Generation of 1.5MW-140GHz pulses with the modular pre-prototype gyrotron for W7-X

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***Abstract* — In anticipation of an Electron Cyclotron Resonance Heating system upgrade for the stellarator Wendelstein 7-X, a 1.5 MW – 140 GHz continuous-wave gyrotron is under development. In order to provide a first experimental verification of the scientific RF and electron beam optics design of the gyrotron with ms pulses, the Karlsruhe Intitule of Technology has developed a short-pulse pre-prototype gyrotron. In this work, we present details regarding the construction of the pre-prototype as well as measurements from the first experimental campaign delivering up to 1.6 MW in short pulses.**

***Index Terms*—Electron cyclotron heating, gyrotrons, high power microwave generation, plasma fusion devices.**

I. INTRODUCTION

NUCLEAR fusion in magnetically confined plasmas needs temperatures as high as 10^8 K. One efficient way to heat plasmas is by injecting millimeter waves with a frequency close to a harmonic of the cyclotron motion of the electrons in the confining magnetic field. Gyrotrons are able to cover the electron cyclotron resonance heating (ECRH) and current drive (ECCD) needs of modern plasma fusion devices. One fusion experiment, using 1 MW - 140 GHz gyrotrons [1]-[3], is the stellarator Wendelstein 7-X (W7-X) [4]-[7]. In the first experimental campaign, a notable performance was reached. The highest fusion triple product recorded for stellarators and pulse lengths up to 100 s were achieved by using the highly reliable 140 GHz ECRH system that delivers 7.5 MW in the plasma. In addition, ECCD was proven as an efficient means to compensate the bootstrap current in the plasma [7].

From the experiments it became clear that the power of the ECRH system needs to be increased, to reach operating regimes with plasma beta and collisionality of the order expected for reactor-scale devices. The upgrade is planned with the development of a Continuous-Wave (CW) 1.5 MW–140 GHz prototype gyrotron, which will be followed by three series production tubes. In order to mitigate the development risk and reduce the cost, the design of the 1.5 MW tube is based on the existing Thales W7-X gyrotrons [8], [9]. For achieving the 1.5 MW level some improvements are necessary [10], [11]. A modified cavity is needed to bring the interaction efficiency close to the theoretical maximum, in order to ensure compatibility with the available high-voltage power supplies. The efficiency of the cavity cooling has also to be improved. Due to the higher beam-current needed to deliver 1.5 MW, a beam-tunnel with enhanced parasitic-signal suppression properties is required. Finally, the 3rd mirror of the quasi-optical output coupler, right before the gyrotron window, is foreseen to be adjustable to ensure optimal alignment of the RF beam on the window.

In order to support the development of the 1.5 MW CW gyrotron and validate the scientific RF and electron beam optics design before the industrial partner (Thales, France) starts the manufacturing, the Karlsruhe Institute of Technology (KIT) has developed, manufactured and tested a modular short-pulse (SP) pre-prototype gyrotron, which shares the same scientific design [11] with the CW prototype. In this work, we report on the first results that were achieved with the pre-prototype. In Section II we describe the construction of the SP tube and the preparation for the experiments. Then, in Section III, we present the measurements that support the validation of the scientific design. Our conclusions and outlook for future experiments are summarized in Section IV.

II. THE SHORT-PULSE PRE-PROTOTYPE

Fig. 1 presents the KIT 1.5 MW–140 GHz pre-prototype. The gyrotron has a well-tested flanged construction that allows easy modifications [12]. All the key components interfaces have HELICOFLEX® seals that ensure high vacuum quality. The tube is pumped by two ion getter pumps, whereas a third sublimation pump is activated if necessary.

