KIT In-House Manufacturing and First Operation of a 170 GHz 2 MW Longer-Pulse Coaxial-Cavity Pre-Prototype Gyrotron

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Abstract*— In frame of the work package "Heating and Current Drive" within the HORIZON 2020 EUROfusion program the development of multi-megawatt gyrotrons for the DEMOnstration fusion power plant is ongoing at KIT. Additionally, possible future upgrades of gyrotrons for e.g. for W7-X and ITER, are under consideration. Using the KIT modular-type 170 GHz 2 MW short-pulse (ms-range) coaxial-cavity pre-prototype the superior performance of the coaxial-cavity gyrotron technology has been already demonstrated for pulse lengths of up to a few milliseconds, achieving an RF output power of 2.2 MW. This short-pulse pre-prototype is now being upgraded in two steps to allow investigation of long-pulse behavior. The first step allows pulse-lengths up to 100 ms. The second step shall allow pulse-lengths up to 1 s. The first step in the upgrade was finished just recently. Considering a multi-megawatt output power at around 50 % total efficiency of the tube, the upgrade of the pre-prototype did require significant developments in the areas of basic construction, in particular with regards to cooling technologies, and in the final assembly. In this paper, the basic construction, the manufacturing details and the assembly are shown. Additionally, it is planned to show the very first performance results of the long-pulse tube based on the measurements which will be achieved in the time frame before the conference.

Keywords*— Nuclear fusion, electron cyclotron resonance heating, ECRH, gyrotron, ITER, DEMO, high power microwave sources, vacuum electronics, manufacturing technologies

I. INTRODUCTION

At the stellarator Wendelstein 7-X (W7-X), IPP Greifswald, Germany, Electron Cyclotron Resonance Heating (ECRH) is the day one heating system for plasma startup and control [1]. Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, together with Thales Electron Devices (TED), Vélizy-Villacoublay, France has been responsible for the development and manufacturing of 9 out of the 10 gyrotrons currently running at W7-X [2]. One gyrotron was developed and manufactured at CPI, Palo Alto, USA. As member of the European GYrotron Consortium (EGYC) and being involved in the HORIZON 2020 EUROfusion program, KIT is involved in the development of gyrotrons for ITER [3] as well as for a future DEMO [4]. As seen from above, ECRH is playing a superior tool in the plasma heating and plasma control of future nuclear fusion devices. Firstly, it is because ECRH offers excellent localized coupling of the RF power to the fusion plasma. Even more, gyrotrons already today are satisfying the basic requirements for ECRH of present and possibly near-future fusion devices [5]. Nevertheless, for fusion power plants which shall generate significant electric power such as DEMO the required RF power, efficiency, and operating frequency of gyrotrons needs to be further improved. A minimum RF output power of 2 MW at continuous wave (CW) and at operating frequencies up to 240 GHz are required. In order to satisfy the requirements of future power plants, KIT is working on advanced gyrotron concepts, such as the coaxial-cavity gyrotron technology. Experiments at KIT did demonstrate the superior performance of this technology by demonstrating an RF output power above 2.2 MW in short pulses (ms-range) at an operating frequency of 170 GHz [6]. In comparison to the classic hollow-cavity gyrotron technology widely used in today's fusion gyrotrons the coaxial-cavity gyrotron technology offers reduced voltage depression and mode competition. That allows for an operation at very high-order modes, and, correspondingly, leads to a significant higher RF output power. At KIT a modular-type 170 GHz 2 MW short-pulse (ms) coaxial-cavity pre-prototype gyrotron operating at very short pulses up to a few milliseconds has been used to verify the superior performance of the coaxial-cavity gyrotron technology so far. Considering a CW operation of fusion gyrotrons in future, the main focus of KIT must be to verify the performance of the coaxial-cavity gyrotron at longer pulses.

