6]. For the development of the 140 GHz gyrotrons a European gyrotron collaboration has been established between European research laboratories (mainly FZK Karlsruhe and CRPP Lausanne) and European tube industry (Thales Electron Devices, (TED), France). The results obtained within this collaboration are very convincing. With a prototype of the 140 GHz gyrotron the capability of CW operation around 1 MW microwave output power has been

practically demonstrated. The obtained results have lead to the decision to start with the series production of seven gyrotrons of this type as needed at the W7-X stellarator .
To reduce the costs of the installations of the ECW system at ITER and to allow a compact upper port launcher an increase of the output power per gyrotron is desirable. Coaxial cavity gyrotrons have the potential to generate microwave power in excess of 1 MW, CW at frequencies around 170 GHz since very high-order volume modes can be used. 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 competing modes [7]. The feasibility of manufacturing a 2 MW coaxial gyrotron operated in CW has been demonstrated and data needed for an industrial design has been obtained [8,9]. The suitability of the major gyrotron components for CW operation has been examined and according to a first draft integral design no technical constraints have been found for manufacturing of a 2 MW, CW coaxial gyrotron as could be used for ITER. Based on these results the manufacturing phase of a first prototype of such a coaxial cavity gyrotron at 170 GHz started recently within the above mentioned European gyrotron collaboration. The technical design including integration of all components as well as thermo-mechanical calculations and specifications of auxiliary systems needed for operation of the tube is in progress. The delivery of the first prototype is expected for beginning of 2006. The SC magnet has been specified and has been already ordered. A test facility for testing the 2 MW tube up to CW is under construction at CRPP Lausanne [10].
In the following, first the main results and the status of the 1 MW, CW, 140 GHz conventional gyrotron for W7-X will be given and then the work on the 2 MW, CW, 170 GHz coaxial cavity gyrotron will be described.

2. 140 GHz gyrotron for W7-X

The development of the 1 MW, CW, 140 GHz gyrotron for the W7-X stellarator in Greifswald/Germany started a few years ago within the above mentioned European gyrotron collaboration. The $TE_{28,8}$ mode has been selected as operating cavity mode. The gyrotron has been equipped with a highly efficient internal quasi-optical mode converter, a single-stage depressed collector and an edge-cooled, single-disk CVD-diamond window. The main design parameters are summarized in Tab. I.

TABLE I: Main design parameters of the 140 GHz gyrotrons for W7-X.

operating cavity mode	$TE_{28,8}$
RF output power, P_{out} / MW	1
accelerating voltage, U_{acc} / kV	81
beam current, I_b / A	40
RF output efficiency, η_{out}	≥ 45%

A pre-prototype (maquette) and a prototype tube have been built and tested at FZK till now. In Fig. 1 both the bare gyrotron and the tube installed in the superconducting (SC) magnet for testing are shown. With the prototype tube the design specifications have been almost fulfilled. A maximum RF output power of 970 kW with an output efficiency of ~44% has been achieved for a pulse length of 11.7 s. For 180 s an output power of 890 kW has been obtained. The 180 s pulse was limited due to the capability of the high voltage (HV) power supply available at FZK.
At a beam current reduced to about 25A, at which the HV power supply allows an operation

Fig. 1.: Photo of the 140 GHz gyrotron, bare tube (left side), assembled for operation (right side).

up to CW, an output power of 540 kW with an efficiency of 41% has been obtained with the prototype tube for a pulse length of 937 s limited by a pressure increase inside the gyrotron [6]. At further reduced beam current with an output power of ~250 kW the pulse length was extended up to 1300 s. In Fig. 2 the results are summarized. The mode purity of the Gaussian output beam is as high as 98 %. The pressure increase is assumed to be caused due to warming up of internal parts of the ion getter pumps, placed inside the mirror box, to temperatures above 250^{0}C by the microwave stray losses inside the tube. The microwave stray losses have been measured to be as low as 3.2% of the output power in good agreement with the calculated value of 2.1 %. The internally absorbed part of the stray radiation was experimentally determined to only 1.4 %. Even this low value caused an increase of the temperature of the internal ion getter pumps as has been clearly shown by temperature measurements with an infrared camera. In order to avoid the pressure rise due to the warming up of the pumps in the series gyrotrons the ion getter pumps will be placed outside the mirror box.

