Experimental Testing of the European TH1509U 170-GHz 1-MW CW Industrial Gyrotron – Long Pulse Operation

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***Abstract* — The upgraded European 1-MW, 170-GHz continuous wave (CW) industrial prototype gyrotron (TH1509U) for electron cyclotron resonance heating and current drive in ITER was tested at the Karlsruhe Institute of Technology (KIT). In this work, we report on the major achievements during the experimental campaigns that took place intermittently between October 2020 and July 2021. The upgraded gyrotron clearly surpassed the performance of the previous TH1509 tube. In particular, TH1509U delivered (i) 0.9 MW in 180 s pulses (maximum possible pulse length with the KIT test stand) and (ii) more than 1 MW at a pulse length limited to 40 s, due to an unforeseen problem with the test stand cooling circuit at that time. In addition, it was possible to also demonstrate gyrotron operation at (iii) 0.5 MW in 1600 s pulses. The experiments will be continued at the FALCON test stand at the École Polytechnique Fédérale de Lausanne (EPFL).**

***Index Terms*— Electron cyclotron resonance heating and current drive, gyrotron, ITER.**

I. Introduction

ITER is relying on twenty-four Continuous Wave (CW) 1 MW gyrotrons operating at 170 GHz to cover its electron cyclotron resonance heating and current drive needs [1]. Such tubes have been developed in Russia [2] and Japan [3] and a European gyrotron targeting the ITER gyrotron specifications has also been under development by the European Gyrotron Consortium (EGYC) in cooperation with the industrial partner THALES, France, and under the coordination of the European Joint Undertaking for ITER and the Development of Fusion Energy (F4E) [4].

The development of the first European prototype gyrotron for ITER (TH1509) started in 2008 and was completed at the end of 2015. Major experiments with the prototype took place in 2016 at KIT. With these experiments, most of the ITER specifications were achieved, including the high voltage (HV) properties of the gyrotron, the frequency of the nominal cavity mode, the stability of the tube vacuum, as well as the TEM_{00} mode purity and the alignment of the RF beam at the output optics unit. The maximum RF power achieved in 180 s pulses, which is the pulse length limitation of the KIT test stand, was 0.8 MW at various operation points with a maximum efficiency of 38 % in depressed collector operation [5]-[7]. Similar performance was achieved later at the FALCON test stand at EPFL. The experiments did not continue to pulses longer than 215 s due to external factors such as the overheating of the external Matching Optics Unit.

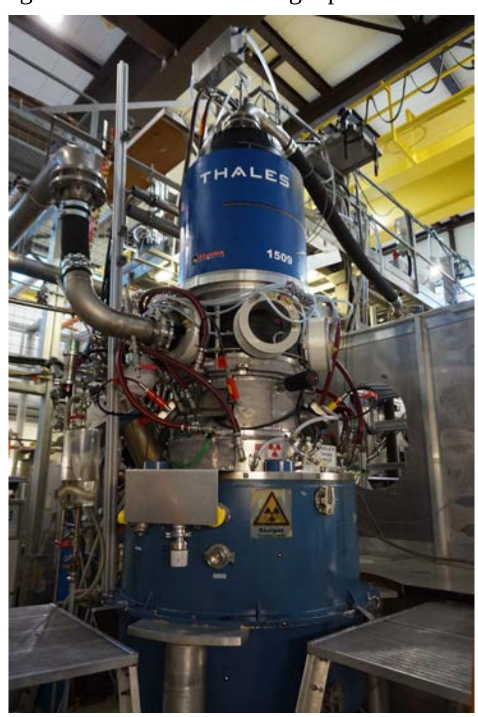

Fig. 1. The EU 1 MW, 170 GHz upgraded gyrotron (TH1509U) installed at the KIT test stand.

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Following the experiments at EPFL, the TH1509 prototype was subjected to a thorough expertise by THALES to increase further its performance. The tube was then refurbished, with slightly modified RF and cooling designs, and an improved assembly procedure. In particular, (i) the cavity length was increased to reach a higher quality factor to increase the RF generated power by 15 %, (ii) the cavity cooling was slightly extended towards the up-taper area, (iii) cathode emitter has been upgraded with an improved centering structure and (iv) general alignment procedure of the tube assembly has been improved. The upgraded prototype (TH1509U) was reassembled in the first half of 2020, factory-tested at Vélizy-Villacoublay, France, and delivered to KIT in July 2020. In this work, we report on the performance achieved during the experimental campaigns at KIT that took place intermittently between October 2020 and July 2021. In Section II we focus on the performance achieved with 1 ms pulses, whereas in Section III long-pulse operation up to 1600 s is reported. Our conclusions and an outlook are summarized in Section IV.

