Report of recent experiments with the European 1 MW, 170 GHz CW and SP prototype gyrotrons for ITER

Zisis Ioannidis[1], *Tomasz* Rzesnicki[1], *Ferran* Albajar[2], *Stefano* Alberti[3], *Konstantinos* Avramidis[1], *William* Bin[4], *Tulio* Bonicelli[2], *Alex* Bruschi[4], *Ioannis* Chelis[5], *Francesco* Fanale[4], *Gerd* Gantenbein[1], *Virgille* Hermann[6], *Jean-Philippe* Hogge[3], *Stefan* Illy[1], *Jianbo* Jin[1], *John* Jelonnek[1], *Walter* Kasparek[7], *George* Latsas[5], *Carsten* Lechte[7], *François* Legrand[6], *Ioannis* Pagonakis[1], *Francisco* Sanchez[2], *Martin* Schmid[1], *Christian* Schlatter[3], *Manfred* Thumm[1], *Ioannis* Tigelis[5], *Minh Quang* Tran[3], *Anastasios* Zisis[5], *Andy* Zein[1]

[1]IHM, Karlsruhe Institute of Technology (KIT), Kaiserstr. 12, 76131 Karlsruhe, Germany
[2]European Joint Undertaking for ITER and the Development of Fusion Energy (F4E), Barcelona, E-08019, Spain
[3]Swiss Plasma Center (SPC), Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland
[4]Institute of Plasma Physics "P.Caldirola", National Research Council of Italy, Milan, Italy
[5]Faculty of Physics, National and Kapodistrian University of Athens, Zografou, GR-157 84, Athens, Greece
[6]Thales Electron Devices, 2 rue Marcel Dassault, Vélizy-Villacoublay, F-78141, France
[7]IGVP, University of Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany

Abstract. The European 1 MW, 170 GHz industrial CW prototype gyrotron has been designed within EGYC (European GYrotron Consortium) in collaboration with the industrial partner Thales Electron Devices (TED) and under the coordination of Fusion for Energy (F4E). This is a conventional (hollow) cavity gyrotron that is based on the 1 MW, 170 GHz short-pulse (SP) modular gyrotron, which has been designed and manufactured by KIT in collaboration with TED. The SP prototype has been tested in multiple experimental campaigns since 2015 and the nominal cavity mode $TE_{32,9}$ is exited at 170.1 GHz, producing RF power above 1 MW with 35 % interaction efficiency. The first phase of the experiments with the CW industrial gyrotron was successfully completed at KIT in 2016, verifying most of the ITER specifications. Short pulses (<10ms) deliver RF power higher than 0.9 MW with a total efficiency of 26 % (in non-depressed collector operation). The Gaussian mode content of the RF beam is 97 %. Pulses with duration of 180 s (limited by the high-voltage power supply at KIT) produce power more than 0.8 MW with maximum efficiency 38 % (in depressed collector operation). In this work the achievements with the SP and the CW prototype gyrotrons are summarized.

1 Introduction

Europe is making significant effort for the development of high-frequency, high-power gyrotrons able to cover the electron cyclotron resonance heating (ECRH) and current drive (ECCD) needs of modern fusion devices, such as the ITER tokamak. In particular, the European GYrotron Consortium (EGYC) in cooperation with Thales Electron Devices (TED) and under the coordination of Fusion for Energy (F4E) is developing the EU 1 MW, 170 GHz (hollow-cavity) gyrotron.

According to the project planning of F4E, the development of the European prototype gyrotron for ITER is organized in two steps. First, a modular short-pulse prototype was developed by the Karslruhe Institute of Technology (KIT) in cooperation with TED in order to verify the scientific design of the gyrotrons key components with pulses in the ms range. Then one CW industrial prototype tube (with the same scientific design) was developed in order to verify the ITER requirements, in terms of output RF power, efficiency, RF beam quality and pulse length.

