High-efficiency, long-pulse operation of MW-level dual-frequency gyrotron, 84/126GHz, for the TCV Tokamak

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***Abstract*— The first unit of the dual-frequency gyrotron, 84-126GHz/1MW/2s, for the upgrade of the TCV ECH system has been delivered and is presently being commissioned. During a first phase, long-pulse operation (T_{RF}>0.5s) has been achieved and powers in excess of 0.93MW/1.1s and 1MW/1.2s have been measured in the evacuated RF-load at the two frequencies, 84GHz ($TE_{17,5}$ mode) and 126GHz ($TE_{26,7}$ mode), respectively. Considering the different rf losses in the experimental setup, the power level generated in the gyrotron cavity is in excess of 1.1MW and 1.2MW, with a corresponding electronic efficiency of 35% and 36%. These values are in excellent agreement with the design parameters and would likely lead to a gyrotron total efficiency higher than 50% in case of implementation of a depressed collector. The gyrotron behavior is remarkably reliable and robust with the pulse length extension to 2s presently only limited by external auxiliary systems.**

I. INTRODUCTION

THE X3 upgrade project [1] of the Swiss Plasma Center consists of adding two dual-frequency gyrotrons (126 or 84GHz/1MW/2s) with a total power of 2MW at 126 GHz (for top-launch (TL) X3-mode) or at 84 GHz (for low field side (LFS) injection X2-mode). The gyrotron design is the result of a collaborative effort between SPC and KIT and its manufacturing is made by theThales.

The tube design is largely based on the existing Thales TH1507 140 GHz/1 MW gyrotron developed by KIT and SPC for W7-X [2,3], for which some components have been modified either to include state of the art design criteria or to optimize the operation at the two different frequencies. This encompasses the use of a triode gun instead of a diode gun to keep control of the electron beam parameters at both frequencies, an increase of the cavity length to ensure an optimized interaction length at the two frequencies, a hybrid-type launcher designed to provide a high output beam gaussian content for the two modes of operation, an adjustable last mirror to center the output beam at the window in case of necessity, an optimized collector cooling geometry and a diamond window thickness adapted at 84 and 126 GHz.

The first unit has been manufactured by Thales and delivered in the third quarter 2018 [4]. The pulse length extension to 2s is ongoing and presently limited by external auxiliaries.

II. EXPERIMENTAL RESULTS

Short-pulse (≤20ms) and long-pulse operation (≥500ms) has been successfully achieved during the commissioning phase without facing any issues. For long-pulse operation, a novel power deposition scheme on the gyrotron collector, based on an AM modulation of the collector sweeping coil, has been fully validated and ensures an homogenous power distribution along the collector walls [5]. The experimental set-up during commissioning is shown in Fig.1.

Fig.1. Layout of the experimental setup used for long-pulse characterization of the dual-frequency gyrotron. Via an evacuated MOU (rectangular metallic box), the rf-power at the two frequencies is transmitted to the evacuated high-power load [6] using a HE_{11} (63.5mm diameter) evacuated waveguide.

During the commissioning, the gyrotron optimization was guided by extensively using the modeling tools available at SPC [7,8]. In long-pulse operation (T_{RF}>0.5s) stable monomode operation was reached and the cavity generated rf-power is well in excess of 1MW at the two frequencies with corresponding electronic efficiencies higher than 35%. A summary of the achieved gyrotron performances is given in Table 1.

TABLE 1. Achieved long pulse (≥ 500 ms) performance of the gyrotron.

Parameter	**X2**	**X3**
Frequency [GHz]	84	126
Mode $TE_{m,p}$	$TE_{+17,6}$	$TE_{+26,7}$
Beam current I_b [A]	40	42
Cathode voltage V_k [kV]	80	81.5
Beam energy V_b [kV]	78	79.5
Anode voltage V_a [kV]	44	55.5
P_{RF} load [MW]	0.93	1.04
Load reflection [%] (est.)	4	4
TL losses (5 mirrors) [%] (est.)	0.8	0.8
Internal mirr. losses [%] (est.)	0.3	0.3
Launcher losses [kW] (meas.)	16	20
Cavity losses [kW] (meas.)	32	42
Stray radiation [kW] (calc.)	60	40
Cavity RF-power [MW]	1.09 ± 5%	1.2 ± 5%
Electronic efficiency [%]	35 ± 1.5	36 ± 1.5
Frequency shift [MHz]	180	350

Time traces of the relevant quantities for the two frequencies are shown in Fig.2&3.

