Theoretical Study on the Possibility for Stepwise Tuning of the Frequency of the KIT 2 MW 170/204 GHz Coaxial-Cavity Gyrotron

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***Abstract*—A first theoretical study on the possibility for stepwise frequency tuning of a dual-frequency 170/204 GHz $TE_{34,19}/TE_{40,23}$-mode coaxial-cavity gyortron pre-prototype, under development at KIT, has been done. A bandwidth of ± 10 GHz around both center frequencies has been considered as tuning range. For each of the two bands, in total 11 modes have been selected to cover the entire frequency range. The theoretical study has shown that just changing the azimuthal index of the operating mode to obtain an appropriate mode series for frequency step-tunability is insufficient because the insert loading constraint is not fulfilled. A new mode series has been found, where the insert loading constraint is obeyed.**

I. INTRODUCTION

THE baseline of the European DEMO (DEMOnstration Fusion Power Plant) [1] considers gyrotrons with 2 MW RF output power for Electron Cyclotron Resonance Heating and Current Drive (ECRH&CD). Gyrotron operation at either the center frequency of 170 GHz or 204 GHz has to be considered. At both center frequencies, a stepwise tuning in steps of 2 - 3 GHz in the range of ± 10 GHz is also desired for frequency steering of the RF beam to facilitate suppression of possible instabilities in the plasma.

Currently, at KIT, a 170/204 GHz dual-frequency pre-prototype gyrotron is under development. It bases on the existing 170 GHz 2 MW coaxial-cavity short-pulse pre-prototype gyrotron [2]. The target is to verify the basic possibility for frequency step-tuning and the final performance around its center frequencies of 170 GHz ($TE_{34,19}$-cavity mode) and 204 GHz ($TE_{40,23}$-cavity mode). In general, there are several methods for tuning the frequency of a gyrotron [3]. However, only tuning by the magnetic field and switching to different cavity modes ensures a tuning range in a large frequency band of ± 10 GHz [4].

II. STUDY ON FREQUENCY-STEP-TUNABILITY OF THE COAXIAL-CAVITY GYROTRON

There are three criteria, which the selected cavity mode series should fulfill to ensure a stepwise tuning of the frequency. That are: (i) the mode eigenvalues have to correspond to the frequencies of the desired band at a given cavity radius, (ii) a strong coupling of the modes to the electron beam has to be secured and, (iii) for good operation of the same quasi-optical launcher the modes should have similar caustic radii $m/\chi_{m,n}$, where m is the azimuthal index, and $\chi_{m,n}$ is the mode eigenvalue. In addition, in case of a coaxial-cavity gyrotron the insert loading of the coaxial insert should be taken into account during the mode selection process.

Considering criterion (i), a mode series with equidistant frequency steps of ~2.1 GHz can be obtained by keeping the radial index constant and changing only the azimuthal index [5]. The identified mode series around the center $TE_{40,23}$-mode at 204.15 GHz starts with the $TE_{45,23}$-mode operating at

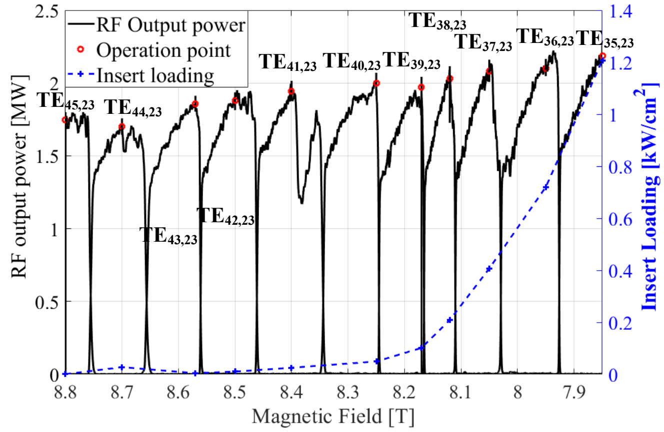

Fig. 1. Simulation of stepwise tuning from high to low frequency by changing the magnetic field and the beam radius to cover a bandwidth of ± 10 GHz around the center frequency of 204.15 GHz of the $TE_{40,23}$-mode. The mode series is keeping the same radial index.

