Tests and Qualification of the European 1 MW, 170 GHz CW Gyrotron in an ITER relevant configuration at SPC

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***Abstract*—After an initial testing period at the Karlsruhe Institute of Technology, the upgraded EU 1 MW, 170 GHz continuous wave (CW) industrial prototype gyrotron (TH1509U) for Electron Cyclotron Resonance Heating and Current Drive (ECRH&CD) in ITER has been transferred to the Swiss Plasma Center (SPC) to be tested in an ITER relevant configuration, to reach the performance level required by Fusion for Energy (F4E) to qualify it for the ITER project, and to increase the pulse length to very long pulses.**

I. Introduction

In the frame of the European gyrotron development for ITER carried out in a collaborative effort between the European GYrotron Consortium (EGYC), Fusion for Energy (F4E), and the commercial partner Thales, the first prototype (TH1509) of the 170 GHz, 1 MW, continuous wave (CW) gyrotron, that reached a performance of 0.8 MW during 180s, was refurbished to incorporate improvements such as a slightly modified RF and cooling design aiming at reaching the MW level in CW operation.

The TH1509U upgraded prototype was first delivered to the Karlsruhe Institute of Technology (KIT), where it produced 0.92 MW during 180s and 1.04 MW during 40s, limited by the test stand capabilities [1,2]. The tube was then transferred to the European gyrotron test stand at SPC in view of increasing the pulse length and testing it in a configuration closer to that of ITER.

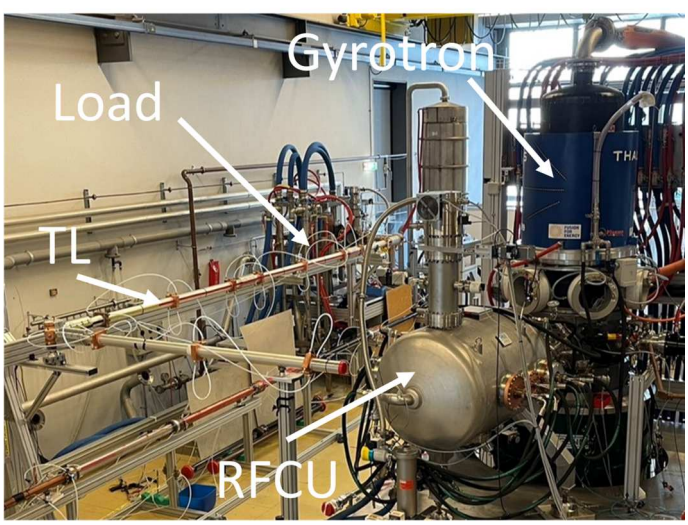

Figure 1: European Gyrotron test stand at SPC. The gyrotron, the RF Conditioning Unit, the transmission line (not connected to the RFCU in this picture) and the spherical load (partially hidden) appear on the picture.

Both test facilities are very similar. In particular, they are equipped with SCM magnets that provide field profiles leading to electron beam properties that can be varied in similar ranges. The electron beam is precisely aligned with dipole coils at KIT and with an XY-Table at SPC. The main differences lie in the testing configuration which at SPC incorporates an evacuated RF-Conditioning Unit (RFCU) and a ~10 m, ϕ63.5 mm HE_{11} transmission line (TL, ϕ50 mm in ITER) including 2 miter bends that propagates the microwave power to the spherical load developed by CNR [3]. The TL is cooled with Cu clamps periodically spaced by ca. 1 m. It should be noted that the RFCU is an old unit initially foreseen for a 170 GHz/2 MW coaxial gyrotron and is not intended to be used on ITER. A picture of the installation is shown on Fig. 1.

II. Results

After installation in the Cryogenic Ltd LHe-free magnet at SPC, the tube went through a short pulse (< 10 ms) test period dedicated to the electron beam alignment optimization by means of the XY-table. In this configuration, the power was measured directly at the window, with a very short pulse calorimeter.

The RFCU, the transmission line and the spherical load were then connected and aligned in view of the second part of the experimental campaign.

In long pulses, the power was measured in the spherical load. A correction factor of 1.05 was applied to estimate the power at the gyrotron window, accounting for the power dissipated in the 5 mirrors (previously incorporating 2 corrugated polarizer mirrors, now replaced by flat mirrors) RFCU (3% measured) and the TL (2% estimated, mostly in the miter bends –all in E-plane).

In order to maintain the operation on the design mode and avoid mode jumps, an optimized filament heating boosting sequence was developed, and complemented by adaptations of the accelerating voltage at properly selected times.

The best results, illustrated in Fig. 2 were obtained at the so-called Low Voltage Operating Point (LVOP) with the following parameters: cavity magnetic field B_0 = 6.69 T, beam radius r_b = 9.4 mm, average pitch factor α = 1.3, accelerating voltage V_a = 77 kV (48kV cathode voltage + 29 kV body voltage in 3 steps), beam current I_b= 55 A as depicted in Fig. 2 (top) for the pulse #10024 with a pulse length τ_{RF}= 178s and an efficiency η=35.2%. Also shown in the bottom panel of Fig. 2 are the time traces of the load and collector instantaneous power. It can be

seen that the parameters reach a quasi-steady state ca. 50s after the start of the pulse. The estimated power at the window averaged during the last 100s window of the pulse shown of Fig. 2 was 0.954 MW, which demonstrated for the first time in Europe the requirements set by F4E to qualify the tube for the ITER project.

