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Experimental verification of the European 1 MW, 170 GHz industrial CW prototype gyrotron for ITER

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HIGHLIGHTS

- Development status of the EU, 1 MW gyrotron for ITER.
- Verification and experimental results obtained with 1 MW, short-pulse prototype tube.
- Recent experimental results with the 1 MW, CW prototype gyrotron.

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ABSTRACT

The EU 1 MW, 170 GHz gyrotron with hollow cylindrical cavity have been designed within the European GYrotron Consortium (EGYC) in collaboration with the industrial partner Thales Electron Devices (TED) and under the coordination of Fusion for Energy (F4E). In the frame of the EU program, the short-pulse (SP) version of this tube was designed and manufactured by KIT in collaboration with TED. The experimental verification of the SP gyrotron prototype was successfully completed in 2015. The achieved experimental results show a very stable gyrotron operation with RF output power above 1 MW at good cavity interaction efficiency around 35%. The gyrotron was operated up to 10 ms pulse length; the nominal cavity mode $TE_{32,9}$ has been excited at the frequency 170.1 GHz in agreement with the corresponding ITER specification. The Gaussian mode content of the output RF beam was about 98% and the total level of internal stray radiation was in the range of 2–3%. The manufacturing of the first industrial continuous-wave (CW) prototype gyrotron, based on the SP gyrotron design, was completed in November 2015 at TED. The tube was delivered to KIT and the experimental verification started in February 2016. Operation of the gyrotron with ms pulse duration resulted in stable excitation of the nominal mode at 170.22 GHz for a wide range of operating parameters and with a level of stray radiation comparable with the SP version. The maximum RF power achieved up to now in short-pulse operation at a level of 1 MW. The measured Gaussian mode content of the RF beam is 97%. Currently, further preparation for the CW operation of the gyrotron is in progress.

1. Introduction

The European GYrotron Consortium (EGYC) in cooperation with its industrial partner Thales Electron Devices (TED) has designed

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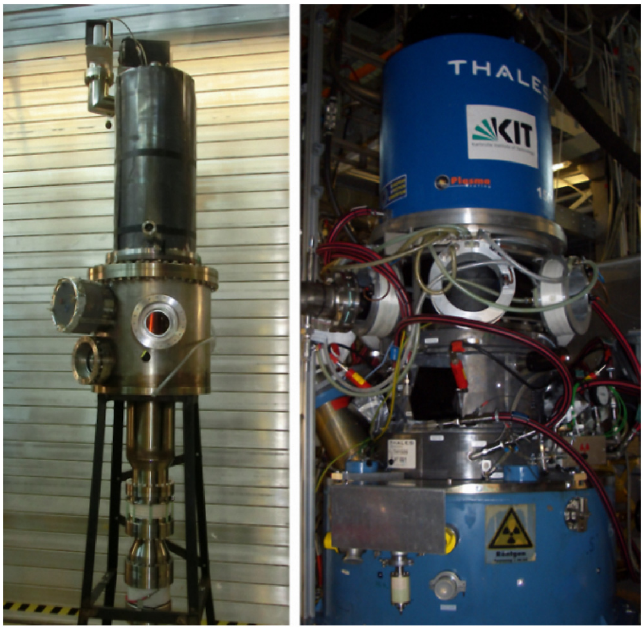

Fig. 1. EU 1 MW, 170 GHz gyrotron prototypes for ITER: short-pulse gyrotron (left) and industrial CW tube, installed with its auxiliaries in the Oxford Instruments (OI) super-conducting magnet at KIT (right).

Table 1
Design parameter and simulated performance at the Low-Voltage (LVOP) and High-Voltage (HVOP) operating points.

Parameter	HVOP	LVOP
Operating mode	$TE_{32,9}$	$TE_{32,9}$
Magnetic field	6.78 T	6.69 T
Accelerating voltage	79.5 kV	71.0 kV
Depression voltage	35 kV	35 kV
Beam current I_b	40 A	45.3 A
Beam radius R_b	9.44 mm	9.44 mm
Pitch factor α	1.29	1.22
Output power at window	1 MW	1 MW
Frequency	170.23 GHz	170.23 GHz
Interaction efficiency	35%	35%
Overall efficiencyw/o depressed collector	32%	33%
Overall efficiency w/depressed collector	>50%	>50%
Peak Ohmic wall loading	2.1 kW/cm^2	2.1 kW/cm^2