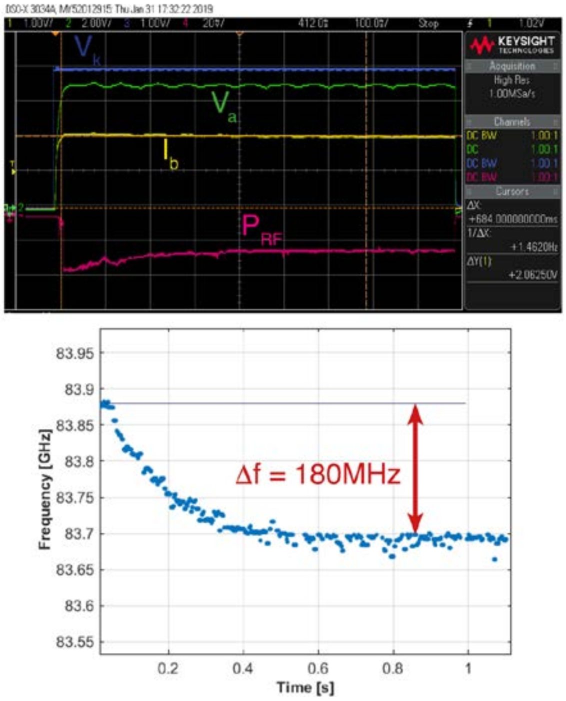

Fig.2. For the operational point @84GHz shown in Table 1, on top, time traces of the electron beam-parameters and RF-power (Schottky diode). Bottom, frequency time evolution.

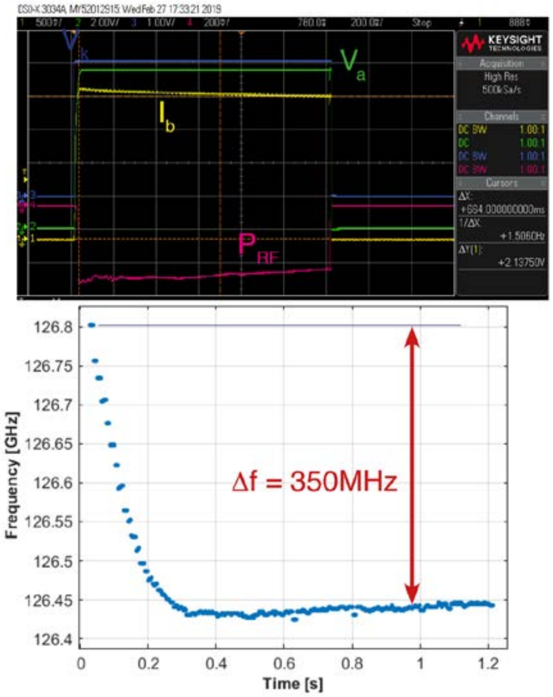

Fig.2. For the operational point @126GHz shown in Table 1, on top, time traces of the electron beam-parameters and RF-power (Schottky diode). Bottom, frequency time evolution.

III. CONCLUSIONS

The first dual-frequency gyrotron at 84 GHz and 126 GHz for TCV has been delivered by Thales and commissioned at SPC. The nominal power of 1 MW has been reached at both frequencies, with electronic efficiencies of the order of 35%, suggesting that an efficiency of 50% could be reached if a depressed collector was used. The specific design options – increased cavity length, triode gun, hybrid-type launcher, improved collector cooling and sweeping scheme – have been validated. An excellent agreement was found between the experimental observations and numerical simulations performed with the monomode code TWANG. In addition, no parasitic oscillation has been detected. The extension to the nominal pulse length (2 s) will be carried out once present limitations have been overcome. The second gyrotron will be delivered in July 2019 and the first operation on TCV is foreseen during the 2nd half of 2019.

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