The longest pulse that was obtained with a power level of 0.92 MW at the window was τ_{RF}= 256s.

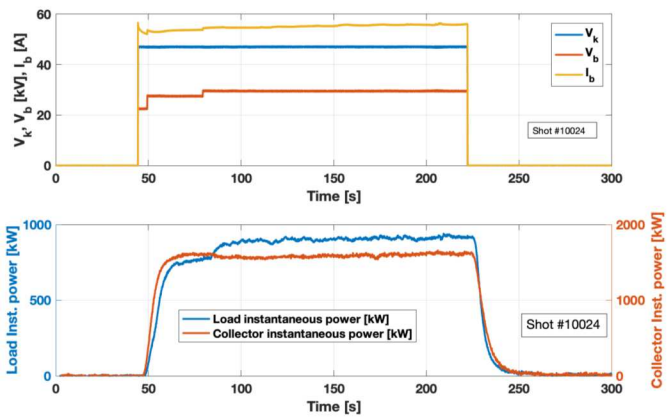

Figure 2: Top: Main electron parameters during pulse #10024. Yellow: beam current Ib, blue: cathode voltage Vk, orange: anode voltage Vb. The total accelerating voltage is Vk+Vb. Bottom: blue: Instantaneous microwave power measured at the load, orange: instantaneous collector power.

The oscillation frequency time dependence is shown in Fig. 3. It starts around 170.2 GHz and stabilizes around 169.95 GHz in this particular case. The jumps observed at 5s and 35s correspond to the accelerating voltage adjustments necessary to maintain the oscillation in the right mode at highest power.

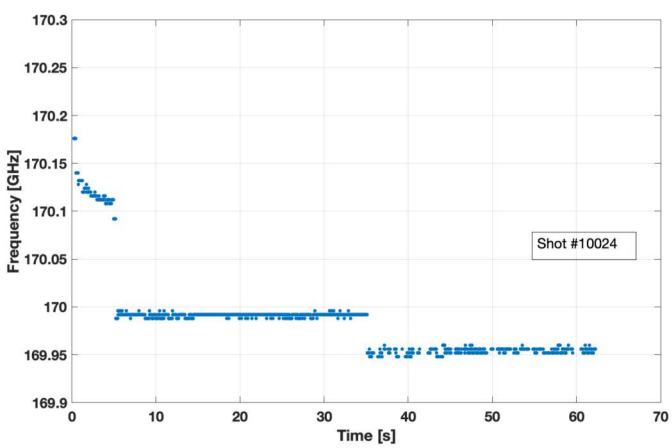

Figure 3: Frequency versus time for the first 60 seconds of shot #10024.

In all cases, the pulse was stopped for reasons external to the tube itself. The main limitation came from a temperature interlock in the transmission line.

An IR image of the TL is shown in Fig. 4 (top), and the temperature profile along the line is shown at the bottom. The image covers a sector that follows the first miter bend. Although the periodically spaced cooling clamps play their role (see pixels #100, #240, #320 and #500), they are unfortunately not

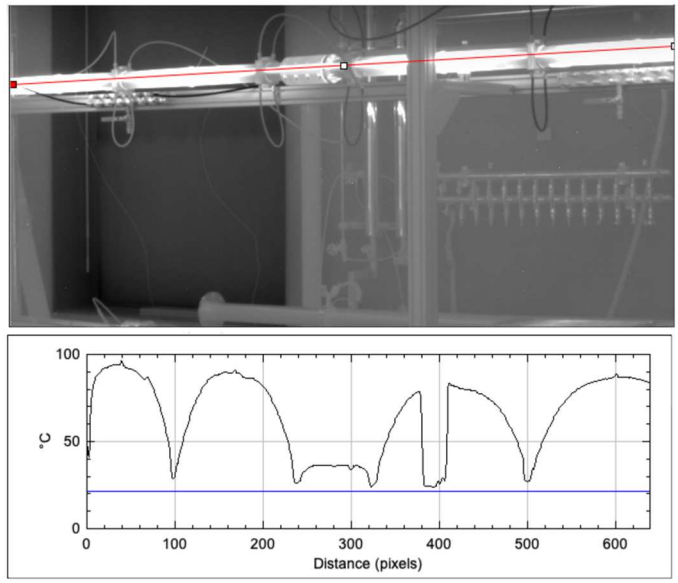

Figure 4: Top: IR image of a section of the transmission line after a pulse. Bottom: Temperature, as measured along the red line of the top picture. The dips correspond to the cooling clamps, to a connector, and to the shadow of a supporting element.

sufficient to limit the temperature, which evolves linearly in time up to the arbitrarily set limit of 100°C.

III. Conclusion and Outlook

The European 170 GHz, 1 MW upgraded gyrotron tube for ITER (TH1509U) has been tested in long pulses at SPC with performance levels of 0.95 MW/>100s and 0.92 MW/256s (power estimated at the window) that qualified it for the ITER project. The present limitation is the temperature rise in the TL. Cooling improvements are underway to further increase the pulse length up to 3600s, which is the maximum pulse length required for ITER.

Acknowledgment

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