The Development of the European 1 MW, 170 GHz CW Gyrotron for the ITER Electron Cyclotron Heating System

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Abstract. The EU gyrotron for the ITER Electron Cyclotron heating system has been developed in coordinated efforts from several EU institutions and under the supervision of ITER Organization Central Team. This paper presents the main experimental results from the main prototyping and qualification activities aiming to demonstrate compliance with the ITER specifications and reduce the technical risks during the series production phase.

1. Introduction

The EU 1 MW, 170 GHz, continuous-wave (CW) gyrotron for ITER has been designed within the European Gyrotron Consortium (EGYC)[1] in collaboration with the industrial partner Thales Electron Devices (TED). Coordination of the development is under the responsibility of Fusion for Energy (F4E). Following a low-risk approach, the design of the ITER gyrotron is based on the proven mechanical concepts of the 140 GHz, high power (920 kW), long-pulse (CW) gyrotrons in operation for the W7-X Stellarator at IPP Greifswald

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[1] EGYC is a collaboration among SPC, Switzerland; KIT, Germany; HELLAS, Greece; IFP-CNR, Italy, with the University of Stuttgart, Germany, and the Institute of Solid State Physics, Latvia, as 3rd Parties.

[1]. The ITER gyrotrons have similar specifications as the W7-X gyrotrons but a different frequency (170 GHz) and slightly higher output power (1 MW) and overall efficiency (50%).

F4E is in charge of procuring six gyrotrons for the Electron Cyclotron (EC) Heating and Current Drive system of ITER. Based on the W7-X gyrotron design [2], the EU gyrotron incorporates further developments recently validated on different pre-prototypes (e.g. the 2 MW 170 GHz coaxial-cavity gyrotron), mainly on the electron gun to avoid electron-trapping phenomena and to improve the quality of the electron beam at the cavity entrance [3], [4], and on the quasi-optical system equipped with a new type of mirror-line launcher and three mirrors with quadratic surface contour functions [5] to enhance the output RF beam at the window. Both are key aspects for the performance of the gyrotrons and, as a result, of the EC system. The design has also been verified by analysis with the cutting-edge suite of modeling codes developed inside EGYC during the last years for nonlinear the time-dependent self-consistent beam-wave cavity interactions (EURIDICE [6], SELFT [7], TWANG [8]), the parasitic interaction at the beam tunnel (NESTOR [9]), the electron beam optics (ARIADNE [10], ESRAY [11]), and the synthesis of advanced launchers [12].

The design parameters and the expected simulated performance are shown in Table 1. In addition, two operating points have been identified, respectively labeled HVOP (High Voltage Operating Point), which is close to the operating parameters of the W7-X gyrotron, and LVOP (Low Voltage Operating Point), at a higher beam current, taking advantage of the operational flexibility of the power supplies of the ITER EC system[2] [13].

TABLE 1: DESIGN PARAMETERS AND PERFORMANCE SIMULATED WITH THE MULTIMODE CODE EURIDICE AT THE LVOP AND HVOP OPERATING POINTS.

Parameter	*HVOP*	*LVOP*
Operating mode	$TE_{32,9}$	$TE_{32,9}$
Cavity 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 efficiency without depressed collector	32%	33%
Overall efficiency with depressed collector	>50%	>50%
Peak Ohmic wall loading	21 MW/m^2	21 MW/m^2

The development of the EU gyrotron and auxiliaries is carried out in close collaboration with the ITER Organization Central Team (IO-CT) to ensure an optimal integration into the ITER

[2] The ITER EC power supplies are rated at 55 kV and 35 kV for the cathode and body voltage respectively (therefore accelerating voltage of 90 kV), and 55 A for the beam current per gyrotron.

building considering the space available for operation and maintenance, stray fields from the tokamak and the neighboring gyrotrons, and interfaces with the auxiliaries (e.g. cooling, control) and the transmission line for an optimal coupling of the output microwave power from the gyrotrons.

