Operating the KIT 170 GHz 2 MW Coaxial-Cavity Gyrotron at 204 GHz: Performance Expectations and First Cold Test of the Quasi-Optical System

Tobias Ruess[1], Konstantinos A. Avramidis[1], Gerd Gantenbein[1], Zisis Ioannidis[1], Stefan Illy[1], Jianbo Jin[1], Felix C. Lutz[1], Ioannis Gr. Pagonakis[1], Sebastian Ruess[1,2], Tomasz Rzesnicki[1], Manfred Thumm[1,2], Dietmar Wagner[3], and John Jelonnek[1,2]
[1]Institute for Pulsed Power and Microwave Technology (IHM),
[2]Institute of Radiofrequency Engineering and Electronics (IHE),
Karlsruhe Institute of Technology (KIT),
Karlsruhe Germany,
[3]Institute for Plasma Physics (IPP)
Max-Planck-Association
Garching, Germany
E-Mail: tobias.ruess@kit.edu

***Abstract*—The KIT 170 GHz $TE_{34,19}$-mode coaxial-cavity gyrotron has been studied for an upgrade towards a dual- or even triple frequency operation at 170/204/(238) GHz. For this reason, the electron magnetron injection gun (MIG), the cavity and the launcher are simulated for operation with the $TE_{40,23}$-mode and $TE_{48,26}$-mode at 204 GHz and 238 GHz, respectively. A modification of the coaxial-cavity midsection length leads to an increase of the theoretical RF output power from 1.6 MW to around 2.1 MW at 204 GHz. Further, first experimental cold tests using a mode generator setup, show a successful excitation of the $TE_{40,23}$-mode, which is the highest-order mode ever excited.**

Keywords—multi-frequency, gyrotron, mode generator setup, fusion, coaxial-cavity, high-order mode

I. Introduction

A DEMO (Demonstration Fusion Power Plant) [1,2] requires megawatt-level gyrotrons for electron cyclotron resonance heating and current drive (ECRH&CD) for plasma heating and stabilization. It is beneficial if these gyrotrons operate at multiple frequencies. A possible frequency series considered in EU [3] is given by 170, 204 and 238 GHz which is determined by the thickness of a 1.85 mm thick chemical vapor deposition (CVD) diamond window disk. Recently, the KIT 170 GHz $TE_{34,19}$-mode coaxial-cavity pre-prototype, which delivers an RF output power of more than 2 MW in short-pulse operation [4], has been modified towards longer-pulse operation of up to 100 ms, in a first step [5]. In parallel, the modular short-pulse coaxial-cavity pre-prototype is being upgraded towards dual- or even triple frequency operation [6]. The design of this multi-frequency gyrotron is on the basis of the existing $TE_{34,19}$-mode coaxial-cavity gyrotron. The suitable modes are $TE_{34,19}$, $TE_{40,23}$ and $TE_{48,26}$ operating at 170, 204.1 and 237.3 GHz, respectively. Herein, the focus is mainly on a dual-frequency operation at 170/204 GHz. The magnetic field strength for an operation at 204 GHz is 8.23 T and 9.6 T for 238 GHz. These fields can be realized with a new 10.5 SC magnet procured by Tesla Engineering Ltd., Storrington, UK within the new KIT gyrotron test stand FULGOR [7].

This work has been partly carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Comission. Part of the simulations were performed on the EUROfusion High Performance Computer (Marconi-Fusion).

II. Modification Steps Towards A Dual-/ Triple-Frequency Operation

The existing demountable 2 MW coaxial-cavity gyrotron operating at 170 GHz will be upgraded towards a multi-frequency gyrotron. Therefore, the existing magnetron injection guns (MIGs), the coaxial-cavity and the launcher of the quasi-optical output coupler are simulated finding a configuration for a proper operation at 170 and 204 GHz.

A. Start-up simulations

First of all, the start-up scenario of the two existing guns, namely the inverse magnetron injection gun (IMIG) [8] and the new coaxial MIG with non-emissive coating of the emitter edges [9], are simulated using the magnetic field distribution of the future 10.5 T SC Tesla Engineering Ltd. magnet employing the ARIADNE code [10]. A reduction of the pitch factor (nominal α = 1.3 at 170 GHz) to α = 1.23 leads to a more stable operation at 204 GHz. The corresponding alpha spread has been simulated to be $\Delta\alpha$ = 5.4 % for the coaxial MIG with the edge-coated emitter and $\Delta\alpha$ = 7.1 % for the IMIG.