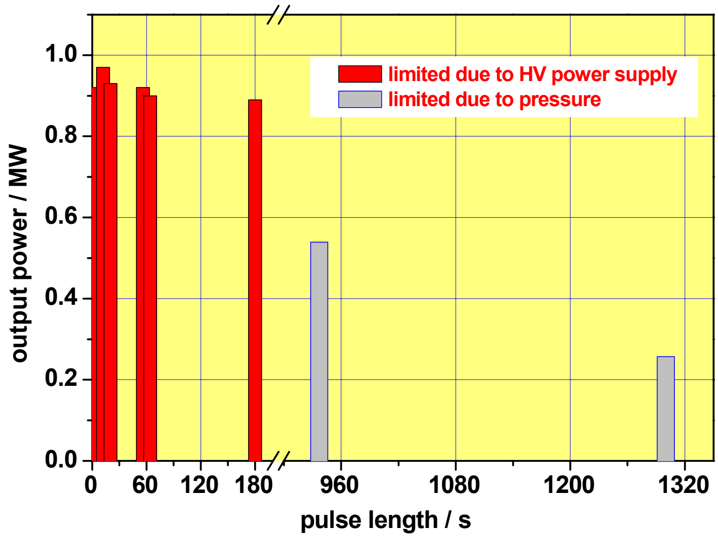


Fig. 2: Maximum RF output power versus pulse length as obtained with the 140 GHz prototype tube.

The design output power of 1 MW was not fully achieved. This is suspected to be due to azimuthally inhomogeneous electron emission of the emitter ring which may result in a degradation of the electron beam quality and, as a consequence, in a limitation of the microwave output power to values slightly below 1 MW. For the seven series gyrotrons under production special attention will be paid to the quality assurance of the emitter rings.

3. 2 MW, CW, 170 GHz coaxial cavity gyrotron for ITER

The feasibility of manufacturing a 2 MW coaxial gyrotron operated in CW has been studied experimentally and theoretically during the last years at FZK. The investigations have been performed on a coaxial gyrotron operated at 165 GHz in the $TE_{31,17}$ mode described in detail in [8]. This experimental gyrotron is demountable and enables an easy replacement of the components. Its cooling performance allows an operation only at short pulses (typically ≤ 10 ms). With this gyrotron problems specific to the coaxial arrangement as mechanical stability of the coaxial insert, required alignment accuracy, leakage current to the insert and losses have been studied. A limitation of the HV performance due to build up of a Penning discharge inside the coaxial electron gun has been successfully suppressed by modifying the gun geometry such that electron trapping is avoided. A maximum RF output power P_{out} of 2.2 MW has been obtained in single-mode operation and efficient microwave generation has been demonstrated. The conversion of the high-order cavity mode into a free space Gaussian mode has been performed in a quasi-optical (q.o.) RF output system consisting of a smooth launcher with a cut and of two mirrors. The microwave stray losses captured inside the tube body have been investigated and the amount of the losses has been measured. The feasibility of the main gyrotron components for use in CW operation has been examined and demonstrated. According to a first draft integral design of a 2 MW, CW coaxial gyrotron no technical constraints have been found [9].

Based on these results it has been decided to begin within the European gyrotron collaboration the development of a coaxial cavity gyrotron with an RF output power of 2 MW, CW at 170 GHz as could be used in the ECW system of ITER. The conceptual design of such a tube compatible with CW operation has been completed and the manufacturing phase of a first prototype started recently. The first prototype is expected to be delivered beginning of 2006. A superconducting (SC) magnet has been specified and already ordered. A test facility designed to host the 2 MW, CW gyrotron and to perform experimental investigations up to full performances is presently built up at CRPP Lausanne.