In this paper, the main experimental results from a short-pulse gyrotron aiming at verification of the internal gyrotron design are presented in section 2. The activities related to the 1MW CW gyrotron industrial prototype including experiments so far are described in section 3, whereas the parallel qualification and design activities are reported in section 4. A summary is given in section 5.

2. The 1 MW Short-Pulse Gyrotron

In the frame of the F4E gyrotron programme, a short-pulse gyrotron (SP) was first manufactured by KIT using a magnetron injection gun (MIG) manufactured by TED (see FIG.1). The SP has the same physical design of the electronic and RF components as the CW industrial gyrotron. On the other hand, the SP, which is operating at pulses of a few milliseconds, is simpler thanks to the limited cooling needs and the flanged concept allowing for an easy replacement of the internal parts.

FIG. 1. The short-pulse gyrotron installation at KIT for RF testing.

The SP experiments in 2015 have shown that the tube is capable to generate RF output power significantly higher than 1 MW at the nominal oscillation mode $TE_{32,9}$ and at the right frequency (~170.1 GHz) in stable and reproducible conditions, in the two operating regimes, HVOP (~87 kV, ~40 A) and LVOP (~78 kV, ~45 A)[3] [14]. The measured performance is above the ITER specifications and, as illustrated in FIG.2, is in excellent agreement with the

[3] The accelerating voltage after full neutralization, and therefore in CW conditions, is reduced by ~7kV due to the space-charge effects.

predicted results from the simulations [15]. The electronic efficiency (~35%) is consistent with an output efficiency of ~50% in final configuration using a single-stage depressed collector. Parasitic oscillations have not been observed and the deduced level of stray radiation is low (<3%). Additionally, a high quality of the output RF beam is measured (TEM_{00} ~98%). Therefore, the results have validated the design of the key gyrotron components, particularly the MIG, beam tunnel, cavity, launcher and internal quasi-optical system.

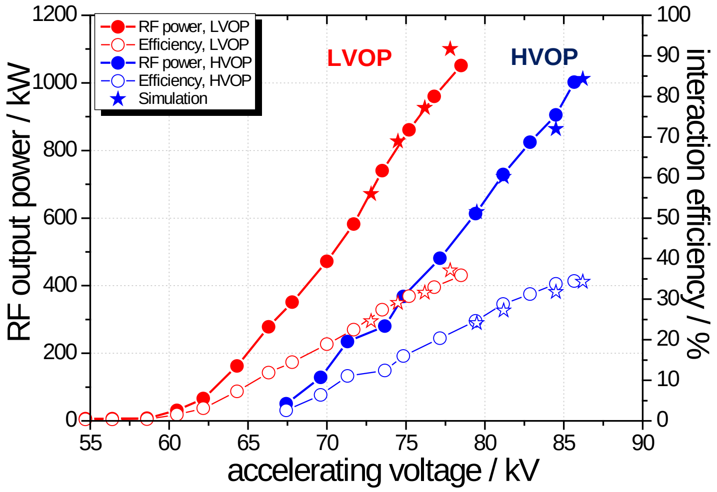

FIG. 2. Output power in the TE32,9 mode vs accelerating voltage, as simulated (stars) and experimentally measured (circles) for the LVOP and HVOP operating points of the SP gyrotron.

Specific experiments on the alignment of the SP gyrotron were performed to assess the reproducibility of the gyrotron performance in an industrial fabrication process. Using both the dipole coils of the superconducting magnet at KIT and an active alignment table between magnet and SC gyrotron, the tests have shown that the output power remains higher than 90% of the nominal value for misalignments of the electron beam at the cavity < ±0.25mm, which is a manufacturing tolerance that can be reasonably achieved.

