Abstract

The EU 1 MW gyrotron for the ITER Electron Cyclotron Heating and Current Drive (EC H&CD) system has been developed in coordinated efforts from several EU institutions (EGYC) and with support of F4E. In a first experimental campaign the tube has been optimized in short pulse operation and has been conditioned for long pulse operation at the KIT teststand up to 180 s. In a second experimental campaign the tube has been transferred to SPC, EPFL, for operation in a dedicated superconducting magnet at increased pulse length. This paper presents the main experimental results of the prototype tube achieved at KIT.

1. INTRODUCTION

The European 1 MW, 170 GHz industrial prototype CW gyrotron for the ITER EC H&CD system [1] is a conventional (hollow-cavity) gyrotron, which has been developed by the European GYROtron Consortium (EGYC) in cooperation with the industrial partner Thales Electron Devices (TED) and under the coordination of the European Joint Undertaking for ITER and the Development of Fusion Energy (F4E).

The present development of the gyrotron started in 2012 and was completed at the end of 2015 after manufacturing of the tube by the industrial supplier. The physical design of the CW gyrotron and its main components (i.e. magnetron injection gun (MIG), beam tunnel, cavity, launcher and quasi-optical output system) is completely based on a corresponding modular short-pulse (SP) prototype [2], the technical design is based on the 1 MW, 140 GHz CW gyrotron for W7-X [3].

In a first step, at KIT short-pulse experiments (with pulse length below 10 ms) have been performed in order to optimize the gyrotron alignment in the magnetic field, verify the optimum operating parameters (i.e. accelerating voltage, beam current, magnetic field profile) for maximum generated RF power. A summary of the first short-pulse experiments at KIT with the CW prototype is presented in [4, 5].

Based on these results the gyrotron has been conditioned and the teststand has been prepared for long pulse operation. Long pulse operation up to 180 s is possible at the KIT teststand due to a limitation of the HV power supply.

In this work we give an overview of the experimental set-up at KIT and report on experiments in long-pulse operation.
2. EXPERIMENTAL SETUP

At KIT the gyrotron has been operated in an Oxford Instruments (OI) magnet (see Fig. 1) which allows a maximum B-field of 6.78 T, but having the advantage of a large borehole diameter (270 mm) and the possibility to excite dipole coils which can move the position of the electron beam in the cavity laterally. Three (out of four coils) of the superconducting set of coils which define the field profile along the axis are connected to individual power supplies and can be adjusted independently.

Prior to installation of the gyrotron into the magnet the magnetic field profile was measured carefully with hall-probes located in an apparatus which is centered by a reference surface in the top plate of the magnet. Thus the information of the magnetic field components in longitudinal and radial direction is obtained. By moving of the probe along the mechanical axis of the magnet and additional azimuthal rotation the data are collected. Based on further computation of the data a position of the magnetic field axis with respect to the mechanical axis of the magnet can be defined. The measurements have been performed for the main coil energized which uses the same winding body as the other coils of the magnet. The maximum displacement of the magnetic and mechanical axis was below 0.1 mm which is smaller than the mechanical accuracy of the measurement system. The tilt of the magnetic field axis was estimated to be close to 0.14 mrad.

The proper alignment of the magnetic axis, the gyrotron axis and centering of the electron beam in the cavity is very important for efficient interaction and avoidance of parasitic effects. The OI magnet is equipped with a set of dipole coils, which move the electron beam in two orthogonal radial directions in the cavity region during operation, allowing to verify the optimum position by monitoring the excitation of the mode in the cavity [6]. It was found that the misalignment is in the order of 0.5 mm. This can also easily be compensated by a mechanical movement of the tube with an X-Y table on the top plate of the magnet.

First operation of the tube has been performed in short pulse regime with a pulse length up to ~10 ms (see [4] and [5]).

![Fig. 1. The European 1 MW 170 GHz CW ITER gyrotron installed at the KIT test facility.](image)
For long pulse operation the RF output beam of the gyrotron is directed into a metallic measurement chamber which confines the RF radiation and houses transmission line components and diagnostics (see Fig. 2). The RF beam from the synthetic diamond window of the gyrotron is transmitted to the absorber load by four mirrors, one of them (mirror 3) having a corrugated surface to transfer the linear output polarisation to elliptical polarisation. The position and the orientation of the mirrors are optimised in order to meet the axis of the absorber load with the beam. The transmission system is operated under ambient air pressure inside the microwave chamber.

The RF diagnostics is realized by a waveguide coupling structure embedded in mirror 1. The signal is transmitted to an RF diode and is used to stop gyrotron operation in case of mode loss or excitation of a wrong mode. Details regarding the design of mirror 1 can be found in [7]. The frequency measurement is realized by a filter-bank, a time-domain frequency measurement system [8] and a pulsed spectrum analysis system (PSA) [9], which are fed by a signal from a relief window in the mirror box of the gyrotron. This ensures that the frequency of the design mode and of possible parasitic oscillations, which have usually a much lower amplitude along the nominal beam path, can be monitored.

