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Theoretical Study on the Operation of the EU/KIT $TE_{34,19}$-Mode Coaxial-Cavity Gyrotron at 170/204/238 GHz

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Abstract. The 170 GHz 2 MW short-pulse modular coaxial-cavity pre-prototype gyrotron ($TE_{34,19}$-mode) was recently modified in order to verify the multi-megawatt coaxial-cavity technology at longer pulses. In parallel, theoretical investigations on a possibility to operate this gyrotron at multiple frequencies up to 238 GHz are started, with the goal to find a configuration in which the tube could operate in the KIT FULGOR gyrotron test facility using a new 10.5 T SC magnet. This paper investigates which adjustments have to be taken into account and show the feasibility of the multi-frequency operation. Small modifications of the cavity allow an RF output power of more than 2 MW at 170 and 204 GHz. Further, a new launcher of the quasi-optical output coupler is designed having a Gaussian mode content of more than 96% at these frequencies.

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1 Introduction

Gyrotrons are RF microwave sources used for fusion plasma applications. These vacuum tubes are the only sources for electron cyclotron resonance heating and current drive (ECRH&CD) in nuclear fusion devices and for plasma stabilization. An example is the stellarator Wendelstein 7-X (W7-X) in Greifswald, Germany, where ten 1 MW gyrotrons operating at 140 GHz and at 1 MW (1800s) are operating and demonstrate an excellent reliable performance [1]. An actual fusion plant project under construction is placed in Caderache, France and is called ITER [2]. After ITER, the first fusion power plant is planned called DEMO [3], which is intended to generate net electricity. Fusion gyrotrons for DEMO and future FPP (**F**usion **P**ower **P**lants) will require multi-megawatt continuous-wave (CW) operation at multiple frequencies starting from 170 GHz up to significantly above 200 GHz. The conceptual design of EU DEMO is ongoing within the Horizon 2020 EUROfusion program.

The EU ITER gyrotron has been designed in the conventional hollow-cavity technology [4]. These technology provides a quite a good performance and a reliable operation even at frequencies above 200 GHz, as design studies show in [5]. However, there are two main issues regarding such hollow-cavity gyrotrons: (i) increasing mode competition with raising mode order, which can be a problem at the operation above 200 GHz and (ii) voltage depression caused by space charge effect of the electron beam. Overcoming these issues, a gyrotron using an insert (coaxial-cavity) can be used. The coaxial-cavity reduces mode competition and voltage depression [6,7]. The first KIT modular coaxial-cavity pre-prototype gyrotron has demonstrated an RF output power of more than 2 MW at 170 GHz in short-pulse operation [8,9]. The operating parameters are summarized in Tab. 1. Forwarding this technology, the pre-prototype has been upgraded towards longer-pulse operation of 100 ms, and in next stage up to 1 s. Reaching the condition for future DEMO gyrotrons, multi-frequency operation at two or three selected frequencies among the set 136 GHz, 170 GHz, 204 GHz, or 238 GHz is required. The aim of this work is given by a study if the operation at these frequencies is possible with the existing coaxial-cavity pre-prototype in the KIT FULGOR gyrotron test facility [10] using the new 10.5 T SC magnet, without a major effort on development of new components.

This paper is structured in the following way: Firstly, an overview on the mode selection for the possibility of multi-frequency operation is presented. Initial studies regarding multi-frequency operation using the available

Table 1. Design Parameters for the Coaxial-Cavity Gyrotron [8].

Oxford Instruments are targeted with the knowledge that this magnet cannot provide the necessary magnet field strength. Further, a study about the geometrical issues regarding the new configuration of the 10.5 T SC magnet from Tesla is started. Taken this into account realistic start-up scenarios are simulated under consideration of for the new coil configuration of the Tesla magnet and real gun parameters. Comparisons are made between the results considering the cavity with and without non-linear uptaper. Additionally, a modification of the coaxial-cavity is made to increase the performance. In the last section the behaviour of the existing launcher is investigated.

