Performance Expectation and Preparation of the First Experimental Campaign of the KIT 2 MW 170/204 GHz Coaxial-Cavity Gyrotron

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***Abstract*—The existing KIT 2 MW 170 GHz coaxial-cavity short-pulse pre-prototype gyrotron is being prepared to be upgraded towards multi-frequency operation at 170/204 GHz in the new FULGOR test facility. Therefore, each existing component was examined for the need for modification. A new anode, an elongation of the coaxial insert, the XY-table, and the HV oil tank have to be modified for the first operation. All required components are already manufactured and are prepared for assembly. In the first short-pulse experiments an RF output powers of 2.2 and 1.7 MW can be expected at 170 and 204 GHz, respectively. In a second experimental campaign the coaxial-cavity and the quasi-optical output system will be replaced for an optimized configuration achieving more than 2 MW RF output power at both frequencies.**

Keywords—multi-frequency, multi-purpose, gyrotron, coaxial-cavity, ECRH

I. Introduction

Gyrotrons having an RF output power in the MW-level and operating between 105 and 240 GHz are used in fusion machines for Electron Cyclotron Resonance Heating and Current Drive (ECRH&CD) and plasma stabilization. Several fusion projects, which are equipped with gyrotrons, are ongoing worldwide. However, DEMO (Demonstration Fusion Power Plant), which is currently under development, will be the first fusion machine producing electricity. The European (EU) DEMO requirements call for gyrotrons delivering 2 MW RF output power at two frequencies, i.e. 170/204 GHz [1]. Higher frequencies could also be considered in the future.

The EU DEMO gyrotron is developed in the coaxial-cavity technology in several steps. First, a short-pulse pre-prototype has been tested at 170 GHz delivering the world-record RF output power of 2.2 MW [2]. After successful proof-of-concept in short-pulse operation, the pre-prototype has been upgraded in a first step to longer pulses up to 50 ms [3] and is foreseen to be upgraded up to 1 s in a future step. In parallel, an investigation is ongoing to perform the 2 MW 170 GHz coaxial-cavity short-pulse pre-prototype in multi-frequency operation at 170/204/(238) GHz. The main idea is to reuse as many components as possible of the existing modular pre-prototype. The theoretical investigation has been completed successfully and the manufacturing process has already been started. The first experimental verification of the 2 MW 170/204 GHz multi-frequency coaxial-cavity pre-prototype gyrotron is planned in the KIT FULGOR gyrotron test facility [4] using a new 10.5 T super-conducting (SC) gyrotron magnet procured from TESLA Engineering Ltd..

II. Performance Expectations of the First Experimental Campaign

In the first experimental campaign, the new FULGOR test facility with its high-voltage power supply and SC magnet will be operated for the first time with a gyrotron. It is planned to modify only the absolutely necessary tube components, discussed below, to validate the new test facility with an almost proven gyrotron. As a result, the performance published in [5] for the optimized configuration of the multi-frequency coaxial-cavity pre-prototype gyrotron will not be achieved in the first experimental campaign.

The magnetic field profile of the TESLA magnet requires modifications on the existing coaxial Magnetron Injection Guns (MIG) at KIT. In order to minimize efforts, only the anode of the coaxial diode MIG has been redesigned with the goal to provide a sufficient beam quality at 170 and 204 GHz. The simulations have been performed using the self-consistent, electrostatic trajectory 3-D code ARIADNE [6]. It is very challenging to find a design in diode regime which satisfies the requirements for the beam quality for both of the chosen modes, namely the $TE_{34,19}$ mode at 170 GHz and the $TE_{40,23}$ mode at 204 GHz. Therefore, the use of the counter-rotating $TE_{-34,19}$ mode and the co-rotating $TE_{40,23}$ mode is proposed, resulting in an anode design which is well suited for both modes. This procedure has already been used in other fusion gyrotrons [7], where the polarity of the SC magnet is reversed for the different mode rotations so that the gyrotron launcher operates correctly. The resulting beam parameters for both frequencies are used in cavity interaction simulations employing the time-dependent, self-consistent multi-mode code-package EURIDICE [8].