A broad energy distribution of the spent electron beam in the collector is achieved by using longitudinal and transversal sweeping systems. The temperature distribution of the collector is monitored by 45 thermocouples distributed at different axial and azimuthal locations. The AC and DC currents of the sweeping systems have been optimized to minimize the maximum temperature in the collector. During operation a maximum interlock value of 200°C has been defined in order to avoid any plastic deformation of the collector.

In this contribution we focus on typical operating parameters of the gyrotron which are given in Table 1. Long pulse operation at the KIT gyrotron teststand is limited due to the HV power supply to 180 s and a 1/10 duty cycle with a beam current up to 50 A. The results shown here are produced with pulses between 60 s and 180 s.

### 2.1. Operational map

A very useful systematic way to define the parameters for optimum operation of the gyrotron is given by variation of the electron beam radius in the cavity ($R_b$) and magnetic field angle at the emitter ($\phi_b$). Both parameters have a very significant influence on the interaction of the beam in the cavity (coupling to the cavity mode) and the pitch factor ($\alpha$) of the electrons (details see [10]). Simulations show that in general $\alpha$ is increasing with decreasing $R_b$ (higher compression) and $\phi_b$ (higher transversal velocity) thus increasing the risk of reflecting electrons due to a non-ideal spread of the beam parameters.
Table 1. Typical parameter for CW operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating mode</td>
<td>TE_{32,9}</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>6.78 T</td>
</tr>
<tr>
<td>Accelerating voltage</td>
<td>79.5 kV</td>
</tr>
<tr>
<td>Depression voltage</td>
<td>35 kV</td>
</tr>
<tr>
<td>Beam current I_b</td>
<td>40 A</td>
</tr>
<tr>
<td>Beam radius R_b</td>
<td>9.44 mm</td>
</tr>
<tr>
<td>Pitch factor α</td>
<td>1.29</td>
</tr>
<tr>
<td>Output power at window</td>
<td>1 MW</td>
</tr>
<tr>
<td>Frequency</td>
<td>170.23 GHz</td>
</tr>
<tr>
<td>Interaction efficiency</td>
<td>35 %</td>
</tr>
<tr>
<td>Total efficiency, w/o depressed collector</td>
<td>32 %</td>
</tr>
<tr>
<td>Total efficiency, w/ depressed collector</td>
<td>&gt;50 %</td>
</tr>
<tr>
<td>Peak Ohmic wall loading in the cavity</td>
<td>2.1 kW/cm²</td>
</tr>
</tbody>
</table>

Fig. 3 shows the RF power (left) and efficiency (right) with respect to the magnetic field angle and the radius of the electron beam (the data were taken with constant magnetic field strength in the cavity). In these figures the white circles correspond to the position where the actual measurements took place (at φ_b = -4°, -3° and -2°). It should be noted that the performance reported for each (φ_b, R_b) combination corresponds to the optimal voltage and beam current operating parameters found at this point, whereas the collector depression voltage is usually set in the range 20 - 25 kV without special optimization.

The highest output power was found at the operating point (φ_b = -3°, R_b = 9.50 mm), where 811 kW were generated with a total efficiency of 36 % (in depressed collector operation).

2.2. Frequency variation

The output frequency of a gyrotron is not constant from the very beginning of the pulse. There are two phenomena which are responsible for variation of the frequency during start up: neutralization of the electron beam and expansion of the cavity due to thermal loading. Both effects tend to decrease the frequency.

The time dependence of the frequency of the nominal mode TE_{32,9} was recorded using the PSA measurement system [9]. Fig 4 shows the frequency of the mode TE_{32,9} versus time for two different cases of the orientation of the magnetic field lines at the emitter and the beam radius at the cavity. The oscillation frequency starts approximately at 170.300 GHz and decreases to 169.950 GHz (Δf ~350 MHz with RF power 650 - 700 kW). This result is in agreement with the ITER requirement of 170 ± 0.3 GHz.
For a given technical design of the cavity and the cooling system $\Delta f$ very much depends on the generated RF power. The dependency of the frequency drop on the generated power is presented in Fig. 4, using experimental data from different operating points and making the assumption that the frequency drop is governed by the total generated power and not by the specific operating parameters of the different operating points. Although the data in the 700-800 kW power level are quite scattered, there is approximately 400 MHz frequency drop for 0.8 MW of generated RF power. First results of multi-physics simulations on the frequency down-shift, taking the thermal loading of the cavity and beam neutralisation into account show a very good agreement.