2 Mode Selection Scheme for Multi-Frequency Operation

The investigations are based on the existing coaxial-cavity design of the KIT pre-prototype. This cavity has a total length of 68 mm and a midsection length of 16 mm. This corresponds to ~9·λ_{170GHz} where λ_{170GHz} denotes the free-space wavelength at 170 GHz. The possible previous mentioned operating frequencies should correspond to the natural resonances of the synthetic diamond output window using:

Operating mode	$TE_{34,19}$
Frequency, f	170 GHz
RF output power, P_{out}	2 MW
Beam current, I_B	75 A
Accelerating voltage, U_C	90 kV
Velocity ratio (pitch factor), α	~ 1.3
Cavity magnetic field, B_{cav}	6.87 T
Outer cavity radius, R_{cav}	29.55 mm

$$f_{op} = (N \cdot c_0) / (2 \cdot d_{window} \cdot \varepsilon_r^{1/2}), \quad N \in \mathbb{N} \quad (1)$$

where c_0 is the speed of light, d_{window} is the thickness of the window disc and $\varepsilon_r = 5.67$ is the permittivity of the window material (e.g. CVD). Window matching is the first condition for multi-frequency operation. The second condition is given by the launcher performance. Possible modes for multi-frequency operation should exhibit a maximum deviation of the caustic radius R_C of <3-4%, where the caustic radius is determined by:

$$R_C = m \cdot R_o / \chi_{m,n} \ , \quad (2)$$

here R_o is the cavity radius and $\chi_{m,n}$ the mode which is given by the nth root of the characteristic equation [6].

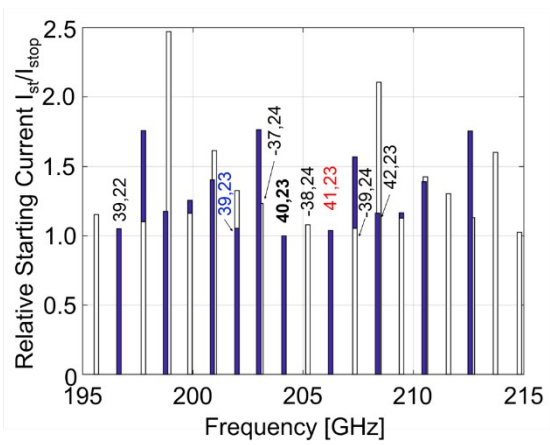

Fig. 1. Relative starting current of competing modes at 8.15 T and I_{beam} = 70 A (filled bars: co-rotating; empty bars: counter rotating modes) [11].

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This condition enables the usage of the existing, or at least of a similar, quasi-optical system. The modes obtained in this way are the $TE_{40,23}$-mode operating at 204 GHz and the modes $TE_{48,26}$- and $TE_{46,27}$-mode operating at 237 GHz and 238 GHz, respectively, by comparing with the caustic radius of the $TE_{34,19}$-mode design, operating at 170 GHz. Table 2 summarizes the properties in terms of window reflection and caustic radius of the chosen modes. The $TE_{40,23}$-mode ($\chi = 126.3$) shows a frequency close to the natural resonance frequency of the diamond window, which results in a very low window reflection. But the difference in caustic radius is 2.01 % and it has to be checked if the operation of the existing launcher and mirror system is still acceptable for this mode. The operation at ~240 GHz can be realised with two possible modes. One of them ($TE_{48,26}$, $\chi = 146.8$) exhibits a relatively high window reflection, whereas the other ($TE_{46,27}$, $\chi = 147.5$) has a high difference of the caustic radius. The simulation results have been quite similar. This means that the mode selection for operation at

~240 GHz should be made after calculating the behaviour of the launcher and mirror system. In the following, results only for the mode $TE_{48,26}$ are reported here.

3 Multi-Frequency Simulations using the existing Oxford Instruments Magnet

In initial studies the KIT pre-prototype cavity, without the non-linear uptaper was considered [11]. The magnetic field profile of the existing 7 T Oxford Instruments superconductive (SC) magnet was used as a typical profile. It should be mentioned, however, that the existing magnet cannot deliver the needed magnetic field strength for frequencies above 170 GHz. The appropriate super-conducting magnet is under procurement and is expected to be delivered by mid-2019 by Tesla (Cf. Section 5). The beam-wave interaction in the cavity for operation at 170/204/238 GHz was simulated using EURIDICE [12]. In order to be as realistic as possible at this initial stage of investigations, the simulations are done assuming a kinetic energy spread of $\Delta E = 0.2$ % rms and a relatively large spread of $\Delta\alpha = 20$ % rms for the electron velocity ratio α.