II. Short-Pulse Operation

Fig. 1 depicts the TH1509U gyrotron installed in the superconducting magnet at KIT. The test stand equipment and the testing procedures are described in detail in [5]. The gyrotron is not equipped with an alignment XY-Table [8] and therefore the dipole coils of the superconducting magnet are used (also in long pulse operation) in order to optimize the position of the gyrotron cavity with respect to the magnetic field axis.

The gyrotron has been designed to provide, essentially, identical performance at lower (Low Voltage Operating Point, LVOP) as well as at higher (High Voltage Operating Point, HVOP) magnetic field values in the cavity [5]. Starting the experiment and in order to support the progressive conditioning of the tube, the gyrotron was operated at the LVOP. Taking advantage of the experience gained in previous experiments with the short-pulse pre-prototype [6] as well as with the CW TH1509 tube, the gyrotron was directly operated with magnetic field profiles (i.e. combinations of magnetic field angle at the emitter and magnetic field value in the cavity) already known as near-optimal.

Fig. 2 presents the output power in 1 ms pulses, versus the accelerating voltage (non-depressed collector operation) and the beam current as a parameter. With current 49.5 A (slightly higher than the nominal one, i.e. 45 A), it is possible to reach the goal of 1 MW power with an efficiency as high as $\eta = 25$ %, even without an optimal placement of the tube. For the same current and by using the dipole coils to optimize the magnetic field alignment, the power increases by an additional 100 kW, raising increasing in this way the efficiency w/o collector depression to $\eta = 27$ %. By further increasing the electron beam current to 53.5 A and 56.5 A it is possible to get 1.1 MW ($\eta = 27$ %) and 1.2 MW ($\eta = 26$ %) output power, respectively.

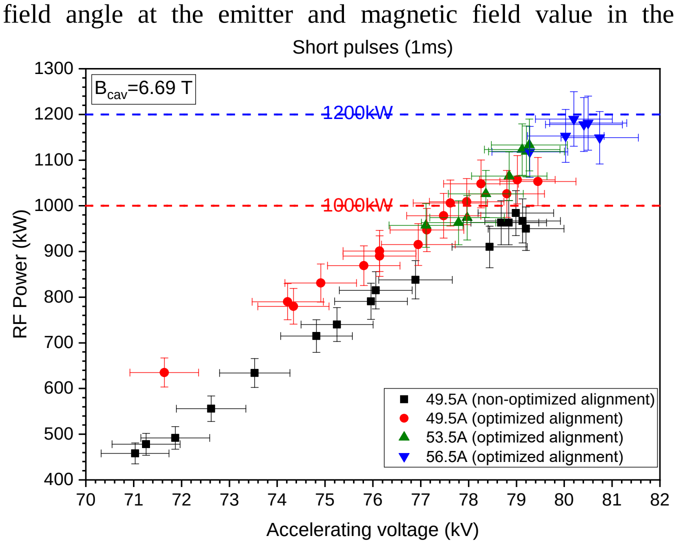

Fig. 2. Power versus the accelerating voltage (non-depressed collector operation) for different values of the beam current.

III. Long-Pulse Operation

A. Operation with 180 s pulses

The currently available high-voltage power supply (HVPS) at KIT is able to provide up to 50 A of electron beam current for 180 s with a 1:10 duty cycle. Considering that at the LVOP (B_{cav} = 6.69 T) we need in practice beam current values close to the HVPS limit, we preferred to condition and operate the gyrotron with longer pulses at the HVOP (B_{cav} = 6.78 T), which requires a lower nominal current of 40 A. This allows addressing the emitter cooling phenomenon by boosting the beam current (through the filament heating) close to 50 A at the beginning of the pulse and then stabilize it within a time span of 20 s at values close to 45 A (again by adjusting the filament current with respect to time).

The high beam-current value at the beginning of the current boosting sequence, in combination with the higher values of the pitch factor $\alpha = v_{\perp}/v_{\parallel}$ before the partial neutralization of the space charge of the beam (at a time scale of ~200 ms), could lead to the excitation of counter-rotating modes during the ramping up of the voltage. To reduce such a risk, the pitch factor at the beginning of the pulse was reduced by adjusting either the gun coil currents of the magnet or the value of the accelerating voltage. Then, and after the beam current was, essentially, stabilized, the magnetic field and the accelerating