In order to demonstrate the operation of the KIT FULGOR test facility and the gyrotron at 204 GHz, the existing coaxial-cavity geometry is intended for the first experimental verification. The existing non-linear up-taper was only optimized in the past for the operation at 170 GHz. A simulation of the non-linear up-taper at 204 GHz show a mode conversion of 0.6 % from the $TE_{40,23}$ mode to the $TE_{40,22}$ mode at 204 GHz operation. The results of the interaction simulations are summarized in Tab. 1. The defined nominal operation point (OP) for the operation at 170 GHz is given by a beam energy of 90.8 keV, a beam current of 72 A, and a maximum magnetic field strength of 6.88 T. The calculated RF power at the end of the up-taper is 2.27 MW with an interaction efficiency of 35.7 % without depressed collector. In contrast, two nominal operation points have been defined for the operation at 204 GHz, where the nominal maximum field strength has been defined to be 8.21 T and 8.25 T, respectively. Therefore, the nominal electron kinetic energy is changing which affects the electron velocity ratio. At OP1/2 the pitch factors are given by 1.06/1.15, respectively. The expected RF output power are 1.7 MW at 204.13 GHz at both operation points.

The design of the quasi-optical (q.o.) output system which converts the rotating high-order cavity modes into linearly polarized fundamental Gaussian beams has been investigated. A study of the existing q.o. output system shows a Gaussian-mode content (GMC) of 96.6/91.6 % for the $TE_{-34,19}$-/$TE_{40,23}$-mode at 170/204 GHz, respectively. A modified q.o. output system having a GMC above 95 % for both modes has already been designed and manufactured. However, the new launcher is only compatible with the modified coaxial-cavity which will be used in the second experimental phase. These results in the existing q.o. output system being considered in the first step of the experiments.

TABLE I. SUMMARY OF THE CALCULATED NOMINAL OPERATION POINTS FOR THE $TE_{-34,19}$- AND $TE_{40,23}$-MODE FOR THE FIRST EXPERIMENTS.

	$TE_{-34,19}$ mode	$TE_{40,23}$ mode	
	OP1	OP1	OP2
Electron kinetic energy [keV]	90.8	84.0	86.8
Beam current [A]	72	70	67
Magnetic field [T]	6.88	8.21	8.25
Electron velocity ratio	1.2	1.06	1.15
Electron beam radius [mm]	10.58	9.77	9.77
Transverse velocity spread [%]	2.8	2.7	2.57
Kinetic energy spread [%]	0.15	0.10	0.10
RF power at end of up-taper [MW]	2.27	1.79	1.67
Interaction efficiency [%]	35.8	31.5	30.0
Maximum wall loading [kW/cm^2]	2.00	2.00	2.00
Maximum insert loading [kW/cm^2]	0.11	0.06	0.06
Frequency [GHz]	170.0	204.13	204.13

III. PREPARATIONS TOWARDS FIRST MULTI-FREQUENCY OPERATION

Besides the anode modification, the housing has to be elongated with respect to the geometrical dimensions of the new SC magnet. The elongation will be performed by the new anode with increased distance between the emitter and the cavity. In addition, the coaxial insert has to be elongated accordingly to position of the insert corrugations to the center of the coaxial-cavity. To be most cost-effective, the existing coaxial insert will be modified accordingly.

In addition, an XY-table is foreseen which will be mounted on the top of the SC magnet. The XY-table can be used to align the position of the gyrotron within the SC magnet, optimizing the performance.

IV. CONCLUSION

In conclusion, following components have been prepared for the first experimental verification: anode, insert elongation, XY-table, adapters for the SC magnet and an HV oil tank. The required modified components are already manufactured. The current schedule calls for assembly in Q1 2021, followed by the first experiments during 2021. In parallel, a new frequency diagnostic system is being prepared for the first experimental verification, which will allow measurements up to 260 GHz. After the first experimental campaign, a new coaxial cavity with improved non-linear up-taper, a new coaxial insert and a new quasi-optical output system will be installed for an optimized configuration, where an RF output powers of more than 2 MW at both frequencies is expected.

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