Efficient Frequency Step-Tunable Megawatt-Class D-Band Gyrotron

G. Gantenbein, A. Samartsev, K. A. Avramidis, G. Dammertz, M. Thumm, and J. Jelonnek
Karlsruhe Institute of Technology (KIT), Institute for Pulsed Power and Microwave Technology (IHM),
Kaiserstr. 12, 76131 Karlsruhe, Germany

***Abstract*—Results of latest experimental studies on the frequency step-tunable (D-band) megawatt class gyrotron which is under development at IHM (KIT) are presented. The goal of the short pulse (~ 1 ms) experiments was to study the performance of an upgraded cavity with longer cylindrical section. Target was to achieve significantly better efficiencies by introducing a cavity with a higher quality factor. The new design of the cavity was numerically optimized using the EURIDICE code.**

I. INTRODUCTION

STEP-TUNABLE Megawatt-class gyrotrons operating at millimeter wave frequencies and capable of being tuned in a broad frequency range of several tens of GHz have attracted large interest for application in advanced electron cyclotron resonance heating and current drive (ECRH&CD) systems for nuclear fusion devices, e.g. as the Demonstration Fusion Power Reactor (DEMO) [1].

This contribution reports on experimental results of the upgraded KIT D-band short pulse gyrotron with a new cavity geometry, which was developed in order to improve the efficiency of the interaction and the output power [2]. Numerical simulations and experimental investigations will be presented.

II. EXPERIMENTAL SET-UP

A modular, demountable D-band gyrotron is used, details are reported in [2].

The magnetron-injection-gun (MIG) is of triode type equipped with a LaB_6 emitter. During the operation the modulation electrode has been grounded (diode mode operation). Initially the design of the MIG was developed for the KIT 1MW gyrotron operating in the $TE_{22,6}$ mode at 140 GHz.

Special attention was paid to the quality of the hollow electron beam inside the cavity. It was noticed during former experiments that the thermal pattern produced by the electron beam on the surface of the collector showed azimuthally non-homogenous electron emission from the cathode of the magnetron injection gun (MIG) and an axially misaligned electron beam. The non-homogeneity of the intensity of the thermal pattern was more than 50 %. The cathode was exchanged with a new one, having better emission properties.

After an iterative alignment procedure of the coils of the superconducting (SC) gyrotron magnet a tolerance of about 0.1 mm axial misalignment between the magnetic and mechanical axis was achieved from the emitter to the cavity. That led to an improved axial alignment of the electron beam.

The gyrotron is equipped with a specially designed collector suitable for thermos-graphical measurements of the electron beam's thermal trace on the collector surface.

In the experiments frequency step-tuning in a broad frequency range is achieved by changing the operating cavity mode. That is achieved by slow variation of the magnetic field produced by the SC gyrotron magnet.

The quasi optical output coupling system (QOS) of the tube has been already described in [3]. The performance of the QOS for most of the measured modes is reported in [4].

Modularity of the gyrotron allowed the simple replacement of the cavity with a new one without complex manufacturing procedures. The numerically optimized cavity (with respect to output power and efficiency) has an extended length of the cylindrical middle section, and therefore a higher quality factor in comparison to the one used before.

A broadband silicon-nitride Brewster-angle window provided by National Institute for Fusion Science (NIFS) in Japan has been used for RF transmission during the present experiments.

III. NUMERICAL SIMULATION

The original axial profile of the cavity and the magnetic field profile supports the $TE_{22,8}$ mode at 140 GHz, The resonator has a cylindrical middle section with 17.96 mm radius and a length of $L_2 = 14.5$ mm. The operating parameters of the gyrotron for numerical simulations are listed in Table 1.

The new version of the cavity was numerically optimized

	Original Version	New Version
Middle section length L_2 (mm)	14.5	17.5
Cold diffractive quality factor Q_{dif}	830	1240
Magnetic field B_0 (T)	5.6	5.6
Accelerating voltage V_c (kV)	90.0/93.0	94.5/95.0
Beam voltage V_b (kV)	83.9/86.5	88.3/88.4
Beam current I_b (A)	39.4/39.9	40.2/40.2
Electron pitch factor α	1.28/1.41	1.31/1.43
Frequency (GHz)	140.11/140.10	140.05/140.06
Power P_{out} (kW) (at end of the uptaper)	1000/1280	1400/1450
Losses P_{ohm} (kW)	40/48	61/62
Ohmic wall loading ρ_{out} (kW/cm^2)	2.0/2.4	3.0/3.0
Interaction eff. η_{elec} (%)	31.5/38.5	41.2/42.5
Transverse eff. $\eta_{\perp}$ (%)	50.7/57.9	65.2/63.3
Output eff. η_{out} (%)	28.2/34.5	36.9/38.0