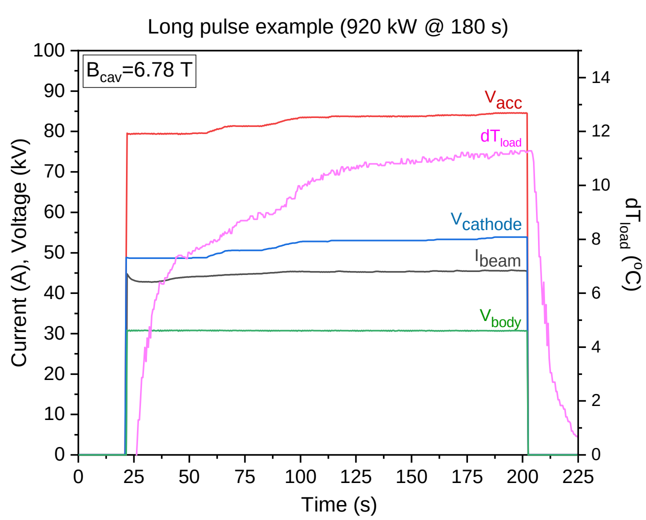

Fig. 3. Example of a 180 s pulse with 920 kW average power and 38 % efficiency (depressed collector operation).

voltage were progressively changed to the optimal values.

Fig. 3 presents the beam current (black curve), the cathode voltage (blue curve), the depression/body voltage (green curve), the accelerating voltage (red curve) and the inlet-outlet temperature difference of the calorimetric load, proportional to the generated RF output power (magenta curve), versus time for a typical 180 s pulse. As described above, the gun coil currents are modified during the pulse (to keep the pitch factor within appropriate limits) and in parallel the cathode voltage is increased in order to enter the high-efficiency area of the nominal mode. With an accelerating voltage V_{acc} = 84.5 kV (collector depression voltage V_{body} = 30.7 kV) and I_{beam} = 44.9 A beam current, the achieved power is 920 kW, which corresponds to a total efficiency of 38 %. The power balance in the system during the pulse was at the level of 99.1 %.

With further optimization of the magnetic field profile, motivated by recent theoretical findings [9-10] utilizing the interaction code EURIDICE [11], an even better performance was achieved: with accelerating voltage V_{acc} = 86.4 kV

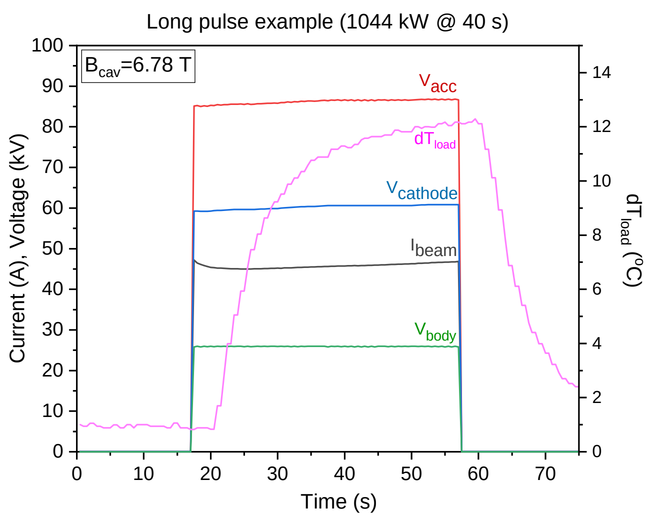

Fig. 4. Example of a 40 s pulse with 1044 kW average power and 38 % efficiency (depressed collector operation).

(depression voltage V_{body} = 26 kV) and beam current I_{beam} = 45.7 A, the average output power at the window surpassed for the first time 1 MW (1044 kW) in long pulse operation, with a total efficiency of 38 % (Fig. 4). Unfortunately, due to a problem with the cooling system of the test stand, the maximal pulse length at 1044 kW was limited to 40 s only. No further steps towards improving the efficiency, i.e. by increasing the depression voltage were performed, due to lack of time because of the very tight experimental schedule of the test stand.

B. Pulses up to 1600 s

By reducing the electron beam current below 30 A it is possible for the high voltage power supply at KIT to make pulses up to 1800 s. At the beam current value limited to 29 A it was possible to demonstrate a 1600 s pulse. With accelerating voltage V_{acc} = 78.5 kV (depression voltage V_{body} = 31.7 kV) the generated output power is 470 kW, which corresponds to a total efficiency of 35 %. By increasing the depression voltage by 2 kV the efficiency was further improved and reached 42 %.

IV. Conclusion

The experiments at KIT showed a very high potential of the refurbished European 170-GHz 1-MW CW gyrotron. Due to the introduced improvements on the tube, in contrast to the campaign in 2016 [5], it was now possible to demonstrate the required power level in a long pulse operation regime; in particular, 920 kW at 180 s and over 1 MW at 40 s (pulse length limited due to the test stand cooling capabilities). The experiments will be continued at EPFL, Lausanne, where further optimization of the gyrotron operating parameters, targeting at higher efficiency of the tube, and finally CW operation up to 1000 s are expected.

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