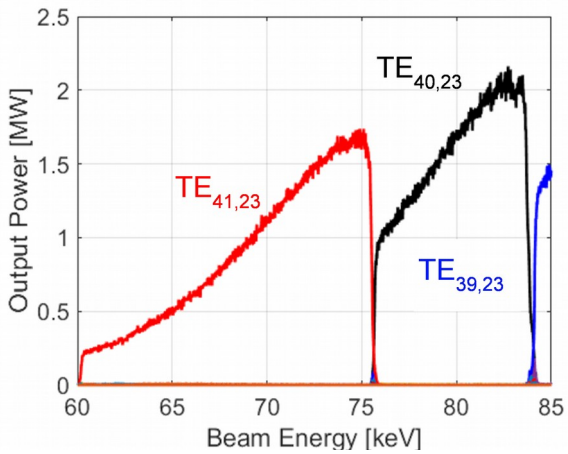

Fig. 2. Adiabatic start-up scenario with the existing coaxial cavity at 8.15 T and $I_{beam} = 70$ A.

The adiabatic start-up scenario was simulated for this setup at 204 and 238 GHz by linearly raising the accelerating voltage. The most important competing modes at 204 GHz are shown in Fig. 2. The simulation results including 72 competing modes and a magnetic field of 8.15 T is shown in Fig. 1.

In the simulations a lower velocity ratio $\alpha = 1.2$ instead of $\alpha = 1.3$ was used to reduce the risk of unwanted parasitic oscillations, especially at frequencies above 200 GHz. The simulation shows a good scenario starting with the $TE_{41,23}$-mode. Mode competition takes place at 75.5 keV and the nominal $TE_{40,23}$-mode becomes dominant. In this case the operating point is defined by the ohmic loading constraints. These constraints permit an insert wall loading of ≤ 0.2 kW/cm^2 and a cavity wall loading of ≤ 2 kW/cm^2. The maximum cavity loading defines the operating parameters of $U_{beam} = 80.7$ keV and $I_{beam} = 70$ A. A cavity RF output power of 1.8 MW at an interaction efficiency of 33 % is obtained at this point. The frequency is 204.14 GHz. The insert wall loading

Table 2. Mode Selection for Multi-Frequency Operation.

Mode	$TE_{34,19}$	$TE_{40,23}$	$TE_{48,26}$	$TE_{46,27}$
Frequency [GHz]	170	204.179	237.242	238.351
Window reflection [%]	0	0.026	0.472	0.101
Rel. caustic radius	0.3232	0.3167	0.3270	0.3119
Diff. in caustic radius [%]	0	2.01	1.18	3.62

amounts to 0.065 kW/cm^2 and is far below the limit. In order to improve the performance at higher frequencies, the midsection length of the coaxial-cavity was reduced to ~ $9\lambda_{204\,GHz}$ (13.6 mm) as a first proposed modification. Reducing the midsection length leads to lower quality factor and thus the wall loading is decreased as well. Hence, the operating parameters of the beam voltage, beam current, and magnetic field can be further increased without violating the maximum allowable wall loading. As a result, the RF output power was also increased. In this case, the operation parameters for the operation at 204 GHz are determined to be $U_{beam} = 88$ keV, $I_{beam} = 75$ A, and $B = 8.23$ T. The cavity RF output power was increased to 2.2 MW with an interaction efficiency of 33.4 % [11].