TABLE II: Design parameters of the prototype and pre-prototype of the coaxial gyrotron.

	prototype	**pre-prototype**
operating cavity mode	$TE_{34,19}$	
frequency, f / GHz	170	
RF output power, P_{out} / MW	2	~ 1.5 - 1.7
beam current, I_b / A	75	
accelerating voltage, U_{acc} / kV	90	~80
pulse length: τ	up to CW	5 - 10 ms
efficiency (with depressed collector), η_{out}	≥ 45 %	
cavity magnetic field, B_{cav} / T	6.87	6.66 - 6.70
velocity ratio, $\alpha = \beta_\perp / \beta_{\|\|}$	1.3	

In parallel to the work on the industrial tube, the design of the most critical components of the prototype - as electron gun, cavity and RF interaction and the quasi-optical RF output system - will be verified under realistic conditions. For this the experimental 165 GHz coaxial gyrotron at FZK has been modified for operation at 170 GHz in the $TE_{34,19}$ cavity mode. This tube is considered as a pre-prototype for the 2 MW, CW industrial gyrotron since it is equipped with a cavity and a q.o. RF output system same as designed for the prototype and with an electron gun which is very similar to the gun of the prototype. The nominal design parameters of both tubes, the 2 MW, CW prototype and the short pulse pre-prototype are summarized in Table II. The reduction of the beam voltage to about 80 kV for operation of the pre-prototype became necessary because the maximum magnetic field of the available SC-magnet at FZK is limited to values between 6.66 and 6.70 T. Therefore, in order to be able to excite the $TE_{34,19}$ mode at 170 GHz at the reduced magnetic field, the beam voltage has to be reduced. Consequently somewhat reduced RF output power is expected in the pre-prototype tube.

3.1. First prototype of the 2 MW, 170 GHz coaxial cavity gyrotron

The physical design of main components of the 2 MW prototype tube have already been done and the detailed drawings for manufacturing are in progress. In order to keep the wall loading inside the cavity within technically acceptable limits, the $TE_{34,19}$ mode has been selected as operating mode. The geometry of the cavity is shown in Fig. 3. The coaxial insert is tapered and corrugated as indicated in that figure. This allows a selective influence of the quality factor of neighbouring modes reducing thus the mode competition [7]. The Ohmic losses at the outer cavity wall have been calculated to be within 1 kW/cm² (ideal copper at 273 K) for a generated RF power of 2.2 MW. The corresponding peak losses at the insert have been calculated to be less than 0.1 kW/cm². The start up behaviour has been simulated with a time dependent, self consistent multimode code considering up to 13 competing modes. High efficient, single mode operation is expected over a wide parameter range. The main mode competition occurs between the two mode triplets, $\{TE_{-33,19}, TE_{-34,19}, TE_{-35,19}\}$ and $\{TE_{+32,20}, TE_{+33,20}, TE_{+34,20}\}$. Simulations have also been performed for a cavity with walls slightly deformed due to the Ohmic heat loading.

A new RF output system with 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 - has been designed [11] in order to keep the microwave losses inside the gyrotron tube within technically acceptable limits (≤ ~5% of RF output power). From the use of a dimpled-wall launcher a reduction of diffraction losses at the edge of the launcher cut is expected. The goal for designing the mirrors was to generate an RF output beam with a high Gaussian content. However, because of limitations in the accuracy of mechanical fabrication of the surface structure of the non-quadratic mirror a compromise has been made between the Gaussian content of the RF output beam and the amount of microwave losses inside the tube.