The basic scientific design of the 170 GHz, 1 MW modular prototype was successfully verified in multiple experimental campaigns between 2015 and 2017. Based on the SP gyrotron design, the manufacturing of the first industrial CW prototype gyrotron has been completed at TED in 2015. The testing of the CW industrial prototype is organized in two phases. For the first phase the tube was delivered to KIT in February 2016, where it was operated with the Oxford Instruments superconducting magnet. Due to a limitation of the power supply, the operation of the gyrotron at KIT is limited to 180 s pulses. For this reason, after the successful completion of the experiments at KIT, the CW prototype was delivered to the Swiss Plasma Center (SPC), Lausanne, where the tube is currently operated with a new cryogen-free superconducting magnet manufactured by Cryogenics. One of the key goals at SPC is to extent the pulse length up to one hour. In this work we summarize the key results from the recent experiments with the European

* Corresponding author: zisis.ioannidis@kit.edu

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

1 MW, 170 GHz CW and SP prototype gyrotrons for ITER.

2 Short-Pulse Prototype

Fig. 1 shows the modular short-pulse prototype gyrotron, which has a hollow-cavity (conventional gyrotron). This gyrotron has been tested in many experimental campaigns during the previous years. In the first experimental campaign that took place before the delivery of the magnetron injection gun (MIG), the tube was operated with the MIG that was initially designed for the modular KIT short-pulse pre-prototype 2 MW, 170 GHz coaxial-cavity gyrotron. Details for this campaign are presented in [1]. In this section we focus on the operation of the gyrotron with the nominal MIG that was delivered by TED.

Fig. 1. The EU 1MW, 170 GHz SP gyrotron.

2.1. Operation with the basic configuration

The basic (according to the initial scientific design) configuration of the short-pulse prototype gyrotron with the TED was tested at KIT in 2015 [2]. Taking advantage of the flexibility of the Oxford Instruments superconducting magnet, two different operating points have been defined, in terms of the accelerating voltage. The first one is the Low-Voltage Operating Point (LVOP) with accelerating voltage 76.7 kV and beam current 45 A and the second one is the High-Voltage Operating Point (HVOP) with accelerating voltage 85.1 kV and beam current 40 A.

From simulations, both operating points are equivalent and able to deliver output power 1 MW with practically the same efficiency. Fig. 2 presents a typical example of the output RF power with respect to the accelerating voltage. For both operating points the nominal mode $TE_{32,9}$ is easily excited at the frequency 170.1 GHz and it is possible to generate power higher than 1 MW with 30 % total efficiency in non-depressed collector operation, which corresponds to an electronic efficiency of 35 %, as expected from theory [3]. It is interesting to note that by significantly increasing the beam current to 63 A, more than 1.2 MW power was generated (in non-depressed collector operation) with an efficiency of approximately 30%.

The total efficiency of the gyrotron is further increased, when it is operated with a single-stage depressed collector (SDC). Fig. 3 presents the generated RF power with respect to the depression voltage for the HVOP. By applying 26 kV to the gyrotron body, it is possible to increase the efficiency to slightly higher than 40% without affecting the generated power significantly.

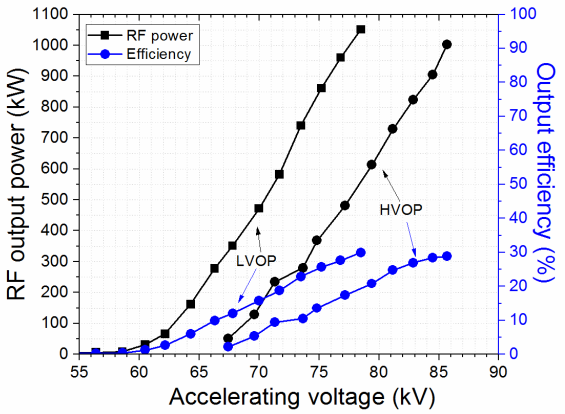

Fig. 2. RF power and corresponding efficiency (in non-depressed collector operation) with respect to the accelerating voltage for the LVOP ($V_{acc} \approx 78$ kV, $I_b \approx 45$ A) and the HVOP ($V_{acc} \approx 86$ kV, $I_b \approx 40$ A).

