Recent Developments of the 2 MW Coaxial-Cavity Pre-Prototype Gyrotron towards Multi-Frequency Operation

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***Abstract*—This paper gives a summary about recent activities at KIT regarding multi-frequency operation of the coaxial-cavity pre-prototype gyrotron. First, progress on gyrotron experiments above 200 GHz is discussed. Therefore, the existing 170 GHz design has been modified to achieve $\geq$ 2 MW RF output power with an interaction efficiency $\geq$ 35 % at 204 GHz operating in a new 10.5 T SC magnet. Second, research is ongoing to improve the cavity mode series for multi-frequency operation satisfying today's and future gyrotron requirements. Here, a new mode series is identified considering improved cavity cooling technology. This mode series shows only a small variation of the caustic radii and has electron beam parameters close to the existing mode series.**

***Index Terms*—gyrotron, multi-frequency, multi-purpose**

I. Introduction

High-power vacuum tubes like gyrotrons are used for Electron Cyclotron Resonance Heating and Current Drive (ECRH&CD) and plasma control in nuclear fusion experiments, like Wendelstein 7-X, ITER or DEMO. Gyrotrons can produce output powers in the MW range at operating frequencies in the millimeter-wave and the sub-THz range. Recently, research and development are ongoing towards gyrotrons for a European (EU) DEMO. They call for tubes with an output power of 2 MW, an efficiency of 60 % and the possibility of multi-frequency operation. Based on the existing 170 GHz gyrotron output window, the additional operating frequencies 136 GHz and 204 GHz are selected. The ability to operate a gyrotron at different frequencies enables its usage for multiple purposes, e.g. plasma start-up, bulk heating, non-inductive current drive and plasma diagnostics, respectively. In addition, plasma instabilities can be suppressed by tuning the operating frequency in steps of 2-3 GHz within a bandwidth of pm 10 GHz at each center frequency. A first theoretical gyrotron design in coaxial-cavity technology for triple-frequency operation at 170/204/238 GHz is presented in [1]. In addition, a coaxial-cavity gyrotron is prepared for a first 136/170 GHz dual-frequency operation [2]. Both designs are based on the 2 MW 170 GHz $TE_{34,19}$-mode coaxial-cavity pre-prototype gyrotron [3].

Part of this work has been carried out within the framework of the EUROfusion consortium, funded by the European Union via EURATOM research and training programme (grant agreement no. 1010522200 – EUROfusion). Part of the simulations were performed on the EUROfusion High Performance Computer (Marconi). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

This abstract gives an overview of the current status and future plans of the activities of the KIT 2 MW 170 GHz $TE_{34,19}$ mode coaxial-cavity pre-prototype gyrotron towards multi-frequency operation with frequencies above 200 GHz.

II. Towards Gyrotron Operation Above 200 GHz

The selected cavity modes for multi-frequency operation in addition to the $TE_{34,19}$ mode at 170 GHz are the $TE_{28,15}$ mode at 136 GHz, the $TE_{40,23}$ mode at 204 GHz and the $TE_{48,26}$ mode at 238 GHz. Those modes fulfill the design requirements in terms of low window reflection ($\leq$ 0.03 %) and a minor deviation in the difference of the caustic radii ($\leq$ 4 %) to guarantee a proper operation of the quasi-optical output coupler. At KIT, the investigation of multi-frequency gyrotron operation is performed in two steps. First, an experiment at 136/170 GHz is planned in the existing 6.9 T SC magnet in mid of 2024. In the second step, an operation above 200 GHz is envisaged using the new 10.5 T SC magnet, which will be delivered to KIT at the end of 2024. This new 10.5 T SC magnet will enable the possibility to operate gyrotrons above 200 GHz. Therefore, several activities are ongoing at KIT for the preparation of tests. Those activities include simulations regarding the changed field profile and the changed geometrical dimensions of the new SC magnet and also the upgrade of the frequency diagnostic systems.