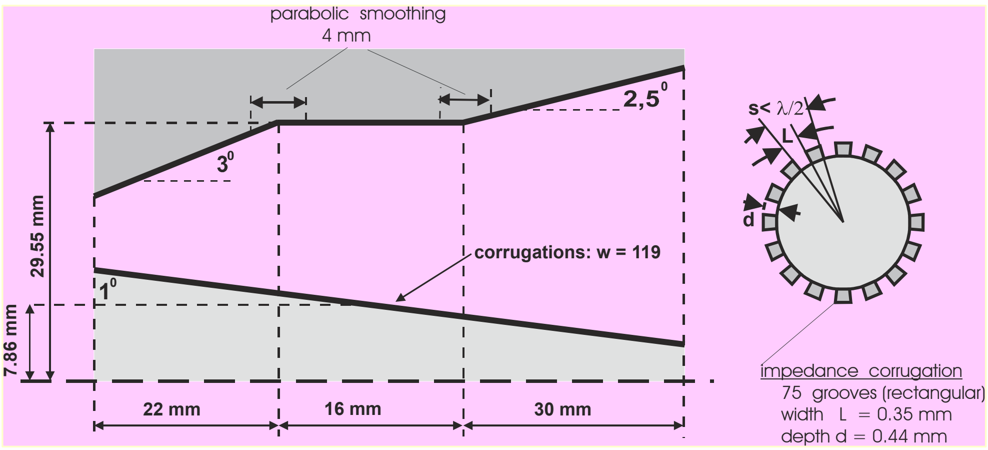


Fig. 3: Cross section of the $TE_{34,19}$ coaxial cavity

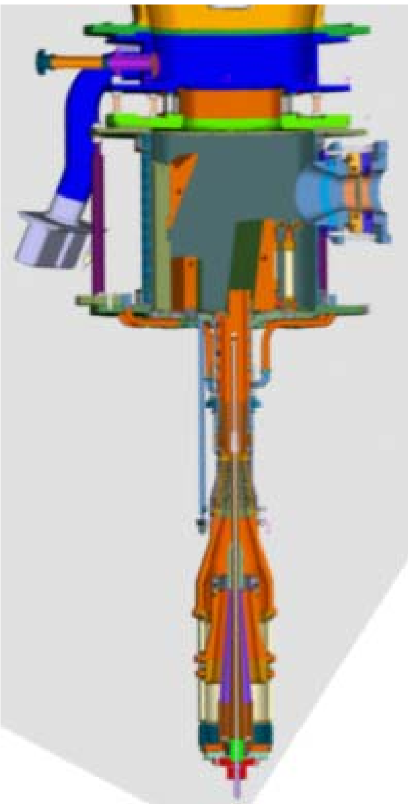
According to calculations the total amount of microwave stray losses inside the gyrotron tube is expected to be within the technically acceptable value (~ 5 % to 6 % of P_{out}). The short-pulse experiment will allow to verify the design performance, to measure the amount of stray losses and to study experimentally possibilities to absorb the microwave losses inside the tube.

A coaxial magnetron injection gun (CMIG) has been designed similar to the gun used in the 165 GHz gyrotron [12]. The emitting current density is about 4.2 A/cm^2 at I_b = 75 A. The inner part of the coaxial insert is cooled with water and its position can be adjusted under operating conditions. Special care has been taken in designing the geometry of the cathode and the insert in order to avoid regions in which electrons can be trapped in order to avoid the built up of a Penning discharge.

As RF output window a single-disk of CVD diamond with a thickness of 1.852 mm = 5λ/2 at 170 GHz will be used. At a loss tangent of 2×10^{-5} (state of the art) 880 W power will be absorbed in the disk [13]. Edge cooling of the CVD diamond disk with water is sufficient for removing the heat load. The window will have an aperture of 96 mm.

To obtain a desired total efficiency of ≥ 45 % a single-stage depressed collector with the collector at ground potential will be used. Under nominal operating conditions the remaining beam power which has to be dissipated in the collector is expected to be about 2.3 MW, CW. In case of fast modulation of the microwave output power as required for NTM stabilisation at ITER the average beam power which has to be dissipated power at the collector walls increases up to ~3 MW. The design optimisation of the collector is in progress.

The magnetic field distribution and the technical parameters of the SC-magnet have been specified and the SC-magnet has been already ordered. In addition to the solenoidal coils the magnet will be equipped with a set of dipole coils generating a transverse magnetic field needed for the alignment of the coaxial insert relative to the electron beam under operating conditions. The warm bore-hole will have a diameter of 220 mm and the distance between the cathode position and the maximum of the magnetic field will be about 380 mm.