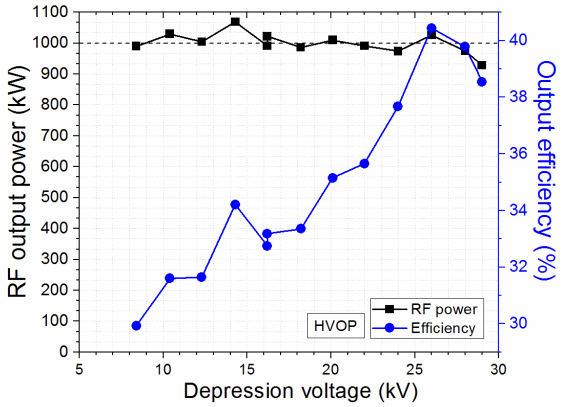

Fig. 3. RF power and corresponding total output efficiency (in depressed collector operation) with respect to the depression voltage for the HVOP ($V_{acc} \approx 86$ kV and beam current $I_b \approx 43$ A).

One of the key parts of the gyrotron that was also verified during this first campaign is the quasi-optical output coupler. The output RF beam of the gyrotron has been studied with an infrared camera. According to post

processing of the experimental data the Gaussian content of the output beam was found to be almost 98 %, which meets very well the theoretical calculations.

2.2. Modified deceleration setups

According to the design/simulations, it should be possible to reach 50 % total efficiency by applying approximately 35 kV depression voltage. However, theoretical studies for the spent beam already predicted a limitation of the efficiency at lower values of the depression voltage [4], due reflection of part of the electrons in the area of the mirror box. In particular, the geometry and the internal arrangement of the mirror box results in an increase of the beam voltage depression and in turn to a significant drop of the kinetic energy of the electrons. For this reason, the maximum applicable deceleration voltage before electron reflections start is lower than initially expected. In order to investigate if it is possible to reach the ITER specifications in terms of total efficiency (larger than 50%), the modular SP was slightly modified and further tests were performed in depressed collector operation.

Fig. 4 (left) presents the first modification that was tested, which was to introduce in the mirror box a construction similar to the cooling pipes of the CW industrial prototype. Note that the SP prototype gyrotron is not equipped with a cooling system for the beam-tunnel, the cavity and the launcher, since this is not necessary for pulses in the ms range. On the contrary, in the CW prototype the pipes of the aforementioned cooling system pass through the mirror box. These pipes are located closer to the electron beam and they reduce the beam's voltage depression. Thus, an improvement of the gyrotron efficiency is expected.

Fig. 5 presents with red circles an example case (LVOP with output power approximately 850kW) of the total efficiency in depressed collector operation with respect to the depression voltage after the installation of the dummy cooling pipes. In the same figure the green triangles refer to the corresponding results of the initial gyrotron setup (without the dummy cooling pipes). Due to the installation of the cooling pipes mockup it was possible to increase the deceleration voltage roughly by 5 kV and to increase the total efficiency by 2 %.

The total efficiency can be further increased provided that the deceleration voltage is applied as close as possible to the collector. Fig. 4 (right) presents the second deceleration setup that was tested, where the SP gyrotron was operated using the isolated collector of the KIT 2 MW, 170 GHz coaxial-cavity short-pulse gyrotron. Using this collector and an additional isolating disc between the gyrotron and the magnet top plate it is possible to set the complete mirror box of the gyrotron to the body voltage and thus start the deceleration of the electrons very close to the collector. As shown in Fig. 5 with black squares, with this configuration it was possible to increase the deceleration voltage up to 39 kV and in this way to increase the total efficiency of the gyrotron to slightly higher than 44 %.

Based on the performance of the gyrotron when the complete mirror box is set on high-voltage, a metallic construction that may be installed inside the mirror box and can bring the body voltage closer to the collector was developed and will be tested [5].

Fig. 4. Upgrades on the SP gyrotron: internal pipes inside the mirror box (left) and gyrotron equipped with an isolated collector and cryostat insulating ring (right).

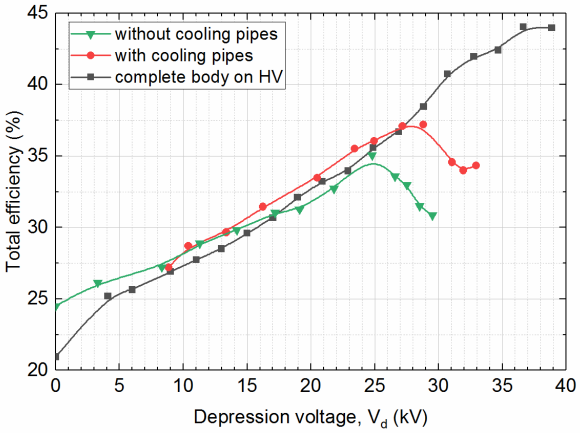

Fig. 5. Measured total efficiency (in depressed collector operation) with respect to the depression voltage for difference configurations of the SP prototype gyrotron (LVOP with average output power approximately 850 kW).

