Recent experiments with the European 1MW, 170GHz industrial CW and short-pulse gyrotrons for ITER

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The European Gyrotron Consortium (EGYC) is developing the European 1 MW, 170 GHz Continuous Wave (CW) industrial prototype gyrotron for ITER in cooperation with Thales Electron Devices (TED) and Fusion for Energy (F4E). This conventional, hollow-cavity gyrotron, is based on the 1 MW, 170 GHz Short-Pulse (SP) modular gyrotron that has been designed and manufactured by the Karlsruhe Institute of Technology (KIT) in collaboration with TED. Both gyrotrons have been tested successfully in multiple experiments. In this work we briefly report on the results with the CW gyrotron at KIT and we focus at the experiments at the Swiss Plasma Center (SPC). In addition, we present preliminary results from various upgrades of the SP tube that are currently tested at KIT.

Keywords: Gyrotron, ITER, ECRH.

1. Introduction

Modern plasma fusion devices such as the Wendelstein W7-X Stellarator and the ITER tokamak rely on efficient, high-frequency, high-power microwave sources, able to cover their needs in electron cyclotron resonance heating (ECRH) and current drive (ECCD). During the last years the European GYrotron Consortium (EGYC) in cooperation with Thales Electron Devices (TED) and Fusion for Energy (F4E) invested significant effort and resources for the development of the European 1 MW, 170 GHz industrial prototype gyrotron. This activity on a hollow-cavity (conventional) gyrotron started in 2008, as a risk mitigation action, during the development of the 2 MW, 170 GHz coaxial-cavity gyrotron for ITER [1].

Taking into account the experience that was gained during the development of the 1 MW, 140 GHz series production gyrotrons for Wendelstein W7-X [2], as well as of the 2 MW, 170 GHz coaxial-cavity gyrotron for ITER, it was decided to organize the project of the European 1 MW, 170 GHz CW gyrotron in two successive steps. In the first step, the Karlsruhe Institute of Technology (KIT) constructed in cooperation with TED, a modular short-pulse prototype gyrotron (Fig. 1a). The main goal of this tube was to verify with short pulses (not longer than 10 ms) the scientific design of the tube. After the successful validation of the design, the following step was to develop a single CW industrial prototype tube (Fig. 1b) in order to verify the ITER requirements regarding the generated RF power, the efficiency in depressed collector operation, the quality of the output RF beam and the pulse length.

The scientific design of the SP prototype gyrotron was successfully tested thoroughly during two experimental campaigns that took place at KIT in 2015. At first, the gyrotron was tested using the Magnetron Injection Gun (MIG) of the 2 MW, 170 GHz modular prototype gyrotron [3], after it was properly adapted. Despite that the coaxial gun design was not optimal for the conventional gyrotron, it was possible to reach the nominal output power of 1 MW [4]. A second experimental campaign followed after the installation of the MIG that was specifically designed for operation with the SP gyrotron. In this campaign it was possible to get 1 MW with 40 % efficiency in depressed collector operation and even surpass the nominal power and achieve more than 1.2 MW [5] by boosting the beam current. The Gaussian content of the output beam was found to be 98 %, which exceeds the ITER specification.

Currently, the experiments with the CW industrial prototype are ongoing. The first phase of the experiments started at KIT in 2016, after the delivery of the tube by TED. Due to the excellent vacuum conditions, it was possible in very short time to operate the gyrotron with longer pulses. In detail, the gyrotron was operated in the Oxford Instruments superconducting magnet with pulses up to 180 s, which is the limit of the KIT High-Voltage Power Supply (HVPS), when it is operated with current

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in the range of 45 A. Under these conditions, 180 s pulses were generated with output power higher than 800 kW. In order to extend the pulse length up to 3600 s, the gyrotron was transferred in 2017 to SPC, Lausanne, where it is operated with a cryogen-free superconducting magnet manufactured by Cryogenic Ltd. In this work we present results from the recent experiments with the European 1 MW, 170 GHz CW and SP prototype gyrotrons for ITER. In particular, we focus on tests with possible upgrades of the SP tube that enhance its performance and on the status of the tests with the CW gyrotron at SPC.