Before the assembly of the tube, the mirror-box has been baked at 400 °C in a nitrogen (N_2) oven. After the thermal treatment, the connection flanges were machined to ensure that the planarity and parallelism specifications are met. The internal gyrotron parts have been treated in a vacuum oven at 500 °C. The gun, the body isolator as well as the assembled

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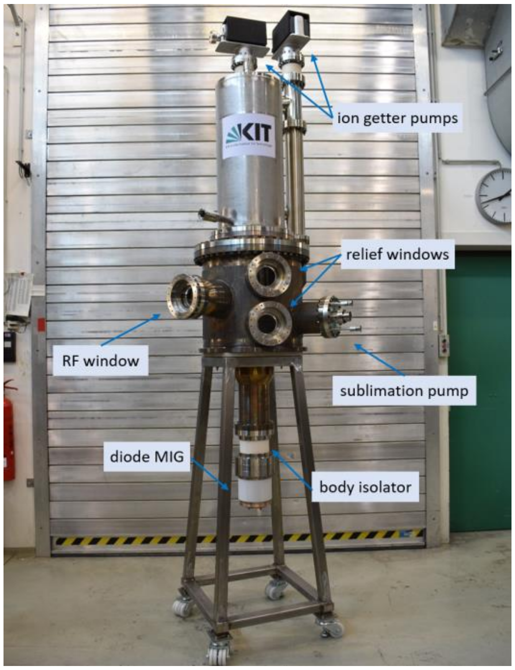

Fig. 1. The 1.5 MW – 140 GHz short-pulse pre-prototype gyrotron.

tube have not been baked to reduce the risk of damage.

The short-pulse gyrotron has been operated in a standard superconducting magnet (SCM) [13]. For the optimization of the electron beam alignment in the cavity, an XY-table [14] is used. The bottom plate of the XY-table is firmly mounted on the magnet, whereas the mirror-box can move on this plate with the help of flat bearings and a set of fine-threaded screws. Non-magnetic gauges are used to monitor and optimize the position of the tube in the magnet.

The RF and electron beam optics design is described in [11]. For the nominal $TE_{28,10}$-mode operation, a magnetic field of 5.560 T and a 55 A electron beam with kinetic energy 80 keV, radius 10.1 mm, and pitch factor 1.2 are required. These parameters refer to CW operation, where partial neutralization of the beam space-charge is expected. However, assuming that there is no neutralization during short (ms) pulses, the beam in the short-pulse pre-prototype is expected to have, approximately, 8 kV voltage depression due to the beam space charge, corresponding to ~8 keV lower kinetic energy. As a consequence, due to the increased accelerating voltage necessary to bring the electron energy close to nominal, the pitch factor is expected to reach higher values, (close to 1.6) for the nominal beam radius. The SCM is driven by only two power supplies and therefore it is not possible to control the pitch factor independently from the beam radius. The main way to reduce the pitch factor to the design values is to increase the electron beam radius, which, however, reduces the coupling of the beam to the field. It is also beneficial to reduce the magnetic field in the cavity and operate at reduced accelerating voltage. Both approaches are used to optimize the performance of the tube in SP operation.

III. First Experimental Results

Before the assembly of the tube, the quasi-optical output

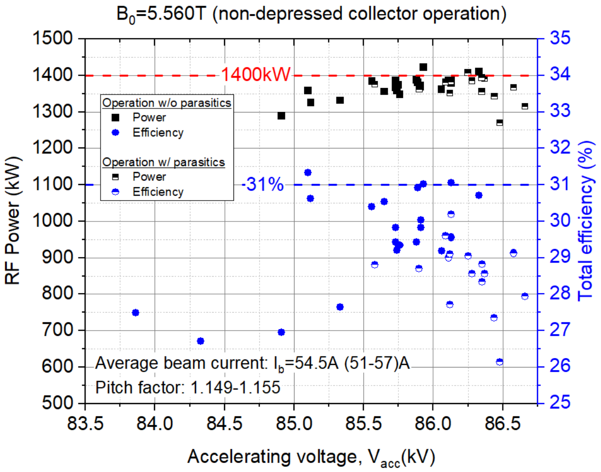

Fig. 2. Operation at the nominal magnetic field B_0 = 5.560 T.