3 Industrial CW prototype

Herein we summarize the latest experimental results with the CW industrial prototype gyrotron at KIT and SPC. A detailed description of the results achieved at KIT is presented in [6]. The experiments at SPC are still ongoing.

3.1. Experiments at KIT

Fig. 6 shows the installation of the CW industrial prototype gyrotron in the KIT superconducting magnet during the 2016 experimental campaign. The KIT magnet is equipped with a set of dipole coils that were used for the optimization of the alignment of the magnetic field axis with the gyrotron cavity axis. The optimization procedure is based on the excitation circle method [7], according to which the beam is shifted by changing the dipole coil currents and the currents for

which the nominal mode switches to one of its azimuthal competitors is recorded. Then the middle point of this area is used as the optimal one for operation.

A significant part of the experiments focused on the optimization of the gyrotron operation in the short-pulse regime. The gyrotron was operated for various magnetic field configurations and the magnetic field profile was optimized in terms of the field angle in the area of the emitter and the electron beam radius in the cavity [8]. In this way is was possible to generate 1 ms pulses with RF power higher than 930 KW and total efficiency 26 % (in non-depressed collector operation) The detailed characterization of the CW tube operated with short pulses is presented in [9].

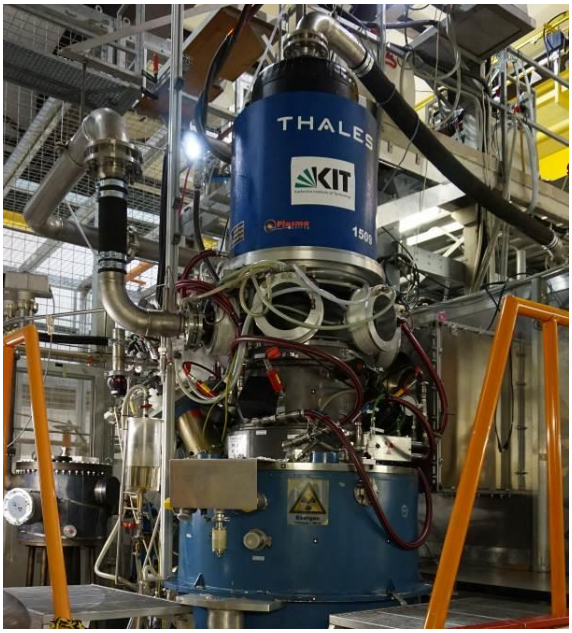

Fig. 6. The EU 1MW, 170 GHz CW industrial prototype gyrotron installed at the KIT superconducting magnet.

Due to the excellent vacuum conditions of the tube the extension of the pulse length from the ms range to the second range was a straightforward procedure and after a few weeks conditioning it was possible to produce 180 s pulses with output power in the range of 800 kW. At KIT it is not possible to make longer pulses at this power level due to a limitation of the High-Voltage Power Supply. Focusing on the LVOP (due to the limited time of the experimental campaign), the gyrotron was operated with different magnetic field profiles. Fig. 7 presents the achieved output power with respect to the magnetic field angle φ_B in the emitter area and the beam radius R_b at the cavity. All the results correspond to pulses with the maximum possible accelerating voltage for each magnetic field profile, length at least 60 s and deceleration voltage in the 20-25 kV range. The corresponding total efficiency (in depressed collector operation) is shown in Fig. 8. The maximum RF output power is achieved when the gyrotron is operated with angle the $\varphi_B = -3°$ and beam radius $R_b = 9.50$ mm. At this operating point the gyrotron delivers more than 800 kW with 36 % efficiency.

The RF output beam of the CW gyrotron was analyzed using the same method as for the SP prototype. In particular, the thermal footprint of the gyrotron output RF beam has been monitored on two different 200 mm diameter target plates, made of PVC and regular office printer paper, respectively. These plates were placed along the path of the RF beam at different distances between 180 mm and 1300 mm measured from the gyrotron output window. According to the measurements, the Gaussian content of the beam has been found to be at least 97 %, which fulfills the ITER specifications.