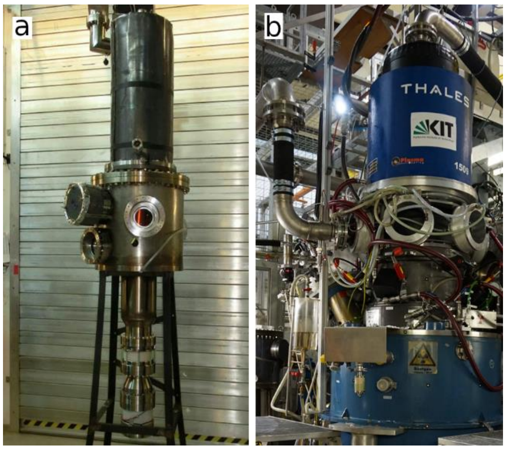

Fig. 1. (a) SP prototype gyrotron (standard configuration). (b) CW industrial prototype gyrotron installed in the Oxford Instruments magnet at KIT.

2. Upgrade of the short-pulse prototype

2.1 Spent beam deceleration schemes

In the experiments with the SP gyrotron, the total efficiency was slightly higher than 40 % [5]. Theoretical studies have already predicted this value and showed that it could be possible to meet the ITER specification, by using alternative deceleration schemes of the spent electron-beam [6]. For this reason, the modular short-pulse gyrotron was modified at KIT and the proposed deceleration configurations are currently tested.

The first modification that was realized was to install a structure of metallic pipes in the area of the mirror-box (Fig 2a). These pipes are similar to the cooling pipes that are installed in the CW prototype and they are located closer to the electron beam. In this way they reduce the depression voltage of the electrons in the area of the mirror-box. It is also possible to increase the total efficiency further by applying the deceleration voltage as close as possible to the collector. Fig 2b shows the 1 MW SP gyrotron, equipped with the isolated collector of the KIT 2 MW, 170 GHz coaxial-cavity short-pulse gyrotron and installed in the cryostat through an insulating ring. In this way it is possible to set the complete mirror-box of the gyrotron to the body voltage and start the deceleration of the spent electron beam as close as possible to the collector. Finally, Fig 2c presents a combination of the two previously mentioned configurations. A metallic structure, which is installed in the mirror-box, reduces the voltage depression of the beam and in parallel starts the deceleration of the beam closer to the collector, without having to set the complete mirror-box on high-voltage.

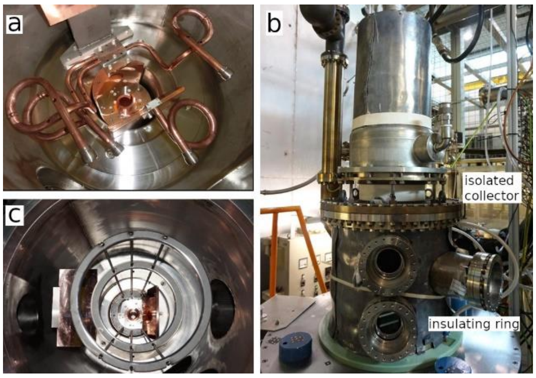

Fig. 2. Upgrades of the SP gyrotron: (a) internal pipes mockup, (b) isolated collector and insulating ring, (c) metallic structure in the mirror-box.

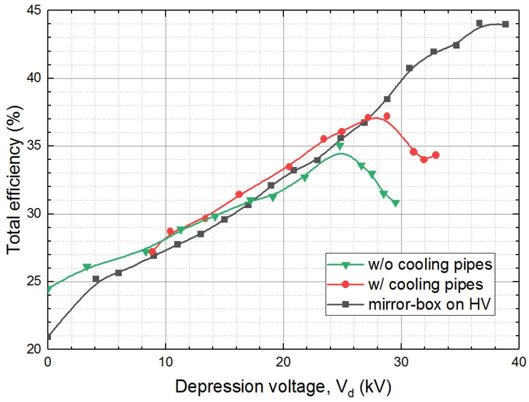

Fig. 3. Significant increase of the efficiency by using alternative deceleration schemes for the electron beam.