At the next higher frequency (~238 GHz) the number of possible competing modes is increased to 90 modes instead of 72 modes. This effect comes from stronger mode competition due to a denser mode spectrum by raising the frequency. At ~238 GHz mode stability has been a problem, especially at high beam voltages and/or beam currents. The operation parameters have been reduced to $U_{beam} = 60$ keV and $I_{beam} = 60$ A. Therefore, the RF output power with the $TE_{48,26}$ mode drops to 1.04 MW at an interaction efficiency of 30.2 %. One of

the problems operating at higher frequencies with the same cavity is the comparatively long cavity, where electron overbunching can occur. Overcoming this issue, the $TE_{48,26}$-mode at 237 GHz was also simulated with the shorter midsection length of the coaxial-cavity. The shortened midsection plus a reduced pitch factor ($\alpha = 1.1$) leads to stable operation at $U_{beam} = 78$ keV, $I_{beam} = 70$ keV, and $B = 9.45$ T. The cavity wall loading is 1.85 kW/cm^2 at that point. The output power reaches 1.6 MW with an efficiency of 30.4 % [11].

4 Feasibility Study including the Field Profile of the new 10.5 T Tesla Magnet

The theoretical feasibility of operation at higher frequencies is shown in the previous section. In terms of the fact, that the frequency of operation and the magnetic field is proportional to each other, the magnetic field has to be increased for higher frequencies (e.g. 204 GHz leads to ~8.15 T and 238 GHz leads to 9.45 T). The current test stand is limited to the maximum magnetic field strength of ~6.9 T of the existing Oxford Instruments magnet. Therefore, the KIT ordered a new SC magnet including following key features:

- Maximum field at cavity: 10.5 T,
- Warm bore hole diameter: 261 mm,
- Dipole coils,
- Cryogen-free cooling system.

The first question to be solved by using the new magnet is to assess whether the currently operating coaxial gyrotron can be used without any modifications. The new coaxial MIG with non-emissive coated edge emitter which was delivered by Thales Electron Devices is considered for the first tests using ARIADNE [13] and the first proposal of the magnet field configuration from Tesla is implemented, as well. A first indication for a not promising results were given by the calculated gun coil currents of ~±123 A. Using this current, simulations show a huge amount of trapped electrons and/or high alpha spread of around $\Delta\alpha = 40\%$ at the maximal velocity ratio of $\alpha = 1.12$, due to the different length of the new magnet and, therefore, misalignment of the gun. For this reason, the distance between emitter and cavity has to be adjusted to the field profile of the new Tesla magnet. This issue can be solved by e.g. inserting a spacer into the beam tunnel. Further, the insert has to be redesigned, since the insert corrugations are misaligned with the cavity. This adjustment has been taken into account in the following simulations shown in this paper.

5 Fully Realistic Start-Up Scenario

After checking the existing setup of the pre-prototype, simulations using the enlarged beam tunnel are performed. For the first time realistic multi-mode start-up simulations are made concerning the coaxial cavity with the expected magnetic field profile of the Tesla magnet and the gun parameters using the non-emissive coated edge MIG [14] at 170 GHz ($TE_{34,19}$-mode) and 204 GHz ($TE_{40,23}$-mode). Further, the simulation results with and without non-linear uptaper are compared to each other. Additionally, a modification of the cavity has been taken into account for a better performance.

5.1 Realistic simulation results at 170 GHz using the existing coaxial-cavity design

Firstly, ARIADNE simulations using the new magnetic field profile are performed and included in EURIDICE. In this simulation at 170 GHz the alpha spread is determined by $\Delta\alpha = 6.08\%$ for $\alpha = 1.3$ and $\alpha = 1.2$. The energy spread amounts to 0.08% and the gamma spread to ~3%. The realistic start-up scenario at 6.86 T without non-linear uptaper is shown in Fig. 3. For the nominal operation parameters of $U_{beam} = 90$ keV and $I_{beam} = 75$ A, the tube can deliver an RF output power of 2.3 MW at an interaction efficiency of 34.5% and an electronic efficiency (electron kinetic energy conversion) of 35.7%. The insert wall loading is 0.11 kW/cm^2 and the cavity loading is 1.85 kW/cm^2. Keeping the maximum allowable wall loading of 2 kW/cm^2 in mind, the operation point can be adjusted to $U_{beam} = 92$ keV, where simulations offer an RF output power of 2.6 MW at an interaction efficiency of 37.1% and an electronic efficiency of 38.1% without depressed collector.