A 170/204 GHz dual-frequency coaxial-cavity pre-prototype gyrotron has already been designed for a specific magnetic field profile by an external supplier in the past. However, this magnet did not fulfill the specifications and was not accepted by KIT. Therefore, an analysis is ongoing to modify this gyrotron design to fit into the new 10.5 T SC magnet. The new distance from the emitter to the center of the cavity midsection is 430 mm and is thus 30 mm longer than before. This requires a corresponding extension of the gyrotron. In particular, the electron beam parameters of the magnetron injection gun (MIG) are affected by the changed magnetic field profile of the new magnet. Therefore, three different MIGs, which are available at KIT, are validated with the in-house code ESRAY [4]. Those are the coaxial triode MIG (cMIG) [5], the inverse MIG (iMIG) [6] and the coaxial diode MIG (dMIG) [7]. It needs to be assessed whether the available MIGs will provide the required beam quality or need to be modified. Initial simulations show that the cMIG does not need any modification besides the elongation of the gyrotron. In contrast, the iMIG needs a modification. The initial radius of the beam tunnel and also the radius of the modulation anode has to be increased to provide a pitch factor of 1.3 with a transverse velocity spread < 2 %. The dMIG is less flexible than the other available MIGs because of its diode configuration. Therefore, a co-rotating mode at 204 GHz ($TE_{40,23}$) and a counter-rotating mode at 170 GHz ($TE_{-34,19}$) is required to provide proper electron beam quality. The resulting electron beam parameters have been included into initial interaction simulations performed with EURIDICE [8]. They show a theoretical RF power level of ≥ 2 MW at the end of the cavity with an interaction efficiency of ≥ 35 % at 170 GHz and 204 GHz, respectively. The new designed and manufactured quasi-optical output coupler provides a Gaussian mode content of > 96 % at the window plane at both operating frequencies [9]. In 2024, final simulations are ongoing and the required gyrotron components are manufactured. After delivery of the 10.5 T SC magnet, the gyrotron will be installed and verified.

III. Identification of an Improved Mode Series for Operation at 136/170/204 GHz

The aforementioned mode series is based on the $TE_{34,19}$ mode operating at 170 GHz, which was not selected for multi-frequency operation in the past. The resulting mode series has a total deviation of the caustic radii that is at the upper limit to ensure a proper operation of the quasi-optical output system. Therefore, a study about an alternative mode series is ongoing, which is divided into two categories. First, identify a mode series that meets the today's gyrotron requirements and second, take into account a modified loading constraint due to anticipated progress in cavity cooling technology.

A. Mode Series Considering Raschig Rings Cavity Cooling

In this section, an alternative mode series is identified considering a maximum Ohmic cavity loading of 2.0 kW/cm^2. Several possible mode series were identified, which satisfy the requirements. The most promising mode series contains the $TE_{24,17}$ mode at 136 GHz, the $TE_{30,21}$ mode at 170 GHz and the $TE_{36,25}$ mode at 204 GHz. Alternatively, the mode series considering the $TE_{28,16}$ mode at 136 GHz, the $TE_{35,20}$ mode at 170 GHz and the $TE_{42,24}$ mode at 204 GHz. In comparison, the benefit of those mode series are reduced deviations of the caustic radii below 1 %. This guarantees a proper operation of the quasi-optical output coupler. Initial interaction simulations provide an RF output power of ≥ 2 MW and an interaction efficiency ≥ 35 % at all three frequencies.

B. Mode Series with Improved Cavity Cooling Technology

Anticipated progress in the cavity cooling system using e.g. mini-channel cooling could allow exceeding the wall loading constraint to around 2.5 kW/cm^2. Therefore, either gyrotrons with increased output power or more compact designs can be targeted. In terms of limited power capability of the output windows, a more compact design with reduced cavity mode eigenvalue is foreseen. This leads to increased mode stability and a less dense mode spectrum. The favored mode series contains the $TE_{28,13}$ mode at 136 GHz, the $TE_{35,16}$ mode at 170 GHz and the $TE_{42,19}$ mode at 204 GHz. Some key parameters are summarized in Table 1. This mode series shows a variation of the caustic radii of only 0.35 %. The corresponding electron beam radius is close to 10.28 mm and is almost identical to the 10.00 mm of the existing mode series. This implies that the existing MIGs can be reused without modification. In addition, the calculated radius of the inner conductor is 8.2 mm, which is almost identical to the existing one. Further, it has a proper thickness to guarantee mechanical stability. Interaction simulations show an RF output power of ≥ 2 MW and an interaction efficiency ≥ 35 % at all three frequencies. In conclusion, this mode series is a possible candidate for future EU-DEMO-relevant coaxial-cavity gyrotrons. In terms of the similar electron beam parameters, this mode series can be verified using the existing coaxial-cavity short-pulse gyrotron housing with a replaced coaxial cavity and a new quasi-optical output coupler.

TABLE I
KEY PARAMETERS OF THE MODE SERIES CONSIDERING ANTICIPATED PROGRESS IN CAVITY COOLING.

Modes	$TE_{28,13}$	$TE_{35,16}$	$TE_{42,19}$
Rel. caustic radius	0.3621	0.3628	0.3634
Deviation / %	+0.21	0	-0.14
Eigenvalue	77.3	96.46	115.59
Beam radius / mm	10.33	10.28	10.25

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