Experimental Results of Series Gyrotrons for the Stellarator W7-X

G. Gantenbein[1], H. Braune[2], G. Dammertz[1], V. Erckmann[2], S. Illy[1], S. Kern[1], W. Kasparek[3], H. P. Laqua[2], C. Lechte[3], F. Legrand[4], W. Leonhardt[1], C. Liévin[4], G. Michel[2], B. Piosczyk[1], O. Prinz[1,5], M. Schmid[1], M. Thumm[1,5]

[1]Forschungszentrum Karlsruhe, Association EURATOM-FZK, Institut fuer Hochleistungsimpuls- und Mikrowellentechnik, Postfach 3640, D-76021 Karlsruhe, Germany
[2]Max-Planck-Institut fuer Plasmaphysik, Teilinstitut Greifswald, Association EURATOM, Wendelsteinstr. 1, D-17491 Greifswald, Germany
[3]Universitaet Stuttgart, Institut fuer Plasmaforschung, Pfaffenwaldring 31, D-70569 Stuttgart, Germany
[4]Thales Electron Devices, 2 Rue de Latécoère, F-78141 Vélizy-Villacoublay, France
[5]Universitaet Karlsruhe, Institut fuer Hoechstfrequenztechnik und Elektronik, Kaiserstr. 12, D-76131 Karlsruhe, Germany
e-mail: gerd.gantenbein@ihm.fzk.de

Abstract: The stellarator W7-X is presently under construction in Greifswald, Germany. It will have a powerful ECRH which will be used for plasma start-up, heating and current drive. The complete ECRH system, including the RF generators, transmission line and auxiliary power supplies will be provided under the leadership of FZK in a European collaboration. The RF power will be delivered by 140 GHz, 1 MW gyrotrons which are able to operate in continuous wave. Nine (out of 10) of these gyrotron come from a european development program with Thales Electron Devices as industrial partner, one gyrotron has been delivered by Communications and Power Industries. Both gyrotrons have shown the design values. This contribution reports on the present status of the series gyrotrons from Thales Electron Devices.

1. Introduction

The stellarator W7-X will use ECRH as the basic heating and current drive system [1]. In the first stage W7-X will be equipped with a 10 MW ECRH system operating at 140 GHz in continuous wave (CW). The RF power will be delivered by gyrotron oscillators. The complete ECRH-system will be provided by FZK, including the design, development, construction, installation and integrated tests of all components required for stationary plasma heating on site at IPP Greifswald e.g. gyrotrons, transmission lines, power supplies. FZK also coordinates contributions from IPF of the University Stuttgart and from IPP Greifswald. This project benefits also from the collaboration with CRPP Lausanne, CEA in Cadarache and Thales Electron Devices (TED) in Vélizy. After completion of the development phase seven series gyrotrons have been ordered at TED. First operation and long pulse conditioning of these gyrotrons will take place at the test stand at FZK where pulses up to 3 minutes at full power and 30 minutes shots at reduced electron beam are possible (limited by power supply). 30 minutes shots at full power are possible at IPP. The first TED series gyrotron has been tested successfully and has shown full performance on site at IPP Greifswald. One gyrotron has been developed at Communications and Power Industries, Palo Alto, USA (CPI). This gyrotron also achieved the specifications. Including the pre-prototype tube, the prototype tube and the 140 GHz CPI-tube, ten gyrotrons will be available for W7-X.

2. Configuration of the gyrotron and experimental set-up

A DC heated magnetron injection gun which works in the temperature limited region is used. It is designed as a diode type gun (without intermediate anode) and operates at an accelerating voltage of 80 kV creating a beam current of 40 A with a current density of 2.5 A/cm^2, the average velocity ratio of the electrons ($v_\perp/v_{||}$) is 1.3. The gun cavity region (beam tunnel) is equipped with stacked copper and RF-absorbing ceramic rings in order to avoid spurious oscillations which could degrade the beam quality and lead to high thermal load.

The cavity is a standard cylindrical design, optimized for the mode $TE_{28,8}$. In order to minimise mode conversion at the transition from the input taper to the cylindrical section and to the output taper these sections have been smoothed, resulting in a mode purity of 99.9 %. The realistic thermal peak wall loading of the cavity is less then 2 kW/cm^2. The electron beam is placed at the first radial maximum of the electrical field of the $TE_{28,8}$ mode to ensure a strong interaction of the electrons with the design mode. The nominal value of the compression ratio (B_{cavity}/B_{gun}) of the beam is 23.5.