and developed the EU 1 MW, 170 GHz gyrotron for ECH&CD on ITER, under the coordination of the European domestic agency F4E. The development of the tube was initiated in 2008 as a risk mitigation action during the development of the 2 MW coaxial cavity gyrotron for ITER [1] and was successfully completed at the end of 2015. According to the project strategy followed by F4E, two prototypes were developed. The first one is a modular short-pulse (SP) prototype tube built for design validation, in terms of generated RF power, efficiency and quality of the RF output beam of the main gyrotron components for millisecond pulses. The second prototype is a long-pulse industrial tube with the additional goal to fulfill the ITER requirements in terms of pulse length and continuous wave (CW) operation regime. Photos of both gyrotrons are depicted in Fig. 1. The technological design of the gyrotron was decided to resemble as much as possible the 1 MW, 140 GHz CW Wendelstein W7-X gyrotron [2] in order to take advantage of the experience gained during the manufacturing of the 8 tubes of the industrial series production. The nominal design and performance parameters of the gyrotron are summarized in Table 1.

The SP prototype was operated successfully in two experimental campaigns in 2015. In the first campaign, which took place prior to the delivery of the magnetron injection gun (MIG), the MIG from

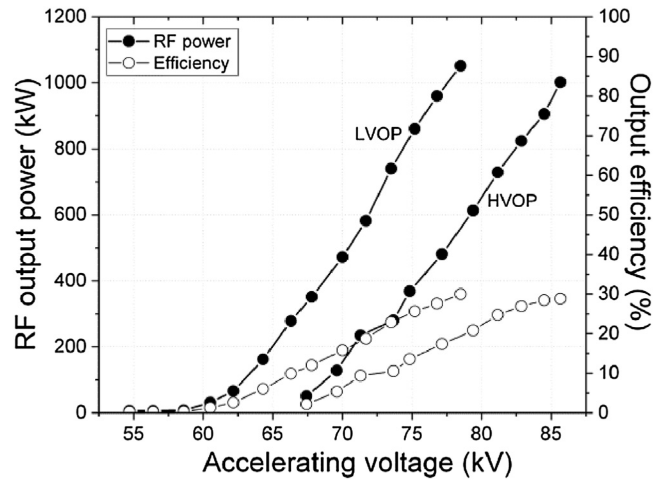

Fig. 2. RF output power and output efficiency as a function of accelerating voltage measured at both low-voltage (LVOP: ~78 kV and I_b ~ 45 A) and high-voltage (HVOP: ~86 kV and I_b ~ 40 A) operating points without depressed collector.

the 2 MW modular SP tube has been adapted and successfully used [3], whereas in the second one the nominal electron gun has been installed [4]. The most important experimental results achieved with the SP gyrotron are briefly reported in Section 2. The CW tube was delivered to KIT and prepared for the operation at the beginning of 2016. First experiments with the goal to optimize the operation of the CW prototype in the short-pulse regime started in February 2016. Recently achieved results and progress status of this campaign are reported in Section 3. In June 2016 preparation for the CW operation of the tube started with the goal to extend the pulse duration up to 3 min. Further increase of the pulse length at full power (1 MW) is not possible at KIT due to the limitations of the available power supplies. The tests with the 1 MW CW prototype will be continued at longer pulse lengths in the European Gyrotron Test Stand at EPFL-SPC in Lausanne.

2. Results of the SP prototype gyrotron

In order to have more flexibility concerning further optimization of the operating gyrotron parameters, two operating scenarios: at higher (HVOP) and lower (LVOP) voltage (Fig. 2) have been considered. After conditioning and optimization of the operating parameters, a stable gyrotron operation has been achieved. Apart from the nominal high-voltage (~86 kV) operating parameters (HVOP, mentioned in Table 1) the operation of the gyrotron has also been investigated at a Lower-Voltage Operating Point (LVOP, ~78 kV). At both operating points a generated RF output power was above 1 MW with an output efficiency of around 30% (interaction efficiency ~35%) (Fig. 2), being in very good agreement with theoretical predictions [5]. The gyrotron was operated with pulse lengths up to 10 ms. The nominal mode has been excited at 170.1 GHz, which is in agreement with the ITER specification. Furthermore, in order to prove the capability of the tested gyrotron in terms of achievable RF output power, the beam current has been increased up to around 63 A. At that operating point, at ~74 kV (LVOP) an RF output power around 1.4 MW with output efficiency ~30% (interaction efficiency ~35%) has been obtained. In addition, the performance of the quasi-optical (q.o.) mode converter, based on a mirror-line launcher and three mirrors with nearly quadratic surface contour function [3], has been validated. Precise beam profile measurements with an IR camera system and careful analysis of the RF output beam pattern showed a very good Gaussian mode content of about ~98%. The total level of internal stray radiation is in the range of ~3% of the RF output power.

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