3. The 1 MW CW Gyrotron prototype

After the successful validation of the RF design on the short-pulse gyrotron, the manufacturing of an industrial CW prototype gyrotron was completed by TED, delivered in November 2015 and installed in the KIT gyrotron test facility (see FIG.3), which has been adapted for this ITER prototype tube. The purpose of the tests at the KIT gyrotron facility in 2016 is the complete verification of the technical design, and the demonstration of compliance with the main ITER specifications for long pulses.

After verification of the high-voltage stand-off characteristics and cathode conditioning, the microwave tests started in short pulses with the aim of characterizing and optimizing the operation regime. The first experimental results have shown that the CW gyrotron prototype is operating in stable and reproducible conditions at the design mode $TE_{32,9}$ for a wide range of parameters. In the millisecond pulse range, the frequency is ~170.2 GHz (within the ITER specifications 170 ± 0.3 GHz) and an output power in the 1MW level at the window has been measured for the LVOP. As illustrated in FIG.4, there is a good agreement between the experiments and initial simulation results regarding the output power versus voltage dependency, in which the current, the average pitch angle α, the α spread (Δα/α ~5%) and the beam depression due to space charge have been taken into account.

FIG. 3. The 1MW CW gyrotron assembly at the KIT test facility.

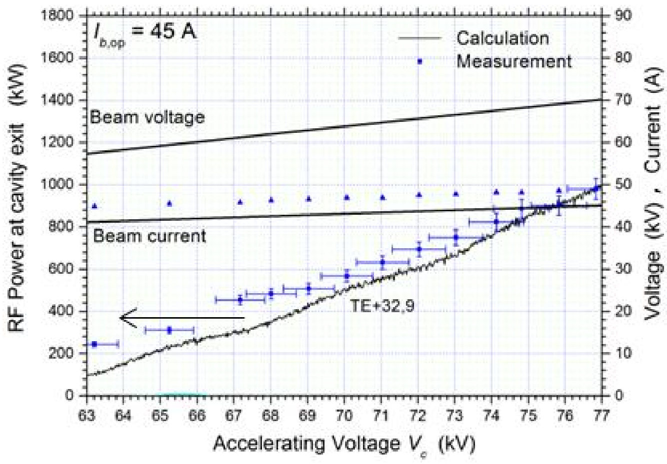

FIG. 4. Comparison between experimental results (in blue) and simulation results from the multi-mode code EURIDICE (in black) at the LVOP for an electron beam radius of 9.55mm and a magnetic field angle at the emitter of -2 deg.

An extensive parametric study has been performed using the flexibility of the superconducting (SC) magnet at the KIT gyrotron facility to explore the experimental operation map of the gyrotron as a function of the electron beam radius and the magnetic field lines orientation in the emitter region, which has an influence on the pitch factor α and the beam laminarity.

The output beam profile has been recorded with an infrared camera at various distances from the window (in FIG.5), and the complete E-field has been analysed and reconstructed. The beam axis exhibits an acceptable shift with respect to the center of the window of 4.9 mm in the horizontal direction and -2.7 mm in the vertical direction, with respective slopes of 7.8 and 6 mm/m. These deviations from the perfect beam parameters can usually be corrected by the external two mirrors matching optics system. The Gaussian mode content is 97%, which exceeds the ITER target (95%).