After the theoretical verification if the existing MIGs can operate at 204 GHz, the calculated parameters are used for a start-up scenario in the cavity using the EURIDICE code [11]. Simulations show, that a shortening of the cavity midsection length increases the mode stability of the nominal $TE_{40,23}$-mode and in addition, increases the RF output power. Therefore, the total length of the midsection is reduced to $\approx 9\lambda_{0,\ 204\ \mathrm{GHz}}$. The result of the start-up scenario simulation including 72 competing modes is shown in Fig. 1 for the IMIG. The nominal operation point is at a beam energy of 86.4 keV and is limited due to the maximum tolerable cavity loading of 2 kW/cm^2, which is highlighted with the horizontal line. The simulated RF output power of the tube is predicted to be 2.08 MW with the IMIG and 2.1 MW using the coaxial MIG with edge-coated emitter.

B. Launcher design

The existing mirror-line launcher shows a Gaussian mode content of 96.6/91.6 % at 170/204 GHz, respectively, using the TWLDO code [12]. A study has been started to design a new launcher for a proper operation at both frequencies (> 95 %). The latest simulation obtained a design providing a Gaussian mode content of 97.2/96.6 % at 170/204 GHz, respectively. The operation at 240 GHz is currently being checked.

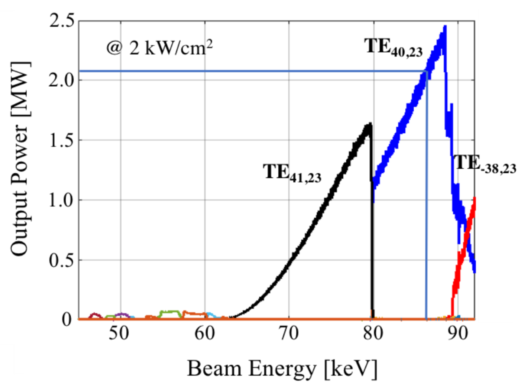

Fig. 1. Start-up scenario with the modified cavity length at 8.23 T and I_{beam} = 68 A without non-linear uptaper using the magnetic field distribution of the future 10.5 T SC magnet and the IMIG with a pitch factor of α = 1.23 at the beam energy of 86.4 keV.

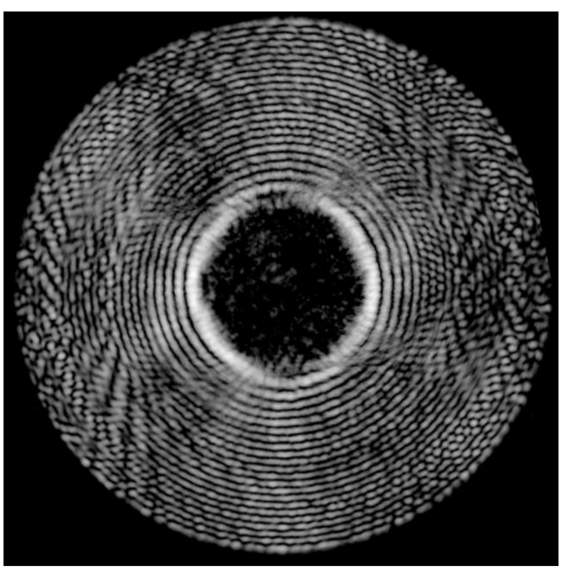

Fig. 2. Measured field intensity pattern of the $TE_{40,23}$ mode operating at 203.92 GHz using a quasi-optical mode generator setup and is limited to a amplitude scale of 21 dB.