TABLE I. DESIGN PARAMETERS FOR THE COAXIAL-CAVITY GYROTRON

Operating cavity mode	$TE_{34,19}$
Frequency, f [GHz]	170
RF output power, P_{out} [MW]	2
Beam current, I_B [A]	75
Accelerating voltage, U_C [kV]	90
Velocity ratio (pitch factor), α	~1.3
Cavity magnetic field, B_{cav} [T]	6.87
Efficiency with SDC [%]	>50

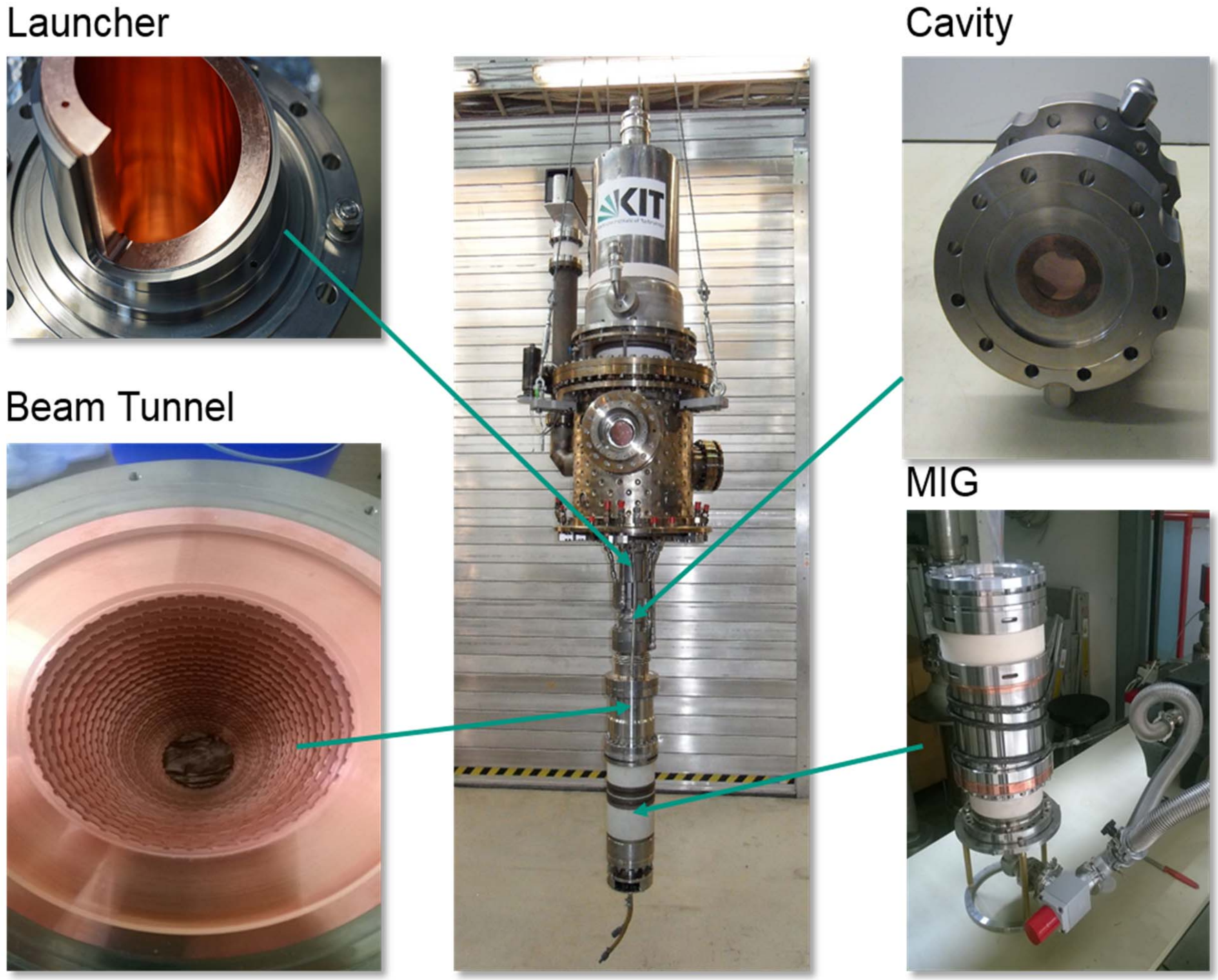


Fig. 1. Main components of the KIT 2 MW 170 GHz coaxial cavity longer pulse gyrotron.