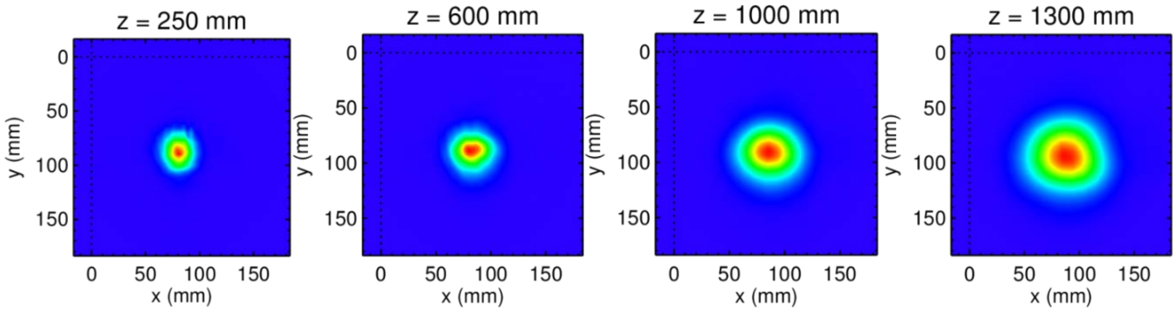

Fig. 5. IR images of the RF output beam profile measured on a PVC target at 250 mm, 600 mm, 1000 mm and 1300 mm from the window respectively.

Then the gyrotron housing and the test facility cooling, control and protection systems have been configured for long pulse operation. The gyrotron window has been connected to a microwave chamber equipped with water-cooled mirrors directing the beam towards the absorber load. The first mirror of the microwave box contains a directional coupler integrated for the monitoring of the forward power and frequency. The sweeping system of the spent electrons in the collector, composed of axial and radial coils, has been activated and optimized for an efficient cooling.

The collector has been conditioned in September 2016 with pulses up to 100 s and ~800 kW power, a step necessary before the RF pulse extension. In this process the vacuum level and the collector temperatures measured by the thermocouples mapping the wall surface have been carefully monitored and found to be in a very safe range. The experimental campaign will continue with the progressive increase of the RF pulse duration up to the maximal full-power capability of the KIT test facility, i.e. 180 seconds.

A second test campaign is planned in 2017 at the SPC-EPFL European EC test facility in Lausanne, Switzerland, to extend the pulse length up to the 3600 s of the ITER specifications. The SPC-EPFL facility is being upgraded by equipping it with ITER-like interfaces and auxiliaries in order to have fully relevant tests. The gyrotron test facility in Lausanne will include a new cryogen-free SC magnet at ~6.8 T, which is currently being manufactured by Cryogenic Ltd, and a CW spherical load concept designed and manufactured by IFP-CNR, pre-validated at the JAEA at 170 GHz and at RF power of ~1 MW with pulses of 300 s and ~1.8 MW with pulses of 15 s [16].

4. Parallel design and qualification activities

The gyrotron development programme also concerns the integration of the EU gyrotron in ITER and the preliminary design of the main auxiliaries, which is currently progressing for the cooling, control and filament power supply system, and has been recently completed for the Matching Optics Unit (MOU). The novel MOU design uses a vacuum vessel milled from a solid block of Aluminium, which provides a stable, compact and precise unit containing the cooled mirrors that transform the RF beam from the gyrotron into a field equivalent to that of the HE_{11}-mode field at the transmission line entrance. The MOU vessel walls are water cooled and internally coated with microwave absorber. The mirrors are steerable and capable of compensating the statistical variations in the alignment of the output RF beams of the fabricated W7-X series gyrotrons. They are equipped with waveguide directional couplers for real time power monitoring and mode control as used in ASDEX Upgrade [17].

Another important group of activities aims at securing the industrialisation thus the series production and enhancing the reliability of the EU gyrotron for ITER. Processes have been established for (i) the direct control of the quality of the electron gun (pitch factor α and homogeneity) before assembling in the gyrotron tube, based on a retarding field energy analyser [18], (ii) the dielectric and mechanical characterization of the diamond disk which is playing a crucial role in the transmission, reflection and strength of the output window, (iii) the dielectric characteristics of the ceramics of the gyrotron body and of the beam tunnel, key for the suppression of parasitic oscillations [19], (iv) mechanical and electrical characterization of Glidcop cavity material, and (v) low RF power measurements of launcher and internal mirrors.