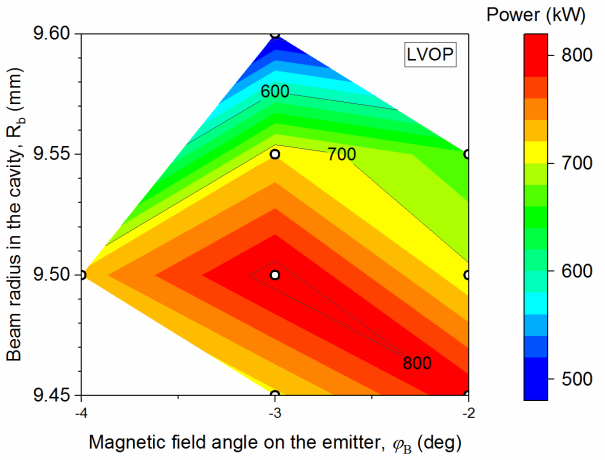

Fig. 7. RF power with respect to the magnetic field angle at the emitter and the radius of the electron beam in the cavity. Operation at the LVOP with long pulses (> 60 s).

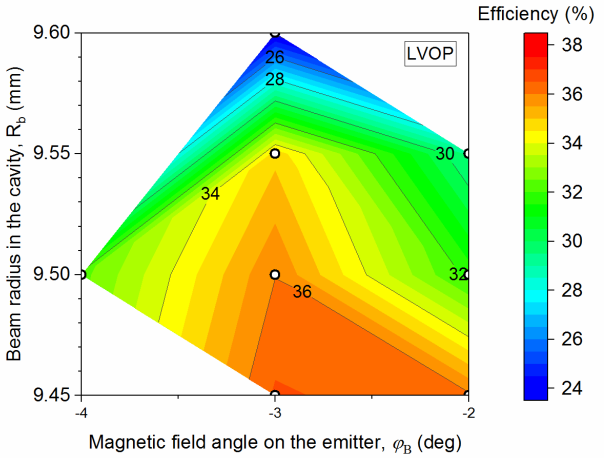

Fig. 8. Total efficiency with respect to the magnetic field angle at the emitter and the radius of the electron beam in the cavity. Operation at the LVOP.

3.2 Experiments at SPC

The industrial CW prototype gyrotron was transferred to the Swiss Plasma Center, EPFL Lausanne in the first quarter of 2017. Due to preparations on the test stand and the control system, the experiments with the gyrotron started at the end of 2017 and are still ongoing. Fig. 9 presents the gyrotron as it is currently installed in the SPC superconducting magnet. In the same figure the RF Coupling Unit (RFCU) and the RF load are also visible.

The superconducting magnet at SPC is not equipped with dipole coils and for this reason the gyrotron was installed in the magnet through an alignment XY-table that was designed and successfully tested at KIT for the SP gyrotron. The XY-table consists of two flat metallic plates that have low friction bearings between them. The bottom plate is mounted on the cryostat and the top plate on the gyrotron. The bearings allow the gyrotron to be mechanically shifted in the cryostat borehole in order to optimize the alignment of the cavity with respect to the magnetic field. A significant part of the experiments focused in the optimization of the position of the gyrotron with respect to the magnetic field axis. The method that has been followed is similar to the one with the dipoles coils and it is based on the recording of the excitation circle of the nominal mode. In particular for a specific accelerating voltage and beam current, the gyrotron was mechanically shifted on the x-y plane and the positions where the nominal mode $TE_{32,9}$ switched to the next azimuthal competitor $TE_{33,9}$ was recorded. Then the gyrotron was shifted to the middle point of the nominal mode's excitation area.