214.7 GHz down to the $TE_{35,23}$-mode at 193.6 GHz. For the $TE_{34,19}$-mode, which is the center mode at 170 GHz, the possible mode series starts with the $TE_{39,19}$-mode operating at 180.6 GHz down to the $TE_{29,19}$-mode at 159.5 GHz. Simulations with the in-house code package EURIDICE [6] were performed to check the performance of the chosen mode series. In the first step a frequency tuning from high to low frequencies were performed. This tuning can be done by reducing the magnetic field, and in parallel modifying the beam radius for the corresponding mode to increase the coupling between the electron beam and the mode. An example of simulation results are shown in Fig. 1, for the higher frequency band around 204 GHz. The dots highlight the operation point of each mode. The operation parameters are optimized for each mode where the maximum allowed wall loading of 2 kW/cm^2 is always fulfilled. The RF output power is in the range of 1.7 MW up to

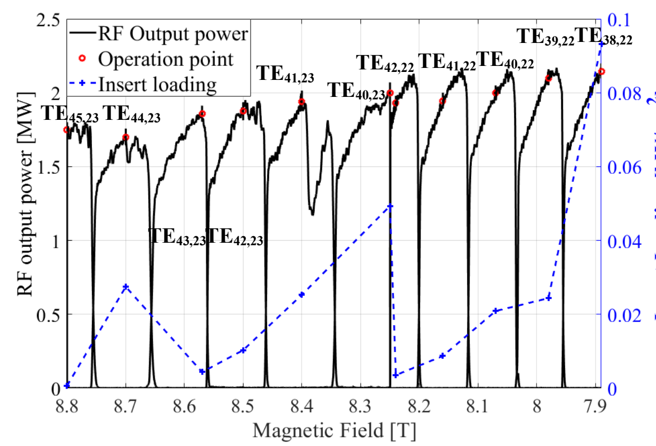

Fig. 2. Simulation of stepwise tuning using a modified modes series from high to low frequencies by changing the magnetic field and the beam radius to cover a bandwidth of ± 10 GHz around the center frequency of 204.15 GHz ($TE_{40,23}$).

Tab I. Summary of the operation parameters and simulation results of the modified mode series for frequency tuning in a range of ± 10 GHz around the center frequency of 204 GHz.

Mode	$TE_{45,23}$	$TE_{44,23}$	$TE_{43,23}$	$TE_{42,23}$	$TE_{41,23}$	$TE_{40,23}$	$TE_{42,22}$	$TE_{41,22}$	$TE_{40,22}$	$TE_{39,22}$	$TE_{38,22}$
Relative caustic radii	0.338	0.334	0.33	0.326	0.329	0.317	0.334	0.329	0.325	0.32	0.307
Frequency [GHz]	214.7	212.6	210.5	208.4	206.3	204.2	203.0	200.9	198.8	196.7	194.6
Beam energy [keV]	95.0	93.5	92.4	93.9	92.5	89.5	90	90.6	90.7	91.5	91.8
Beam current [A]	68	68	68	68	68	68	68	68	68	68	68
Magnetic field [T]	8.80	8.70	8.57	8.50	8.40	8.25	8.24	8.16	8.07	7.98	7.89
Velocity ratio,	1.10	1.10	1.11	1.11	1.20	1.24	1.25	1.25	1.25	1.25	1.25
Beam radius [mm]	10.65	10.50	10.24	10.10	10.00	9.85	10.35	10.24	10.13	9.98	9.85
Wall loading [kW/cm^2]	2.00	1.96	1.98	1.95	2.00	2.00	2.00	1.98	2.00	2.00	2.00
Insert loading [kW/cm^2]	0.001	0.02	0.004	0.01	0.025	0.05	0.003	0.008	0.021	0.045	0.09
RF output power [MW]	1.73	1.70	1.85	1.87	1.92	2.03	1.94	1.96	2.02	2.10	2.13
Interaction eff. [%]	28.1	28.0	30.5	30.0	31.7	34.2	32.6	32.5	33.3	34.8	34.3