II. Coaxial-Cavity Longer-Pulse Gyrotron Design and Manufacturing Process

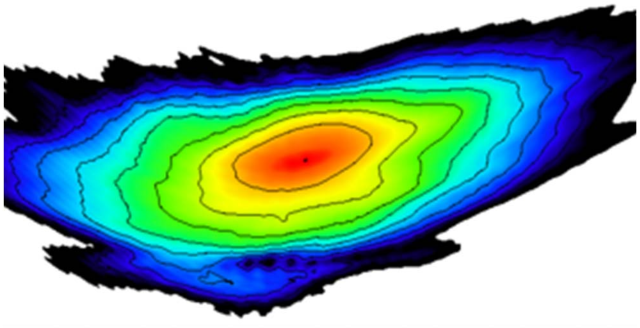
As a first step towards a coaxial-cavity gyrotron operating at CW KIT is extending its short-pulse pre-prototype to pulse lengths up to 1 s. This will allow the investigation of all performance parameters which are relevant for CW operation. Firstly, it is the operation in the neutralized regime partial electron beam space charge neutralization. Secondly, it is the reliable calorimetric investigation of the different gyrotron components, in particular the behavior of the inner conductor, during heating up. Hence, the main issue for a long-pulse gyrotron is the introduction of a reliable cooling system due to the significant losses in the gyrotron [7, 8]. In particular, the beam tunnel, cavity, launcher, quasi optical mirror system, CVD diamond output window, and the collector have to be equipped with active cooling systems. The already assembled longer-pulse gyrotron with the manufactured components and water cooling

pipes is shown in Fig. 1. One of the main advantages of the longer-pulse gyrotron is the complete modularity. This has the advantage of easy implementation and testing of new subcomponents with advanced water cooling systems, material compositions and geometries. In line with the modularity, an independent cooling system for each component is necessary. This concept allows also the monitoring of the internal losses in each gyrotron component and of the final energy balance of the tube during longer-pulse operation [9]. Hereinafter, the advanced water-cooled subcomponents as well as the bake-out procedure will be described.

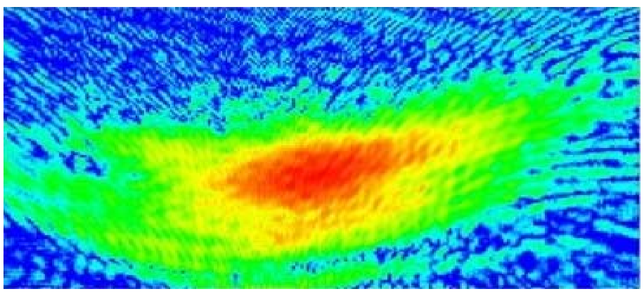
A. *Launcher*

The quasi-optical launcher together with the three mirrors are appropriate for the conversion of the $TE_{34,19}$ mode into a linearly polarized fundamental Gaussian beam mode [10]. During the mode conversion, the wall loading at the top of the launcher, where the RF power is focused, is very high. Therefore, a water cooling system is necessary. The requirement of the launcher cooling are very challenging, because the launcher ranges 60 mm into the mirror box with a surrounding vacuum area. Consequently, the inlet and outlet of the water system is placed at the bottom of the launcher and the water is flowing in a helical-shaped water channel [11]. The launcher and its cooling channels are already successfully manufactured, in-house brazed, tested and implemented. The manufacturing surface tolerances of the launcher are ±10 μm.

In order to verify the manufacturing accuracy of the launcher, its radiated pattern (Fig. 2) was measured at low power in a



(a)



(b)

Fig. 2. Simulated (a) and measured (b) radiation pattern of the longer-pulse launcher (cold measurement).

distance of 10 cm from the launcher. The measurement results Fig. 2(b)) correspond very well to the simulation results (Fig. 2(a)).

B. Cavity

In the cavity an RF power of more than 2 MW is generated, due to an interaction between the transverse component of the electron motion and the transverse RF-field. The power losses in the cavity amounts 35 kW with a maximum wall loading of ~2 kW/cm². This extremely high wall loading leads to very high thermal stresses in the cavity wall. The frequency of the RF wave is strongly dependent to the diameter of the cavity and hence on the deformation and the thermal expansion. Therefore, it is mandatory to implement an efficient water cooling system. For the first operation an annular gap cooling system is implemented, which shows in simulation a maximum surface temperature of 350 °C [11] in CW operation.. To reduce the maximum temperature and also improve the homogeneity of temperature distribution, an advanced micro-channel cooling system [12] is under investigation.

C. Beam Tunnel

In Fig. 1 the inner contour of the beam tunnel is shown. The beam tunnel consists of stacked copper and ceramic rings. The copper rings have corrugations of λ/4 depth in order to suppress unwanted oscillations in the beam tunnel. In comparison to the cavity, the power loading requirement is relatively low. Nevertheless, an active cooling is obligatory and is installed.