Initial studies including the non-linear uptaper have been started. Figure 4 presents the start-up scenario using the same parameters as mentioned before for a better comparison. The shown start-up is not that smooth

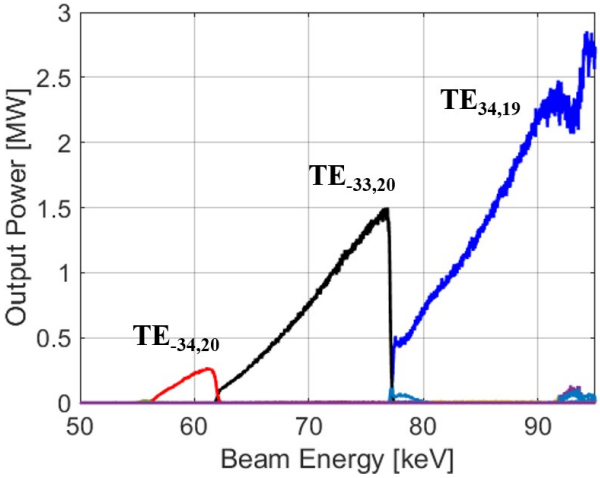

Fig. 4. Realistic start-up scenario with the existing coaxial cavity at 6.86 T and $I_{beam} = 75$ A with non-linear uptaper.

as before, but nevertheless the nominal $TE_{34,19}$-mode is excited well. The wall loading constraint limits the operation to $U_{beam} = 88.5$ keV, due to the effect of increased mode competition. Therefore, the RF output power will decrease towards 2.2 MW at an interaction efficiency of 34% and an insert load of 0.12 kW/cm^2. But competing modes rises at around 80 and 90 keV.

5.2 Realistic simulation results at 204 GHz using the existing coaxial-cavity design

The edge coated gun is simulated via ARIADNE for the operation at 204 GHz using the new magnet for the first time. The gun coil currents were determined by ± 51 A. The gun parameters are selected to give a pitch factor of $\alpha = 1.2$ having an alpha spread of $\Delta\alpha = 4.3\%$ and a gamma spread of ~3%. The simulation shows a goodscenario starting with the $TE_{-40,24}$-mode at ~48 keV in Fig. 5. Starting from 60 keV the $TE_{41,23}$-mode is excited while the nominal $TE_{40,23}$-mode is getting dominant at ~75 keV. Starting from 83 keV the main competing $TE_{-38,23}$-mode, which has nearly the same caustic radius is getting stronger and so the nominal mode collapses. The operation is limited to 79.2 keV due to the wall loading constraint. The tube delivers 1.7 MW RF output power without non-linear uptaper at an interaction efficiency of 31% and an insert loading of 0.06 kW/cm^2. The delivered RF output power is 0.1 MW lower than the results presented in section 3. If the ohmic loading constraint could be relaxed in the future by improving the cooling cavity system, permitting thus up to 2.2 MW RF output power and 35% interaction efficiency.

Initial studies using the non-linear uptaper at 204 GHz are being performed. Figure 6 presents the realistic start-up scenario using the same parameters as mentioned before for comparing the results to each other. The scenario looks pretty similar with and without the non-linear uptaper. The point at which the $TE_{40,23}$-mode collapses is nearly identical as before. Additionally, the $TE_{41,22}$-mode oscillates after the $TE_{40,22}$-mode. The delivered RF output power and the interaction influence are not influenced by the use of the non-linear uptaper.