The launcher and quasi-optical system are optimised to convert the rotating $TE_{28,8}$ cavity mode into a fundamental Gaussian beam with an efficiency of 98 % [2,3]. From calculations a conversion efficiency of the $TE_{28,8}$ to the fundamental Gaussian beam TEM_{00} of more then 98 % is expected.

The output vacuum window is a single, edge-cooled CVD diamond disk with an inner aperture of 88 mm mounted under a small angle with respect to the output beam. To minimise reflections at the window a resonant thickness for 140 GHz has been chosen (two wavelengths inside material). Due to the low loss tangent of diamond the absorbed power for a 1 MW beam is only 705 W, the very high thermal conductivity limits the central temperature increase in CW operation to about 60 °C.

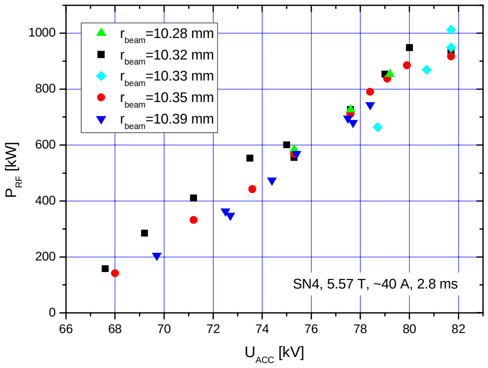
The isolation of the collector from the cavity region allows the application of a decelerating voltage. This measure reduces the residual energy of the spent electrons and lowers the thermal load of the collector resulting in a higher overall efficiency. During operation the collector is at ground potential, the cathode voltage is set to a negative value of 52 - 54 kV and the cavity voltage to 27 - 29 kV. To equalise the thermal loading of the collector, watercooled solenoidal coils sweep the electron beam across the surface in axial direction with a repetition frequency of 7 Hz. An advanced 50 Hz sweeping system using transverse fields has the advantage of a further reduction of the peak wall loading. This system is presently under investigation [4].

Possible stray radiation in the gyrotron and along the transmission line to the cw load is measured calorimetrically. The thermal loading of the gyrotron components and transmission line is monitored continuously.

3. Experimental results of series gyrotrons

3.1 Operation of SN4 at full performance

The series gyrotron SN4 was taken into operation and tested at FZK with short and long pulses. The total RF output power has been measured by a short pulse calorimetric load which is mounted close to the output window of the gyrotron. In the experiments given in Fig. 1 the beam radius has been variied from 10.28 mm to 10.39 mm. In short pulses (2.8 ms) it shows a stable output power of up to 1 MW at the design values.



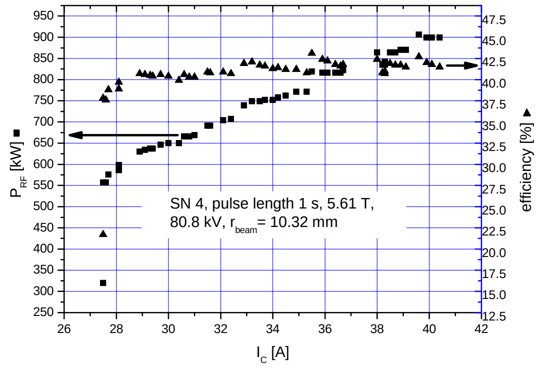


Fig. 1: Output power of SN4 gyrotron in short pulse versus accelerating voltage at different electron beam radii in the cavity.

Fig. 2: Output power and efficiency of series gyrotron SN4 in dependance of beam current.

For medium pulse length (≈0.1 s) and long pulses (several seconds up to 30 minutes) a CW load with massive water cooling is used in combination with an optical transmission system. At pulses longer than ≈0.1 s the gyrotron is usually operated with depressed collector. The efficiency of the gyrotron was around 42 % for beam currents from 28 A up to 40 A with a maximum of 43 % (see Fig. 2). This indicates a good performance of the electron gun and a sufficient electron beam quality. Safe operation of the gyrotron under CW conditions was possible in the current range from 27 A up to 44 A with a depression voltage of up to 28 kV. Pulses have been performed up to 30 minutes, however with a reduced beam current (< 30 A) due to a limitation in the power supply at FZK. The output power obtained was about 500 kW. At maximum RF-power (910 kW) repetitive operation of the gyrotron was possible with a pulse length of 3 minutes.