2.3. Operation with voltage depression

A major effort in gyrotron development is dedicated to the increase of the overall efficiency of the system. As a technology which is commonly applied in vacuum electron devices the operation of the tube with a depression voltage is used. The most popular version is to use a single stage depression voltage for recovery of a part of the energy of the spent electron beam. However, even in that case usually one additional low-power high-voltage system and isolation ceramics in the tube are necessary (for details see e.g. [3]). Fig. 5 presents the RF power and the corresponding total efficiency versus the collector depression voltage for the operating point ($\phi_B = -3^\circ$, $R_b = 9.50\,\text{mm}$). The measurements have been recorded with 60 s long pulses in order to minimize the waiting time between subsequent pulses. By increasing the depression voltage, the generated RF power remains almost constant, while the efficiency practically increases linearly, reaching a maximum value of 38 %. This is a preliminary value, currently several improvement modifications are being investigated in the frame of the short-pulse prototype development. In the next steps (see chapter 3) at SPC it is foreseen to optimize the voltage during the pulse which is expected to increase the efficiency. The maximum value of the applied depression voltage, where stable operation of the gyrotron was achieved is 26 kV. The operation with higher values of depression voltage was quite challenging, since a body current in the mA range and often instabilities during the first seconds of the pulses were observed. Such instabilities, which include arcing and beam current fluctuations, could be an indication of an increased number of reflected electrons [11].

2.4. Long-Pulse Operation

Fig. 6 presents the control system recordings for typical 180 s pulses that were achieved. In this figure the black curve corresponds to the accelerating voltage, which is the sum of the cathode voltage (green curve)
Fig. 5. RF power and efficiency versus the depression voltage ($\phi_b = -3^\circ$, $R_b = 9.50$ mm).

and the depression voltage (red curve, collector grounded with elevated body), whereas the blue curve is the emitted electron beam current. In the current curve it is obvious that during the first seconds of the pulse the emitted current is slightly reduced because of the cathode cooling effect and then recovers towards the targeted value. This recovery is achieved by employing a current boosting scheme, which controls the filament current before and during the pulse.

In the same figure, the olive and yellow curves correspond to the vacuum pressure signal of the ion getter pumps. During most of the pulses including this specific one, the vacuum level remained better than $10^{-8}$ mbar, showing excellent vacuum behaviour of this prototype. The purple curve represents the output voltage of the mode-loss RF diode, which deactivates the gyrotron operation as soon as the signal drops below a predefined

Fig. 6. Typical 180 s pulse achieved during the experiments, the temperature measurement in the load (proportional to RF power) is delayed and shows oscillations at the beginning of the pulse due to the KIT cooling system only (all measurements normalised to the indicated values).
level. This could happen for example in case that the accelerating voltage was increased above the value, which the nominal operating mode could tolerate. In general, no wrong mode excitation took place during the experimental campaign.

The generated power and the dissipated losses on the internal components of the gyrotron as well as of the auxiliaries in the external measurement chamber are monitored through various cooling circuits that are connected to a calorimetry system. The internal losses (internal components of the tube) are in the level of 5\% with respect to the RF power at the synthetic diamond window, whereas the external losses (inside the microwave chamber) are in the range of 2-3\% with respect to the power at the window.

3. NEXT STEPS

In order to increase the pulse length beyond 180 s and to further optimize the performance of the gyrotron the tube and the auxiliary equipment have been transferred to SPC, EPFL. At SPC a specific cryogen-free superconducting magnet manufactured by Cryogenics Ltd. is available. This magnet is not equipped with dipole coils so that shifting of the electron beam relative to the mechanical axis of the gyrotron is performed using an XY – Table [12]. It has been verified that this alternative procedure is in agreement with shifting the beam by dipole coils. The transmission of the RF power from the window to the absorber load is performed via an RF Coupling Unit (RFCU) which includes focusing mirrors to match the output beam to an evacuated HE$_{11}$ circular waveguide. The RFCU includes also two polarizing mirrors to transfer the linear output polarization to any elliptical polarization. The 1 MW matched load [13] has been developed by the Instituto di Fisica del Plasma (IFP) of the Consiglio Nazionale delle Ricerche (CNR) of Milan (Italy). This system uses a pre-load which absorbs reflected stray radiation from the load. Fig. 7 shows the installation at SPC.

The experiments at SPC have been started and are still ongoing. First tests show optimistic results: the pulse length could be increased up to 215 s, the maximum output power measured in the load was 1 MW (short pulse operation) and 810 kW (long pulse operation). It was realized that the performance and pulse duration were limited by external components (RFCU and absorber load). The experiments will be resumed in the second half of 2018 with modified components aiming at increased pulse length and output power.

![Fig.7. Gyrotron installed at SPC teststand, RFCU and absorber load.](image-url)
ACKNOWLEDGEMENTS

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REFERENCES