In order to compare the different schemes and make evident the possibility to significantly increase the efficiency of the gyrotron, an operating point with output power lower than the nominal one has been selected. Fig. 3 summarizes the efficiency with respect to the deceleration voltage for output power approximately 850 kW. With the standard tube configuration (green triangles) a total efficiency of 35 % is achieved for this operating point by applying 25 kV of body voltage. The total efficiency and the corresponding applied voltage are increased to 37% and 29 kV, respectively, when the cooling pipes (Fig. 2a) are installed (red circles). A substantial improvement of the gyrotron operation is succeeded when the mirror-box is set on high-voltage (black squares). In this case, the efficiency is 44 % by applying 39 kV on the body, which is practically the maximum value of the body power supply available at

KIT. The experiments with the potential optimization structure (Fig. 2c) are still ongoing. The first results obtained are very promising and show the possibility to reach practically the same level of efficiency (as with the complete body on high-voltage) without the need of an isolated collector and an isolating ring for the magnet. It is worthwhile to mention that due to the lower quality of the vacuum in the modular gyrotron, the efficiency measurement with short pulses in depressed collector operation are probably underestimating (due to neutralization of the electron beam) the true performance of the tube. Summarizing, by optimizing the potential in the area of the mirror box and also by tailoring the accelerating and the depression voltage during the longer pulses of a CW tube, it is foreseen to reach efficiency in the level of 50%.

2.2 Fully metallic beam-tunnel

Both the SP and the CW prototype gyrotrons do not suffer from parasitic oscillations when operated with currents up to 50 A. In particular when the SP gyrotron is operated with the optimal parameters in terms of output power, no parasitic signals can be detected by the diagnostics. Similarly, during the CW experiments at KIT there were only a few cases where parasitic signals could be marginally detected during the first ms of the long pulses [7]. However, considering that the demand for output power is constantly increasing, it is beneficial to be able to operate with much higher beam currents, while suppressing the possibility to excite spurious oscillation in the beam-tunnel area. In parallel, the goal of having series production gyrotrons points towards easier to manufacture beam-tunnels that avoid the use of expensive and difficult to reproduce dielectric materials.

Fig. 4. Fully metallic beam tunnel that was designed for and operated with the SP prototype gyrotron.

In this context, the SP prototype gyrotron was equipped with the fully metallic beam-tunnel that is presented in Fig. 4. The housing of this novel beam tunnel is practically identical with the one of the stacked beam-tunnel that was previously installed in the SP tube. For this reason the two beam tunnels are easily interchangeable between each other. The inner surface of the metallic beam duct is properly optimized in order to prevent the excitation of parasitic modes.

The results that were obtained during the first experiments with the new beam-tunnel are very promising. In particular, it is possible to excite the nominal mode $TE_{32,9}$ with beam currents almost up to 70 A, without detecting any parasitic oscillations. By boosting the operating current to such levels, it is possible to exceed the nominal output power of the gyrotron and reach 1.2 MW without affecting significantly the efficiency of the tube. A more detailed study of the operation of the beam tunnel is currently ongoing and the performance of the tube is recorded for a wide range of operating parameters in order to have a detailed comparison with the operation achieved with the stacked beam tunnel of the initial design.

3. Experiments with the CW prototype at SPC

A description of the results achieved at KIT during the first phase of the experiments with the CW prototype is presented in [7]. Fig. 5 shows the installation of the CW industrial prototype gyrotron in the cryogen-free superconducting magnet that is available at SPC, EPFL. In the same picture the RF Coupling Unit (RFCU) and the RF load are also depicted. The gyrotron, the coupling unit and the load are connected between each other with transmission lines under vacuum.

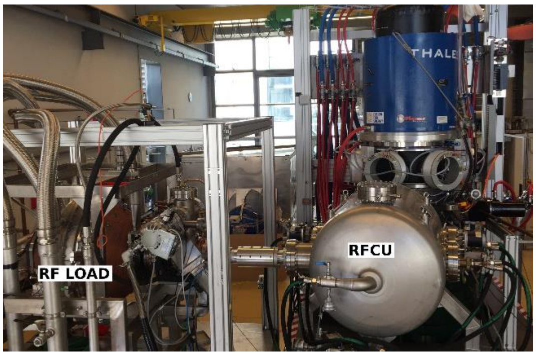

Fig. 5. The CW industrial prototype installed at SPC and connected to the RF coupling unit and the RF load.