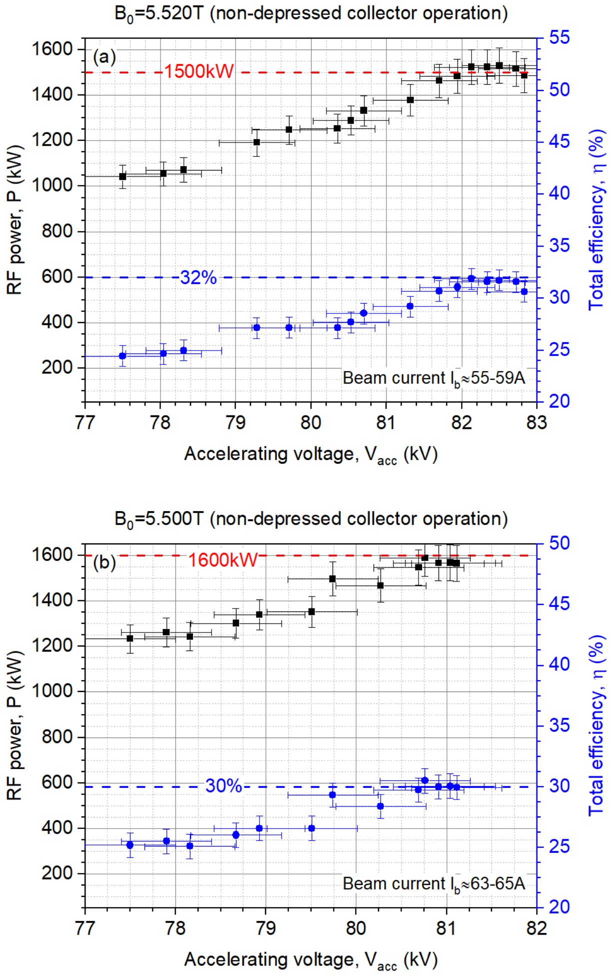

Fig. 3. Operation at lower magnetic field (a) 5.520 T and (b) 5.500 T.

coupler has been tested in a low-power measurement set-up [15] and the fundamental Gaussian mode content of the RF beam is estimated to be ~97%. [11], [16].

The conditioning of the tube started at the nominal magnetic field, B_0 =5.560 T. As expected, according to the discussion in Section II, with electron beam radius close to the nominal 10.1 mm it is difficult to increase the beam energy to 80 kV, while retaining a pure oscillation in the nominal mode,