Dedicated thermal mock-ups of the cavity have been manufactured in order to proof the current cooling concept and investigate the capability of possible alternative techniques. The mock-up of the reference cavity-cooling concept was tested at the high heat flux electron beam test facility (FE 200) of AREVA in nominal heat load conditions. For all operating conditions the temperature of the Glidcop cavity wall surface stayed below the design value (300 °C). Additional tests to determine the ultimate limit of the reference cavity cooling technique and verify an alternative cooling design concept based on mini-channels, are planned in October 2016.

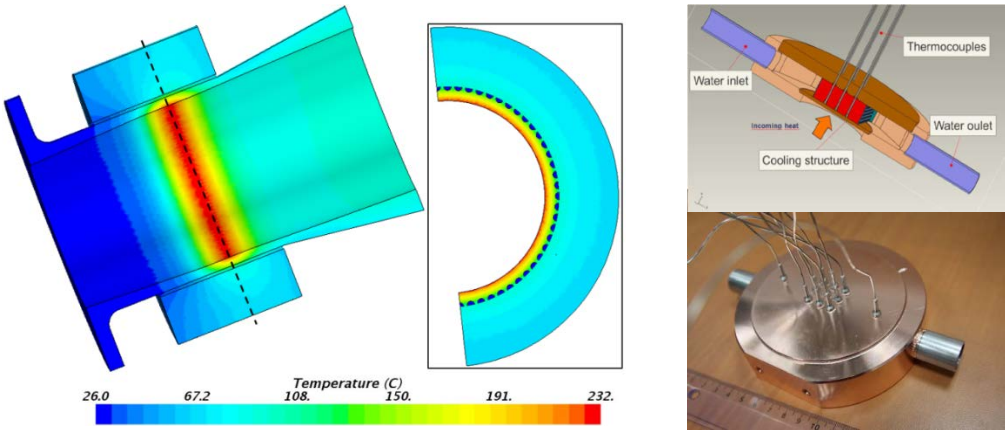

FIG. 1. On the left side, the predicted temperature field on the solid structure of a gyrotron cavity cooled with mini-channels; on the right side, schematic view and photograph of a thermal cavity mock-up to be tested in the AREVA electron beam test facility.

The very large heat loads (~20MW/m^2) localized on the very short axial cavity length (< 1 cm) drives the thermal deformation of the cavity, which, on its turn, influences the electromagnetic field structure, the gyrotron operation, and consequently the peaked profile of the heat load. Therefore, the experimental activities are supported by detailed analysis of the cavity performance that requires the simultaneous solution of the coupled thermal-hydraulic, thermo-mechanic and electro-magnetic fields [20]. For this purpose the commercial code STAR-CCM+ v10, adopting 3D CFD and finite-element solid-stress models, has been coupled with the EURIDICE code for the beam-wave electromagnetic interaction. The results for a mini-channels cooling concept at the nominal gyrotron parameters are shown on the left part of FIG.6; the predicted peak wall temperature is of ~232 °C.

5. Conclusions

The design of the European 1 MW gyrotron for the ITER EC system is based on the tube design of the 140 GHz CW gyrotron produced in series for the W7-X Stellarator, and pre-qualified improvements in order to reduce risks and secure the industrialisation phase. The RF design has been validated with the successful results of the short-pulse gyrotron at KIT and parallel theoretical and qualification activities carried out in a strong collaboration among the EGYC Consortium, TED, F4E, IO and with other fusion labs for specific analyses. An industrial 1MW CW gyrotron prototype aiming at meeting the ITER specifications has been manufactured and is presently being tested to fully validate the technical design. The present status of the experiments with the 1MW CW gyrotron prototype demonstrates safe operation of the tube at the MW level at the LVOP. The gyrotron has been prepared and conditioned for the long pulse operation. The next step is to increase the length of the RF pulse up to the maximal full power capability of the KIT test stand. The industrial gyrotron prototype will be shipped then to the SPC-EFPL test facility in Lausanne, for the extension of the pulses to the 3600 s of the ITER specifications.

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