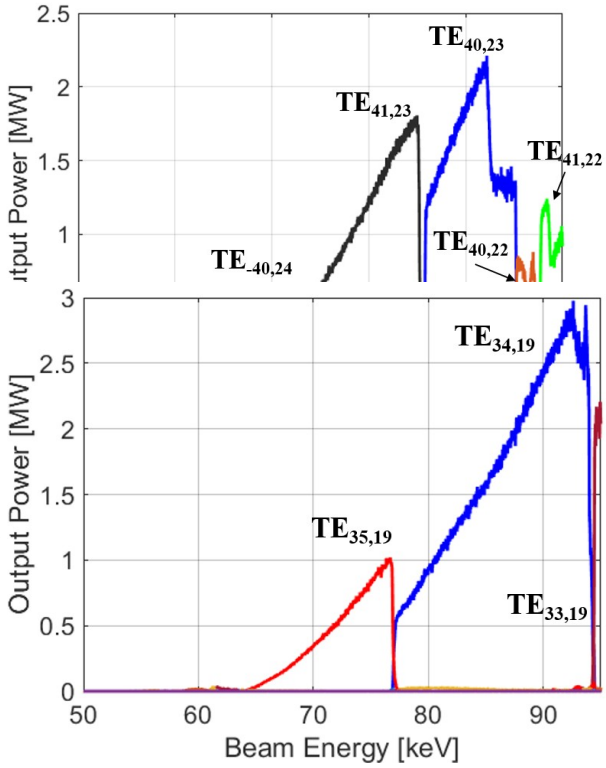

Fig. 7. Realistic start-up scenario with a shortened coaxial cavity length at 6.88 T and $I_{beam} = 75$ A.

5.3 Further modifications

In order to get a dual-frequency gyrotron delivering 2 MW, or even more at both operation frequencies, modifications have to be done. For this reason, the cavity midsection length is reduced from 16 mm, to 13.6 mm, as mentioned in the previous section. The start-up simulation of the shortened cavity for the $TE_{34,19}$-mode case is shown in Fig. 7. Concerning the nominal operation parameters of $U_{beam} = 90$ keV and $I_{beam} = 75$ A, the tube delivers 2.4 MW RF output power at an interaction efficiency of 35.4% having a wall loading of 1.9 kW/cm^2. Compared with the longer cavity the gyrotron can deliver 0.1 MW more RF output power with an increased interaction efficiency of ~1% at this operating point. Concerning the wall loading constraint, the maximum RF output power is determined by 2.5 MW and 37% interaction efficiency, but could be increased in terms of an improved cooling system up to 3 MW and 40% interaction efficiency.

This modification has to be proven for the 204 GHz operation, as well. The simulation shows a good scenario starting with the $TE_{42,23}$-mode, over the $TE_{41,23}$-mode and finally the nominal $TE_{40,23}$-mode is excited till the competing $TE_{-38,23}$-mode raises, shown in Fig. 8. The operation point is found by the wall loading constraint and is determined by $U_{beam} = 86.5$ keV having an RF output power of 2.06 MW at an interaction efficiency of 32.3%. Comparing these results with the existing cavity design, the RF output power can be increased by ~0.4 MW and the interaction efficiency by 1.4%.

6 Multi-Frequency Launcher Design

The operating modes excited in the cavity are converted into the fundamental Gaussian mode using an internal quasi-optical mode converter which contains a mirror-line launcher and three mirrors. The existing single frequency (170 GHz) launcher design is presented in [15]. Helical cooling pipes are milled into the outer wall. The mirror-line launcher is highly tolerant to the fabrication error on the launcher wall contours. Simulation results show that in the case of wall-perturbation uncertainties of up to ± 10 µm, the launcher

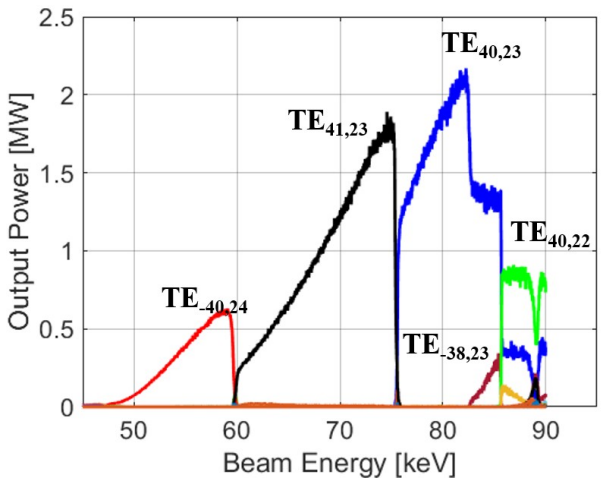

Fig. 5. Realistic start-up scenario with the existing coaxial-cavity at 8.15 T and $I_{beam} = 70$ A without non-linear uptaper.

will still provide a RF beam with high Gaussian mode content. The measurement results at 170 GHz are in a quite good agreement with the simulations. The simulated fundamental Gaussian mode content is 96.3 % at the launcher aperture at 170 GHz [16].