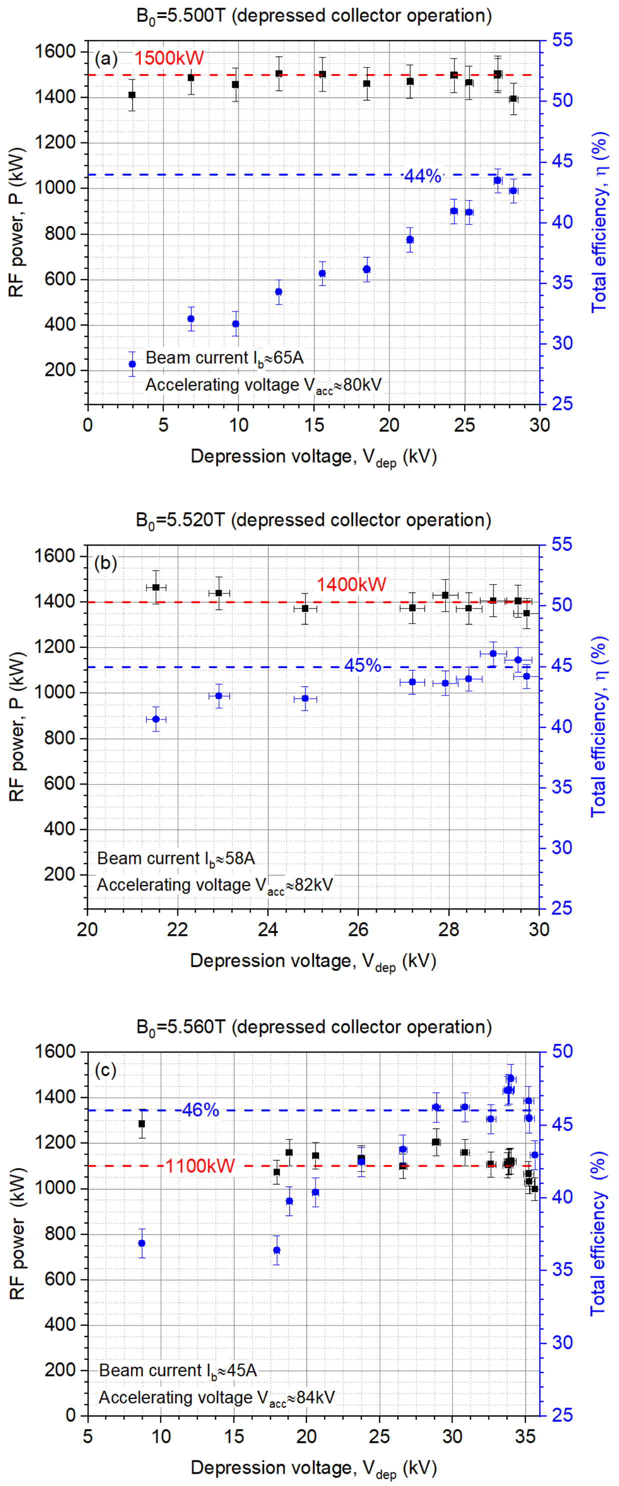

Fig. 4. Depressed collector operation at magnetic field (a) 5.500 T, (b) 5.520 T and (b) 5.560 T.

because of the very high values of the pitch factor. Even for beam-currents ~45 A, parasitic frequencies in the range 127 GHz-132 GHz are excited and multimode oscillation takes place. In order to reduce the pitch factor, the beam radius is increased. Fig. 2 presents the measured RF power and the corresponding efficiency in non-depressed collector operation for beam radius 10.3 mm and pitch factor 1.15 (values estimated by simulation). The pulse length is 0.5 ms to avoid partial neutralization of the beam. With accelerating voltage higher than 85.5 kV and before reaching the nominal beam energy, parasitic oscillations tend to get excited, the power is saturated and the efficiency is reduced. Similar behavior has been observed in [17]. Despite the non-optimal operation it is still possible to reach 1.4 MW with 31 % efficiency.

The same beam-wave detuning for the interaction can be achieved for lower accelerating voltages by reducing the value of the magnetic field in the cavity. Fig. 3 presents the power and the total efficiency (non-depressed collector operation) versus the accelerating voltage for two different values of the magnetic field, which are lower than the nominal value. For each magnetic field, the beam current and the voltage have been adjusted to ensure optimal performance. In both cases the electron beam radius is tuned approximately at 10.3 mm in order to keep the pitch factor low and avoid the excitation of parasitic signals even for beam-current values close to 65 A. As shown in Fig. 3, 1.5 MW with 32% efficiency and 1.6 MW with 30% efficiency are achieved at a magnetic field of 5.520 T and 5.500 T, respectively.

Fig. 4(a) shows the recorded power and efficiency with respect to the applied deceleration voltage in depressed collector operation for the optimal magnetic field identified by the non-depressed collector experiments. It is evident that the nominal power of 1.5 MW is achieved with 44% efficiency. It should be noted that in depressed collector operation it is necessary to ramp up the accelerating voltage more slowly in order to avoid the body power supply from detecting a high transient displacement current (due to the capacitance of the tube) and trip. In order to ensure that the flattop of the pulse is long enough for an accurate power measurement, the gyrotron has been operated with 1 ms pulses (instead of 0.5 ms for non-depressed operation) and the space-charge neutralization starts to appear. As a result the acceleration voltage has to be slightly reduced (80 kV instead of 81 kV shown in Fig. 3(b)) to prevent mode-loss due to drifting of the beam energy. For this reason the RF power is also somewhat reduced. The efficiency with depressed collector can be further increased by operating at higher magnetic field and lower output power. As shown in Fig. 4(b) and Fig. 4(c), by increasing the cavity magnetic field to 5.520 T it is possible to get 1.4 MW with at least 45% efficiency, whereas with a magnetic field of 5.560 T we achieve more than 1.1 MW with an efficiency of at least 46% and a maximum of 48%.

IV. CONCLUSION

The design of the W7-X 1.5 MW – 140 GHz pre-prototype SP gyrotron has been successfully validated in experiment. By operating the tube at different magnetic fields it was possible to demonstrate output power 1.6 MW with 30% efficiency in non-depressed collector operation. In depressed collector operation the efficiency of the tube was increased to 44% for the nominal power of 1.5 MW, whereas it surpassed 46% for 1.1 MW pulses. Despite that there are cases where parasitic modes are excited it is possible to find a wide parameter range for parasitic-free operation. Further experiments are planned with an optimized stacked beam-tunnel [8], [18], targeting at a wider parameter range of parasitic-free operation of the tube.

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