Fig. 3. Mirror Box in the bake out oven.

Furthermore, the development and manufacturing of an alternative full metallic beam tunnel is intensively in process.

D. Mirror Box

The mirrors and the mirror box of the quasi-optical system will be reused from the first industrial coaxial-cavity gyrotron prototype [13] with significant modifications at the absorber ceramics, collector, flanges, and window housing in order to satisfy the requirements of modularity. At the outer bottom ring of the mirror box (see Fig. 1) the water inlet and outlet for the beam tunnel, cavity and launcher are fixed. Due to the fact that the gyrotron will eventually operate at 1 s pulses, it is necessary to bake out the tube at 300 °C. Therefore, the water channels and vacuum connections have to be heat-resistant up to 300 °C. Suitable gaskets are already installed and tested up to a water pressure of 10 bar, which is above the nominal operating pressure.

E. Bake-Out Process of the Mirror Box

After the significant modification, the mirror box was baked-out in the in-house oven up to 300 °C. All the components have been designed for a bake out procedure of more than 400 °C. Especially the solder connections withstand a local temperature of more than 600 °C. At Fig. 3 the longer-pulse mirror box is shown in the bake-out oven on a special support frame. The vacuum pumps are located outside the oven and connected by flexible corrugated hoses to the mirror box. In order to record the temperature, 12 thermocouples are connected to the mirror box. The complete bake out procedure has been controlled by a special control system to which a scenario has been programmed. The bake out procedure consists of three major phases. In the first phase the temperature in the oven is stepwise increased up to the nominal bake out temperature of 300 °C.

In the present case 7 days were spent for the first phase. In the second phase the temperature is kept constant at the nominal value of bake-out for further 7 days. Subsequently, in the third phase, the heating of the oven is switched off and the temperature is decreasing slowly in order

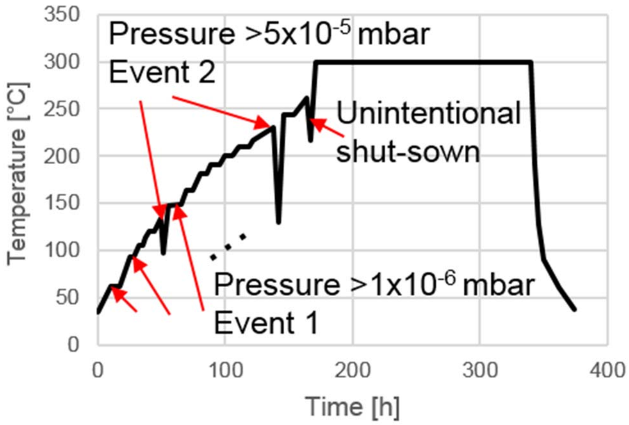


Fig. 4. Temperature curve of the bake out process.

to avoid stresses at the components due to different thermal expansions.

In the control system several interlocks are implemented. The task is to detect and prevent several events. The usually occurring event is the increase of vacuum pressure during the ramp-up process. If the pressure exceeds a value of more than p1 = $1{,}0\text{x}10^{-6}$ mbar the temperature is kept constant until the pressure becomes less than p2 = $5{,}0\text{x}10^{-7}$ mbar (marked in Fig. 4 with event 1). If the pressure is smaller than p2 the oven increases the temperature again. If the pressure is exceeding the pressure level p3=$5{,}0\text{x}10^{-5}$ mbar the control stops immediately the heating process and shuts down the oven in a controlled manner (marked in Fig. 4 with event 2).

Due to the bake-out process the vacuum pressure could be reduced from $2\text{x}10^{-7}$ mbar down to $1\text{x}10^{-8}$ mbar, which is the lower limit of the vacuum turbo pump.

III. Summary And Outlook

The KIT is pushing forward the coaxial-cavity gyrotron development by building up a longer-pulse gyrotron targeting a pulse length up to 1 s. The manufacturing process of the longer-pulse 2 MW coaxial-cavity gyrotron has been already finalized and the whole gyrotron has been successfully assembled. The vacuum tightness has been carefully tested. In addition, the gyrotron was baked-out at 300 °C for better vacuum conditions and is already installed in the superconducting magnet. The longer-pulse 2 MW coaxial-cavity gyrotron will be tested in 2017.

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