III. EXCITATION OF THE $TE_{40,23}$-MODE

First experimental cold tests have been performed in order to excite the rotating $TE_{40,23}$-mode using a quasi-optical mode generator setup [13]. This mode is the highest-order mode which is ever excited in a cold test setup. A mode generator cavity has been designed using a scattering-matrix code [14]. The field intensity pattern in Fig. 2 was measured using the measurement setup presented in [15]. The receiving antenna was an open-ended TE_{10} mode rectangular WR6 waveguide horn antenna. Therefore, always only one polarization part (here horizontal) of the E-field can be detected. This leads to a slightly blurred image in the diagonal areas of the measured mode pattern. The optimal operating frequency of the cavity is 203.92 GHz and the counter-rotating mode content of the pattern in Fig. 2 is approximately 0.8 %. First measurements with the quasi-optical system will be performed soon.

REFERENCES

[1] G. Federici *et al.*, "DEMO design activity in Europe: Progress and updates," *Fus. Eng. Des.*, vol. 126, pp. 729-741, 2018, DOI: http://doi.org/10.1016/j.fusengdes.2018.04.001.

[2] H. Zohm *et al*., "A stepladder approach to a tokamak fusion power plant", *Nucl. Fusion* vol. 57, p. 086002, 2017.

[3] S. Garavaglia et al., "EU DEMO EC System preliminary conceptual design," *Fus. Eng. Des.*, vol. 136, pp. 1173–1177, May 2018, https://doi.org/10.1016/j.fusengdes.2018.04.097.

[4] T. Rzesnicki *et al.*, "2.2-MW record power of the 170-GHz European preprototype coaxial-cavity gyrotron for ITER," in *IEEE Transactions on Plasma Science*, vol. 38, no. 6, pp. 1141-1149, June 2010.

[5] S. Ruess *et al*., "KIT coaxial gyrotron development: From ITER toward DEMO", *International Journal of Microwave and Wireless Technologies*, vol. 10, pp. 547-555, July 2018, https://doi.org/10.1017/S1759078718000144.

[6] T. Ruess, *et al.*, "Theoretical study on the operation of the EU/KIT TE34,19-mode coaxial-cavity gyrotron at 170/204/238 GHz", *EPJ Web Conf*, in press.

[7] M. Schmied, *et al.*, "The 10 MW EPSM modulator and other key components for the KIT gyrotron test facility FULGOR", *Fus. Eng. Des.*, 123, 485, 2017.

[8] S. Ruess *et al*., "An Inverse Magnetron Injection Gun for the KIT 2-MW Coaxial-Cavity Gyrotron," in *IEEE Transactions on Electron Devices*, vol. 63, no. 5, pp. 2104-2109, May 2016.

[9] I. G. Pagonakis *et al*., "Design and experimental verification of the new magnetron injection gun of the 2 MW 170 GHz coaxial cavity gyrotron", to be subitted to *IEEE Transaactions on Electron Devices.*

[10] I. G. Pagonakis and J. L. Vomvoridis, "The self-consistent 3D trajectory electrostatic code ARIADNE for gyrotron beam tunnel simulation," *Infrared and Millimeter Waves, Conference Digest of the 2004 Joint 29th International Conference on 2004 and 12th International Conference on Terahertz Electronics, 2004.*, Karlsruhe, Germany, 2004, pp. 657-658.

[11] K.A. Avramides, *et al.*, "EURIDICE: a code-package for gyrotron interaction simulations and cavity design", in: 17th Joint Workshop on Electron CyclotronEmission and Electron Cyclotron Resonance Heating (EC-17), EPJ Web of Conferences, vol. 32, 2012.

[12] J. Jin, *et al.*, "High-efficiency quasi-optical mode converter for a 1-MW $TE_{32,9}$-mode gyrotron," in *IEEE Transactions on Plasma Science*, vol. 41, no. 10, pp. 2748-2753, Oct. 2013.

[13] N. L. Alexandrov, *et al*., "Low-power excitation of gyrotron-type modes in a cylindrical waveguide using quasi-optical techniques", *Int. Journal of Electronics*, 79, pP. 215-216, 1995.

[14] D. Wagner, J. Pretterebner, M. Thumm., "Design of coaxial gyrotron cavities using a scattering matrix code", *5th Joint Russian-German Meeting on ECRH and Gyrotrons*, pp. 555-565, 1993.

[15] T. Ruess *et al.*,"Computer-controlled test system for the excitation of very high order modes in highly oversized waveguides", to be submitted J. Infrared Milli Terahz Waves (2018).