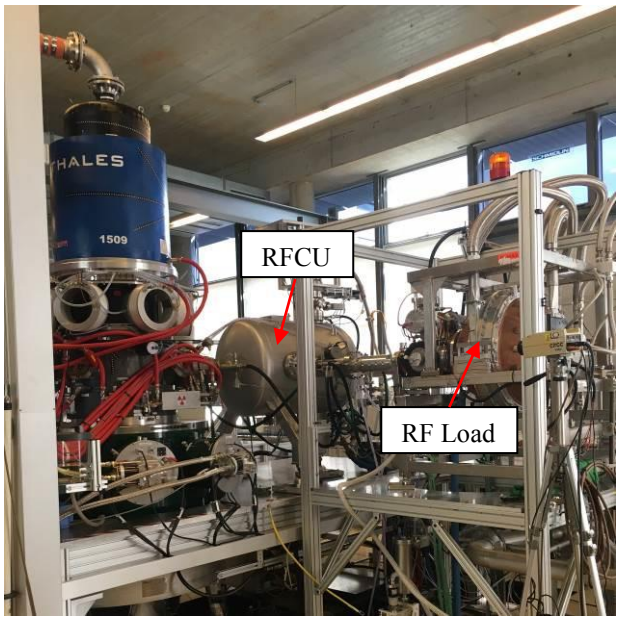

Fig. 9. The EU 1MW, 170 GHz CW industrial prototype gyrotron installed at the SPC superconducting magnet. The gyrotron is connected to the RF load using an RFCU under vacuum.

For the optimal alignment found, the gyrotron operation was first operated with short pulses in the range of 2 – 5 msec. A first coarse optimization of the gyrotron operation took place focusing on the LVOP and it was possible to reproduce the KIT results by achieving power slightly higher than 900 kW. Since the goal of the experiments at SPC was to optimize the operation of the gyrotron with pulses longer than those that are possible at KIT, the short-pulses campaign was relatively short and the short-pulse performance not fully optimized.

Currently the experiments focus on the extension of the pulse length towards 3600 seconds. For this reason, operating points able to provide power in the 500 kW – 800 kW range are selected and the pulse length is progressively increased in order to condition the tube as well as the RFCU and the RF load. In parallel, optimization of the test stand and the control system for long pulses is taking place. Up to now it was possible to make pulses longer than 200 seconds. The experiments were stopped in April and will be continued in the second half of 2018 with the goal to further optimize the operation of the gyrotron in terms of the output power and pulse length.

Acknowledgement

This work was supported by Fusion for Energy under Contract No. F4E-GRT-553 to the European Gyrotron Consortium (EGYC). EGYC is a collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; and IFP-CNR, Italy. The views expressed in this publication do not necessarily reflect the views of F4E or the European Commission.

References

1. I. Gr Pagonakis, et al., Status of the development of the EU 170 GHz/1 MW/CW gyrotron, Fusion Eng. Des. 96–97 (2015)
2. T. Rzesnicki et al., Recent experimental results of the European 1 MW, 170 GHz short-pulse gyrotron prototype for ITER, IRMMW-THz 2015, Proc. 3134554, Hong Kong, Aug. 23–28 (2015)
3. K. A. Avramidis et al., Simulations of the experimental operation of the EU 170 GHz, 1 MW short-pulse prototype gyrotron for ITER, IRMMW-THz 2016, Copenhagen, Denmark, Sep. 25–30 (2016)
4. I. Gr. Pagonakis et al., "Electron Beam Simulation in the Overall Gyrotron Geometry", Proc. 9th Int. Workshop "Strong Microwaves and Terahertz Waves: Sources and Applications", Nizhny Novgorod, Russia, 24-30 July (2014)
5. I. Pagonakis et al., Numerical Investigation on Spent Beam Deceleration Schemes for Depressed Collector of a High-Power Gyrotron, IEEE Trans. Electron. Devices, early access online (2018)
6. Z. C. Ioannidis et al., CW experiments with the EU 1-MW, 170-GHz industrial prototype gyrotron for ITER at KIT, IEEE Trans. Electron Devices, vol. 64, no. 9 (2017)
7. T. Rzesnicki et al., 2 MW Coaxial-Cavity Pre-Prototype Gyrotron for ITER -recent experiments with the modified gyrotron setup-, 37th International Conference on Infrared, Millimeter, and Terahertz Waves, Wollongong, NSW, Australia (2012)
8. I. Gr. Pagonakis et al., "Magnetic field profile analysis for gyrotron experimental investigation", Phys. Plasmas, vol. 24, no. 3 (2017)
9. T. Rzesnicki et al., Experimental Verification of the European 1 MW, 170 GHz Industrial CW Prototype Gyrotron for ITER, Fusion Eng. Des., Fusion Eng. Des., vol. 123 (2017)