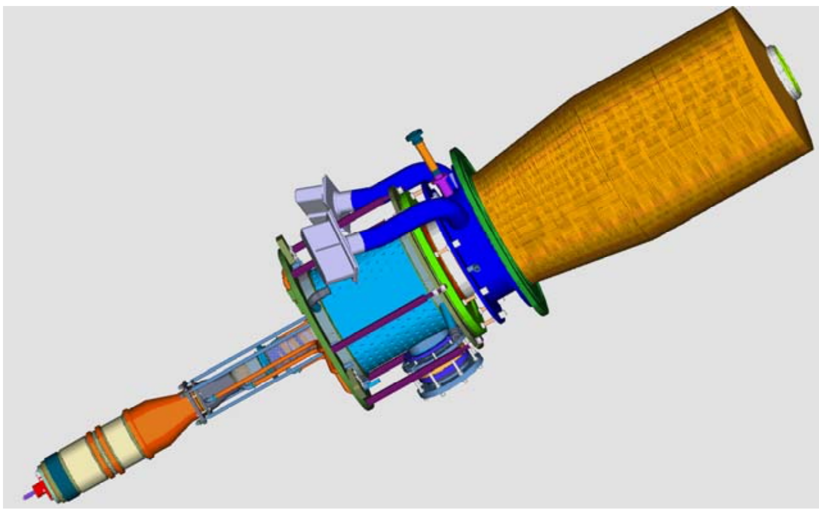


Fig. 4: View of the integrated coaxial gyrotron, cut (left side) and full tube (right side)

An integral design of a 2 MW, CW coaxial gyrotron has been performed as shown in Fig.4. The high voltage insulation between the body and the collector is placed at the top of the mirror box. The overall dimensions of the gyrotron are comparable with the dimensions of a conventional 1 MW, CW, 140 GHz gyrotron.

3.2. The pre-prototype of the 2 MW, 170 GHz coaxial cavity gyrotron

In order to verify the design of the most critical components of the prototype the experimental short pulse coaxial gyrotron at FZK operated at 165 GHz in the $TE_{31,17}$ mode has been modified for operation at 170 GHz in the $TE_{34,19}$ cavity mode. This modified coaxial gyrotron is equipped with an electron gun which is very similar to the gun of the industrial prototype and both the cavity and the quasi-optical RF output system will have the same geometry as in the prototype tube. Thus the generation of the high power electron beam, RF interaction and mode competition as well as the design of the RF output system will be verified and the amount of stray radiation will be measured under realistic conditions. The main nominal design parameters are summarized in Tab. II, both for the 2 MW, CW prototype and for the short pulse tube. The SC-magnet used for the short pulse experiments delivers only a magnetic field up to about 6.68 T. Due to this the beam voltage has to be reduced to values below 80 kV in order to be able to excite the $TE_{34,19}$ mode at 170 GHz. The operation at a lower voltage results in an RF output power reduced to a value of about 1.5 MW depending on the finally obtained magnetic field.

The modifications of the previously used 165 GHz coaxial gyrotron for operation at 170 GHz have already been performed. All components have been fabricated, the pre-prototype has been assembled and installed inside the SC-magnet. A schematic view of the coaxial magnetron injection gun (CMIG) is shown in Fig. 5. The emitting current density is about 4.2 A/cm^2 at $I_b = 75$ A. The inner part of the coaxial insert is cooled with water as needed for CW operation and its position can be adjusted under operating conditions. Regions inside the gun in which electrons can be trapped have been avoided. The pulse length is limited to 5 - 10 ms depending on the beam current. The limitation in pulse length is due to the fact that the cavity, the launcher and the mirrors are not actively cooled and no beam sweeping along the collector surface is foreseen. A disk out of fused silica with a thickness of 6.84 mm $\cong 15\lambda/2$ at 170 GHz is used as RF output window.

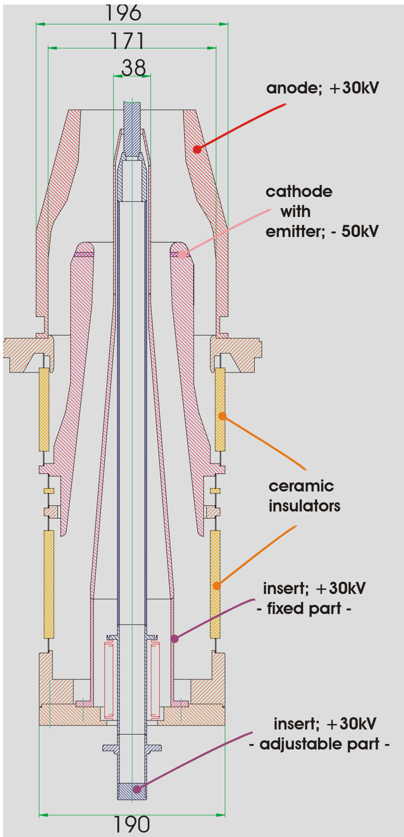


Fig. 5: CMIG gun (dimensions in mm)