The output beam of each gyrotron has been measured and analysed with an infrared system. It was found that the beam parameters of SN4 are within the usual range and the quality is excellent, as in the previous series gyrotrons. The Gaussian mode content of the output beam is 97 %.

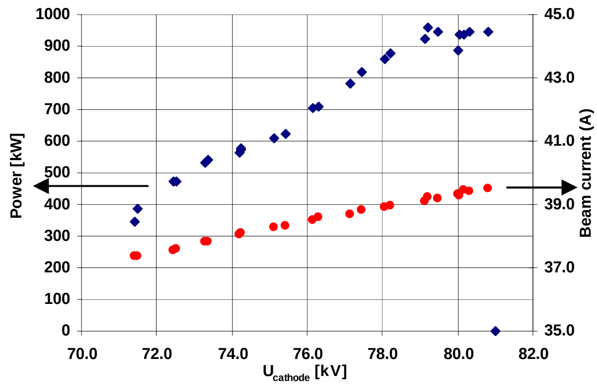


Fig. 3: Influence of accelerating voltage on output power and beam current in short pulse operation of SN2.

3.2 Short pulse results of SN2

The operating parameters of the series gyrotron SN2 have been optimised in short pulses of a few ms. Fig. 3 shows the dependance of the output power on the cathode voltage and the increasing beam current at constant heating of the electron gun. The output power can be variied from 350 kW up to 950 kW by changing the voltage from 72.5 kV to 80.5 kV. At higher voltage the gyrotron oscillates in a wrong cavity mode.

The specified output power (1 MW) of the gyrotron has been achieved with a beam current of 41 A. This is demonstrated in Fig. 4 which also shows a saturation of output power with increasing current (at constant B-field), in

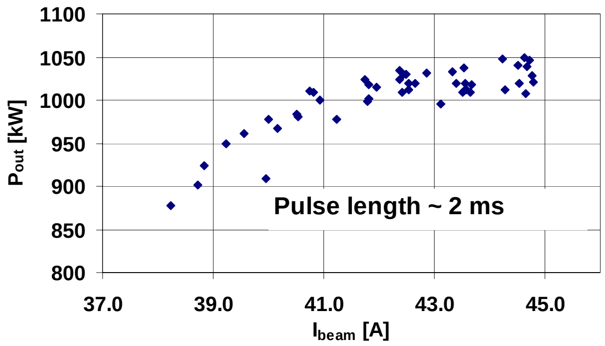


Fig. 4: Saturation of output power with increasing beam current measured with SN2.

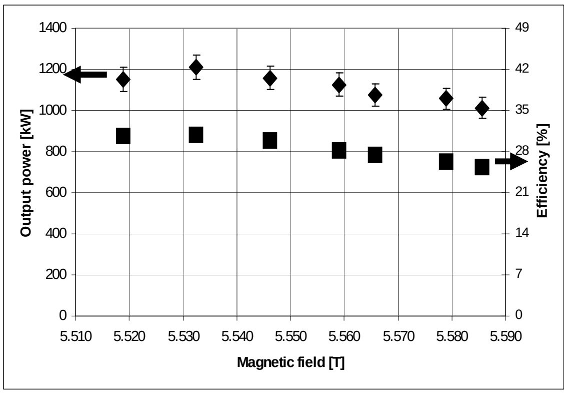


Fig. 5: Output power and efficiency SN2 achieved with 50 A beam current.

particular at a beam current above 40 A. This effect is well known and has been observed at other gyrotrons also (e.g. SN4).

Operation of the tube was possible with currents of up to 50 A. Fig. 5 shows the maximum achieved output power at 50 A (≈ 1200 kW) in dependance of the magnetic field and optimised cathode voltage (76 – 81 kV). Since the gyrotron is operated with non-depressed collector in short pulses the corresponding efficiency is small and variies from 25.4 % to 30 % which is in good agreement with results of previous gyrotrons.

3.3 Performance limitations

Although the series gyrotrons showed a good behaviour in short pulse operation, it was not possible to maintain this performance at longer pulses. In some cases the performance at longer pulses was reduced substantially due to the occurrence of parasitic oscillations with frequencies which are considerably lower then the design frequency. This behaviour suggests the assumption that these parasitic oscillations are generated prior to the cavity rather then in the cavity like the usual competing modes. As one consequence the optimised parameters must be changed substantially to maintain stable oscillations thus resulting in lower output power and efficiency.