Having a dual frequency scenario, the existing mirror-line launcher with radius of 32.5 mm is tested whether the performance is good enough at 204 GHz. First initial studies at 204 GHz for the $TE_{40,23}$ mode show only a fundamental Gaussian mode content of 91.6% at 204 GHz at the launcher aperture. Therefore, a new launcher was designed with good performance operating at 170 GHz and 204 GHz. The new launcher is also a mirror-line launcher, and the radius is 32 mm. This dual-frequency launcher design shows promising results despite the difference of the modes' caustic radii of around 2%. The Gaussian mode content was calculated to be 97.2 % at 170 GHz and 96.6 % at 204 GHz.

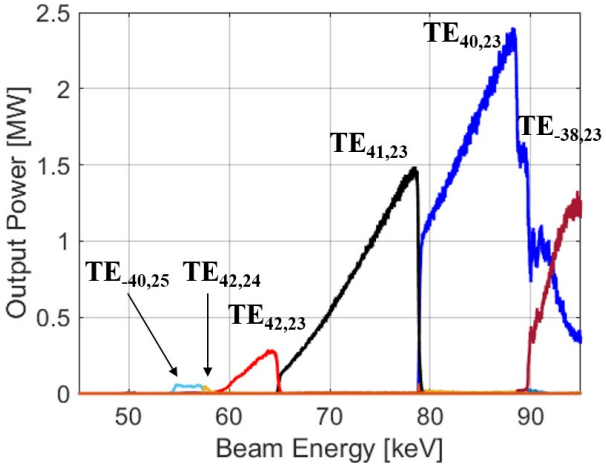

Fig. 8. Realistic start-up scenario with a shortened coaxial cavity length at 8.23 T and $I_{beam} = 75$ A.

Table 3. Summary of the realistic multi-mode simulation results using EURIDICE for the new Tesla magnet configuration (w.o: without).

Mode	$TE_{34,19}$			$TE_{40,23}$		
Configuration	w.o. uptaper	w. uptaper	modification	w.o. uptaper	w. uptaper	modification
Frequency [GHz]	170.005	170.020	170.041	204.145	204.141	204.167
Beam voltage [keV]	90	88.5	90.6	79.2	79.2	86.5
Beam current [A]	75	75	75	70	70	75
Magnetic field [T]	6.86	6.86	6.88	8.15	8.15	8.23
Velocity ratio, α	1.3	1.3	1.3	1.2	1.2	1.2
Interaction length [mm]	16.0	16.0	13.6	16.0	16.0	13.6
Wall loading [kW/cm^2]	1.89	2.00	2.00	2.00	2.00	2.00
Insert loading [kW/cm^2]	0.11	0.11	0.13	0.06	0.06	0.07
RF output power [MW]	2.3	2.2	2.5	1.7	1.7	2.06
Interaction eff. [%]	34.5	34.0	37.0	31	31	32.3

7 Summary and Outlook

The simulations of this paper show that the existing KIT $TE_{34,19}$-mode coaxial-cavity pre-prototype gyrotron is not capable of operation in the KIT FULGOR gyrotron test stand using the new 10.5 T magnet, due to the longer length of the magnetic field. But, using a longer beam tunnel, the principle operation has been proven. Further, the adapted gyrotron is capable of operation as a multi-purpose/multi-frequency device. Without any other modifications the gyrotron delivers at 204 GHz (170 GHz) 1.7 MW (2.5 MW) at an interaction efficiency of 31% (37%). A small modification of the cavity length would increase the RF output power by 0.4 MW and the interaction efficiency by 1.3% at 204 GHz. Operating a dual-frequency coaxial-cavity gyrotron in the new test stand, following aspects have to be taken into account: (i) the length has to be adjusted due to the height of the new magnet, (ii) as a consequence to this, the insert has to be modified by the same length, (iii) in principle the cavity can operate at both frequencies, but with a small reduction of the cavity length the results can be improved, and (iv) the launcher has to improved due to the non-sufficient performance of the existing one at 204 GHz.

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