The experimental operation started recently. First, the radial position of the inner conductor has been aligned with respect to the electron beam within ± 0.1 mm. Stable operation up to $I_b \approx 58$ A (present limit of the HV power supply) and $U_c \approx 80$ kV has been achieved without any instabilities and parasitic low frequency oscillations. No indications of the built-up of a Penning discharge inside the gun have been observed. The oscillation of the nominal $TE_{34,19}$ mode has been observed in a parameter range which is in good agreement with theoretical predictions. Work on optimization of the microwave output power and efficiency is underway. The distribution of the microwave output beam has been found to be not in agreement with the calculations. The reason is not clear yet and a detailed analysis is in progress. The experimental measurements are continuing.

3. Summary and outlook

The development of the 1 MW, CW 140 GHz conventional (hollow waveguide) cavity gyrotron for W7-X was very successful. CW operation at 1 MW output power has almost been obtained and thus the series production of seven additional tubes has started. Encouraged by this impressive progress and based on results of short pulse experiments the development of a 2 MW, CW 170 GHz coaxial cavity gyrotron as could be used for ITER is in progress within the European gyrotron collaboration. The manufacturing phase of a first 2 MW, CW prototype started recently. Delivery of the prototype tube is expected for beginning of 2006. A suitable test facility is under construction at CRPP Lausanne. In parallel to the work on the prototype tube experimental operation with a short pulse pre-prototype tube is in progress in order to verify the design of critical components of the prototype tube.

References

[1] V. Erckmann, et al., "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.

[2] ITER Physics Basis Editors et al.," ITER Physics Basis", Nucl. Fusion, vol. 39, pp. 2137-2638, 1999.

[3] V. E. Zapevalov, et al., "Development of a 170 GHz/1 MW Russian gyrotron for ITER", Fus. Eng. Design 53 (2001), pp. 377-385

[4] A. Kasugai, et al., “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

[5] M. Blank, et al., “Demonstration of High-Power, Long-Pulse, 140 GHz Gyrotron Oscillator”, IEEE Trans. Plasma Science, Vol. 32, No. 3, June 2004, 867-876.

[6] G. Dammertz, et al., “Development of a 140-GHz, 1-MW Continuous Wave Gyrotron for the W7-X Stellarator”, IEEE Trans Plasma Sci., vol. 30, June 2002, 808-818.

[7] C.T. Iatrou, S. Kern, A. Pavelyev “Coaxial cavities with corrugated inner conductor for gyrotrons", IEEE Microwave Theory Tech. vol. 41, No. 1, January 1996, 56-64.

[8] B. Piosczyk et al., "165 GHz Coaxial Cavity Gyrotron - last results", IEEE Trans. Plasma Science, Vol. 32, No. 3, June 2004, 853-860.

[9] B. Piosczyk et al., "A 2 MW, 170 GHz Coaxial Cavity Gyrotron", IEEE Trans. Plasma Science, Vol. 32, No. 3, June 2004, 413-417.

[10] J.P. Hogge et al. “Development of a 2 MW, CW, 170 GHz Coaxial Cavity Gyrotron for ITER”, EC13, May 17-20, 2004, Nizhny Novgorod, Russia.

[11] G. Michel, "Synthesis of Yeti-footprint-mirrors with low stray radiation", EC 13, May 17-20, 2004, Nizhny Novgorod, Russia

[12] B. Piosczyk, “A novel 4.5 MW electron gun for a coaxial gyrotron”, IEEE Trans. Electron Devices, vol. 48, No.12, December 2001, 2938-2944.

[13] R. Heidinger, et al., “CVD diamond windows studied with low and high power waves”, IEEE Trans Plasma Sci., vol. 30,. June 2002, 800-807.