The RFCU consists of five mirrors. The first one (M1) is a flat mirror that directs the output RF beam to the second one (M2). The latter has two angular degrees of freedom to better center the beam at the last mirror M5. In between, the polarizing mirrors M3 and M4 are used to achieve the necessary polarization. Taking the numerically estimated output radiation profile, the estimated Ohmic and truncation losses in the RFCU are 11.2 kW and 16.7 kW, respectively, for 1000 kW leaving the window, and the coupling to the HE_{11} mode is 98.79 %. Thus, 960 kW reach the load in the HE_{11} mode.

The 1 MW matched load [8] has been developed by the Istituto di Fisica del Plasma (IFP) of the Consiglio

Nazionale delle Ricerche (CNR) of Milan (Italy). Based on the design of a similar 2 MW CW load constructed by IFP-CNR [9], the 1 MW load consists of a hollow copper sphere, capable to absorb and measure the gyrotron power. In detail, it includes a spreading mirror, placed opposite to the beam entrance, and a preload installed at the load entrance. The mirror distributes the input beam onto the inner walls, which are coated with absorbing ceramic. The preload reflects a significant part of the escaping stray power back into the load, ensuring the lowest possible propagation into the transmission line. In addition, the preload allows the connection for vacuum pumps and arc detection systems. Each of the two half-shells is provided with 16 spiraling cooling channels, electroformed in the copper wall to maximize the heat diffusion from the inner coating to the water.

The SPC test stand, which was upgraded for the experiments with the CW industrial prototype, is also equipped with a new control system prepared by F4E. Thus, a significant part of the first experiments focused on the optimization of the test stand and the control system. Despite the CW prototype was well conditioned from the experiments at KIT, the experimental campaign started with operation in the short-pulse regime in order to optimize the magnetic field profile in the cryogen-free magnet and the position of the electron beam with respect to the magnetic field axis. The Cryogenic's super-conducting magnet is not equipped with dipole coils and the optimization of the position of the electron beam is performed using an XY – Table [10]. By shifting the gyrotron in the cryostat and monitoring the switch of the nominal mode to a neighboring one, the position of the gyrotron was optimized and it was verified that the optimal position is in agreement with the shift that was induced at KIT by using the dipole coils.

After the optimization of its alignment, the gyrotron was operated with short pulses up to 5 ms. Since the 1 MW load is not compatible with such pulse lengths, the measurement of the power was performed with a ballistic calorimeter. The experiments focused on operating parameters similar to those of the Low Voltage Operating Point (LVOP: magnetic field $B = 6.69$ T, accelerating voltage $V_{acc} \approx 76$ kV, beam current $I_b \approx 45$ A), which was extensively tested at KIT. Despite that not a lot of time was invested in the optimization of the magnetic field profile, it was possible to reproduce the results that were achieved at KIT. In detail, for various operating parameters, it was possible to generate pulses with power in the 1MW range. Having in mind that the main goal of the experimental campaign at SPC is to make pulses longer than 180 s, no further optimization with short-pulses took place.

The brief short-pulse experimental campaign was followed by the conditioning of the gyrotron, the RFCU and the RF load with longer pulses. For the conditioning, operational parameters that give output power in the range 0.5-0.8 MW were selected and the pulse length was progressively increased. In parallel the current driven to the longitudinal and radial collector sweeping coil system was optimized in order to keep the collector wall temperature below 190°C. By the end of April 2018, when the experiments stopped due to utilization of the test stand by other experiments, it was possible to go further than the pulse length achieved in the KIT campaign and reach 215 seconds. During these pulses it was realized that some surfaces of the RFCU could get hot during the longer pulses and thus during the break of the experiments the RFCU will be modified. The experiments will be continued in the second half of 2018 with the goal to maximize the output power and the pulse length.

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