2.2 MW. The dotted line indicates the insert loading of the given modes. The resulting insert loadings are in the range of 0.06 – 1.2 kW/cm^2. The maximum tolerable limit of the insert loading is 0.39 kW/cm^2 as stated in [7], which is exceeded starting with the $TE_{37,23}$-mode at 0.42 kW/cm^2. This implies a reduction of the possible step tuning range from 20 GHz to 16.3 GHz. In addition to the high insert loading, the maximum deviation of the relative caustic radius is about 7.8 % of the mean value and so criterion (iii) is not well satisfied. This high deviation of the caustic radii does not ensure a proper operation of the quasi-optical system. In general, the case is even worse for the lower frequency band around 170 GHz, where frequency tuning is only possible in a bandwidth of 10 GHz from 170-180 GHz due to the increased insert loading. Therefore, at both frequency bands, a mode series with constant radial index, where the caustic radius changing monotonically, is not optimal for frequency tuning. Consequently, for the tuning towards lower frequencies, a change of the radial index within the mode series is required. A possible candidate for the jump after the $TE_{40,23}$-mode is the $TE_{42,22}$-mode operating at 203 GHz. This mode satisfies criteria (i) and (ii), and the insert loading constraint. Criterion (iii) has to be checked in the future. In conclusion, the revised mode series around 204 GHz starts with the $TE_{45,23}$-mode and jumps after the $TE_{40,23}$-mode to the $TE_{42,22}$-mode (frequency step of only 1 GHz), where again azimuthally neighboring modes in steps of ~2.1 GHz down to the $TE_{38,22}$-mode at 194.5 GHz are considered. Using this approach the insert loading can be limited to 0.1 kW/cm^2 and also criterion (iii) is more relaxed, because of a reduced caustic radius deviation. A simulation using the modified mode series is shown in Fig. 2. A stepwise frequency tuning starting from 214.7 GHz down to 194.5 GHz is possible with the modified mode series. The operation frequencies are shown in Fig. 3, where the initial (dotted) and the modified mode series (dashed) are shown. The modified mode series has a 0.9 GHz smaller bandwidth, but still fulfills the required bandwidth of 20 GHz.

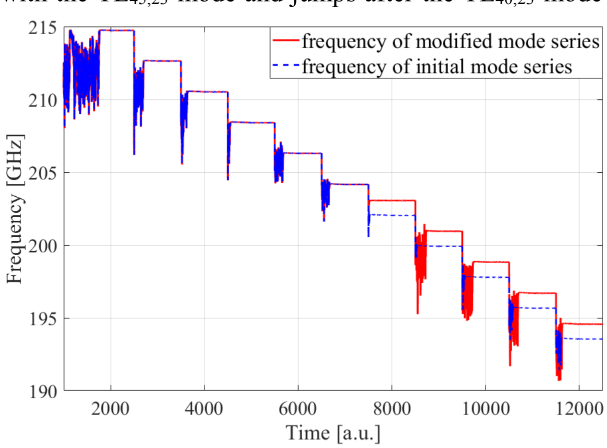

Fig. 3. Frequencies of the magnetic tuned coaxial-cavity pre-prototype gyrotron for the initial (dotted) and modified (dashed) mode series.

In case of the lower frequency band around 170 GHz, the mode series is modified, as well. A jump from the $TE_{34,19}$-mode to the $TE_{36,18}$-mode instead to the $TE_{33,19}$-mode reduces the insert loading and a frequency tuning of ± 10 GHz is theoretically possible.

Continuous magnetic field tuning is an effective method for frequency step-tuning from high to low frequency. However, this method cannot be used for tuning from low to high frequency due to hysteresis effects [8]. In this case, an alternative method must be considered in which the gyrotron is switched off and then started up using the accelerating voltage.

ACKNOWLEDGEMENT

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research 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 Commission. Part of the simulations was performed on the EUROfusion High Performance Computer (Marconi-Fusion).

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