European 1 MW, 170 GHz CW Gyrotron Prototype for ITER - long-pulse operation at KIT -

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***Abstract*—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 was tested at the Karlsruhe Institute of Technology (KIT). The gyrotron surpassed the performance of the previous TH1509 tube. In particular, TH1509U delivered (i) 0.9 MW in 180 s pulses (max. pulse length of the KIT test stand) and (ii) more than 1 MW at a pulse length limited to 40 s, due to a problem with the test stand cooling circuit at that time. In addition, it was possible to demonstrate gyrotron operation at (iii) 0.5 MW in 1600 s pulses.**

I. INTRODUCTION

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} output mode purity and the alignment of the microwave beam at the output optics unit. The maximum microwave power achieved at pulse lengths of 180 s was 0.8-0.9 MW at various operation points with a maximum efficiency of 38 % in depressed collector operation. In 2020 the tube was refurbished, with slightly modified microwave and cooling designs, improved emitter centering structure and better general assembly procedure. The upgraded prototype (TH1509U) was reassembled and delivered to KIT in July 2020 for the first tests (Fig. 1). The summary of the achieved results will be presented and discussed here.

II. RESULTS

A. Short-pulse operation

At first, the gyrotron was operated at short pulses in the ms range in non-depressed collector operation [1]. Fig. 2 presents the achieved output power in 1 ms pulses, versus the accelerating voltage (non-depressed collector operation) and the electron beam current as a parameter. With 49.5 A current (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 dipole coils to optimize the magnetic field alignment, the power increases by an additional 100 kW, 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.

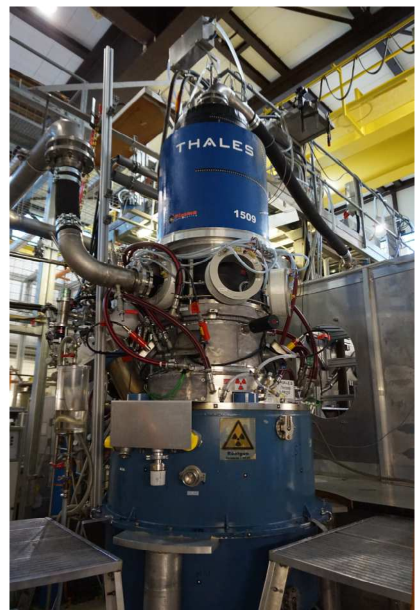

Fig. 1. European 1 MW, 170 GHz CW ITER gyrotron prototype at KIT.

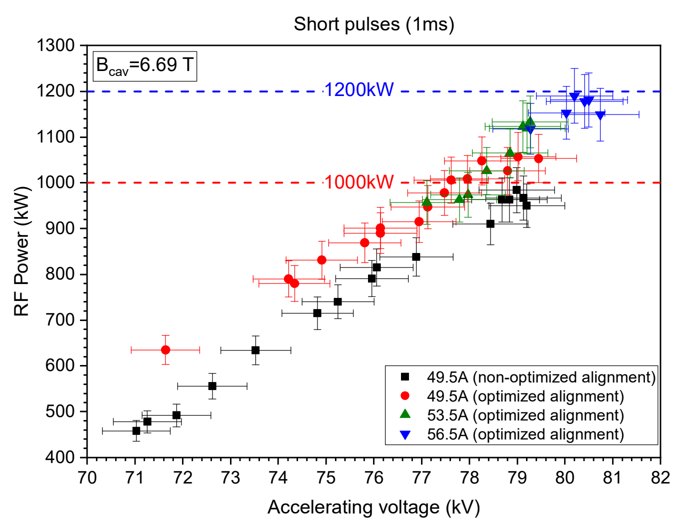

Fig. 1. RF output power versus the electron beam accelerating voltage (non-depressed collector operation) for different values of the beam current.

B. 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 Low Voltage Operation Point (LVOP) (B_{cav} = 6.69 T) we need in practice beam current values close to the HV power supply limit, we preferred to condition and operate the gyrotron with longer pulses at the High Power Operating Point (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 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 tailoring the time dependence of the filament current).

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 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 α within appropriate limits) and in parallel, the cathode voltage is increased in order to enter the high-efficiency domain 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 output 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 an even better performance was achieved: with accelerating voltage V_{acc} = 86.4 kV (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 at that time, 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.

C. 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 RF 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 %.

III. Summary

The experiments at KIT showed a very high potential of the refurbished European 170-GHz 1-MW CW ITER gyrotron. Due to the introduced improvements on the tube 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 have been continued at EPFL, Lausanne, where further optimization of the gyrotron operating parameters in long-pulse operation took place [3].

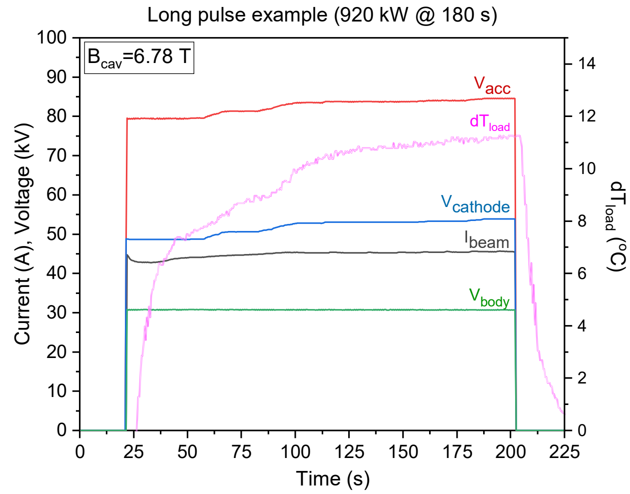

Fig. 2. Example of a 180 s pulse with 920 kW average power and 38 % efficiency (depressed collector operation).

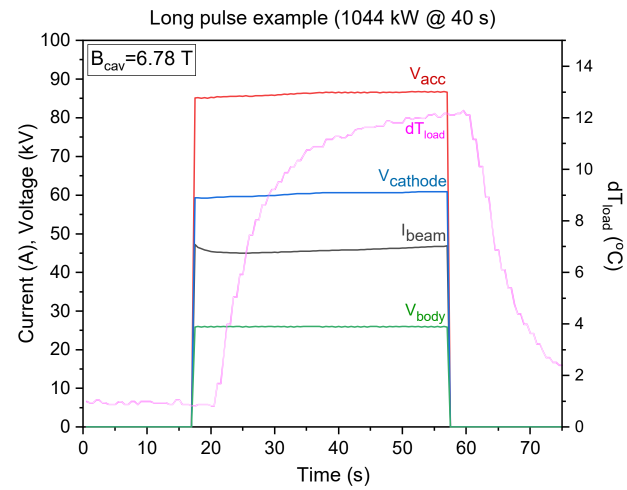

Fig. 4. Example of a 40 s pulse with 1044 kW average power and 38 % efficiency (depressed collector operation).

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