Precise measurements have been performed to monitor possible frequencies which may originate from interactions in the beam tunnel. It has been found that several frequencies in the range of 119 GHz – 132 GHz have been excited simultaneously with the main mode at 140 GHz.

At the mirror box of the W7-X gyrotrons a relief window with a calorimeter is installed which offers the possibility to measure the level of stray radiation in the gyrotron. This measurement is given in Fig. 6 which shows the output power and the relative stray radiation through the relief window versus the accelerating voltage. It is clearly visible that those operating points where only the desired 140 GHz was observed show a smaller amount of relative stray radiation. As soon as additional parasitic oscillations occur, the level of relative stray radiation is increased significantely.

After opening of the gyrotrons SN2 and SN3 the beam tunnel has been examined very carefully. This component consists of sandwiched copper and ceramic rings which have a decreasing inner diameter towards the cavity. Several ceramic rings and brazings close to the entrance of the electron beam to the cavity were damaged due to thermal overload. These observations strongly support the assumptions that the parasitic oscillations are excited in the beam tunnel. A possible improvement towards a more stable single frequency operation in the high power regime has to take into account that the starting current of the parasitics must be increased as much as possible. This can be achieved e.g. by destructing the residual azimuthal symmetry and introducing longitudinal slits in the Cu rings. A different solution has been reported by [5]: the authors replaced successfully the beam tunnel by a full SiC cylinder which absorbs RF radiation on the one hand and which is a semiconductor on the other hand.

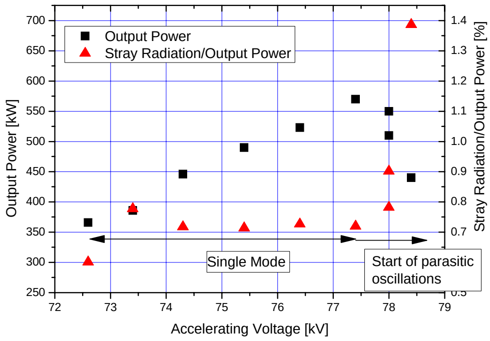


Fig. 6: Output power and relative stray radiation measured at the relief window versus accelerating voltage.

4. Summary

In this contribution we have reviewed experimental results of the series gyrotrons for the ECRH system of the stellarator W7-X. In general the short pulse operation of the gyrotrons show acceptabel results with respect to output power and efficiency. All tested gyrotrons have a high quality Gaussian output beam. The prototype gyrotrons, the series gyrotrons SN1 and SN4 worked well and achieved the specified output power also in long pulse operation.

However, in long pulse operation of SN2 and SN3 a different picture is observed: parasitic oscillations in the low frequency range (≈119 – 132 GHz) may occur and modify the electron parameter prior to the interaction in the cavity. This reduces the output power, efficiency and/or the achievable operating parameters.

The low frequency oscillations may be correlated with an unacceptable increase of the internal currents in the gyrotron and a deterioration of the vacuum conditions in the tube. Operation of a gyrotron in this regime produce a high heat load of the beam tunnel area and may result in severe damages of the components. Although the design of the beam tunnel is basically the same for all gyrotrons tested so far, the occurrence of this feature may depend on small variations on detailed material properties (e.g. RF absorption of the ceramic rings). A more robust design of the beam tunnel with respect to avoidance and suppression of parasitic oscillations is required.

Acknowledgement

This work, supported by the European Communities under the contract of Association between EURATOM and Forschungszentrum Karlsruhe, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] V. Erckmann et al.: Electron cyclotron heating for W7-X: physics and technology, Fusion Science and Technology, **52**, 291-312 (2007)

[2] M. Thumm et al.: EU megawatt-class 140-GHz CW gyrotron, IEEE Trans. on Plasma Science, **35**, 143-153 (2007).

[3] G. Dammertz et al.: High power gyrotron development at Forschungszentrum Karlsruhe for fusion applications. IEEE Transactions on Plasma Science, **34** (2006) 173-86.

[4] H. Braune et al.: Extended operation of the 1 MW, CW gyrotrons for W7-X, Conf. Digest Joint 32nd Int. Conf. on Infrared and Millimetre Waves and 15th Int. Conf. on Terahertz Electronics, Cardiff, UK, 2007, pp. 104-105.

[5] H. Shoyama et al.: High efficiency oscillation of 170 GHz high-power gyrotron at $TE_{31,8}$ mode using depressed collector, Jpn. J. Appl. Phys., **40**, L906-L908 (2002).