Table 1. Operating parameters and simulated performance of the $TE_{22,8}$ mode in the original and new resonator (for low/high pitch factor α)

using the EURIDICE code-package [5]. The target of the numerical optimization was to achieve a highly efficient gyrotron operation. With an extensive parametric study of the optimum cavity geometry, the length L_2 of the middle section has been varied.

It is known that resonators with higher quality factor can lead to an increase of the interaction efficiency. The diffractive quality factor can be increased by increasing the middle section length since $Q_{\mathrm{dif}} \sim (L_2/\lambda)^2$. However, this causes also an increase of the ohmic loading and a decrease of the starting currents of the competing modes, which raises the risk of mode competition. Multi-mode simulations have to be performed to assess the trade-off between interaction efficiency, mode competition and ohmic losses.

For the numerical simulations, the selected reference parameters of the operating point for the $TE_{22,8}$ mode at 140 GHz are: cathode voltage $V_c = 92$ kV, electron beam current $I_b = 40$ A, maximum magnetic field $B_0 = 5.6$ T, and electron beam radius $R_b = 7.95$ mm (for maximum coupling). Because of the voltage depression due to the electron beam space charge in short pulse operation, the given cathode voltage corresponds to a beam voltage $V_b \sim 86$ kV (beam energy). This has been taken into account in the simulations. In order to get theoretical results which are relevant for comparison with measurements, two values of the electron velocity ratio were considered: $\alpha = 1.3$ and $\alpha = 1.4$. For the parametric study, the length L_2 of the middle section of the cavity was changed in steps of 0.5 mm from its value in the original resonator (14.5 mm) up to 20.5 mm. The wall smoothing sections to guarantee the mode purity were kept the same as in the original version but the cavity input and output taper angles were slightly modified in order to secure fixed initial and final wall radii, as well as fixed total length (122.35 mm). The conductivity of the copper used in the calculations is $\sigma = 1.73\times10^7$ S/m which includes the influences of surface roughness and increased cavity temperature.

In the first step, single-mode simulations of the cavity with homogeneous magnetic field were performed. The calculated interaction efficiency versus the accelerating voltage at the pitch factor $\alpha = 1.4$ and for several values of L_2 is shown in Fig. 1. In these simulations, as the accelerating voltage increases, the electron velocity ratio α is changing adiabatically and the beam current is changing according to the Schottky effect formula. Apparently, by increasing the middle section length L_2, no saturation in the maximum achievable interaction efficiency is found. However, after $L_2 = 17.5$ mm the increase in maximum efficiency is small and the required operating parameters are significantly different from the reference values $V_c = 92$ kV and $B_0 = 5.6$ T.

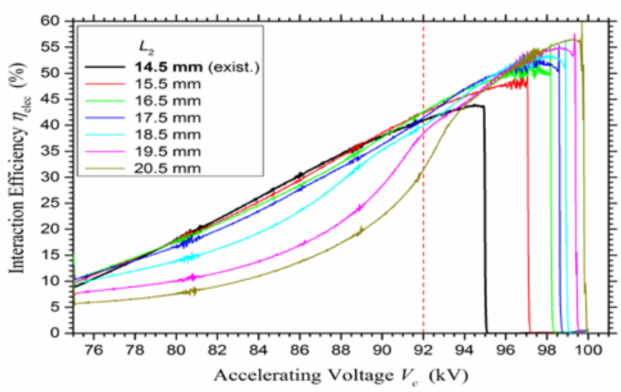

Fig. 1. Single-mode simulations of the $TE_{22,8}$ mode: Dependence of the interaction efficiency on the accelerating voltage for different lengths L_2 of the middle section of the resonator.

In order to investigate the effects of mode competition and the corresponding saturation of the electronic efficiency, the start-up simulations were repeated taking into account 29 competing modes. As competing modes all modes have been identified with operating frequency within 95-105% of the frequency of the operating $TE_{22,8}$ mode and a beam coupling factor larger than 50% compared to that of the main operating mode. In the case of $\alpha = 1.3$ the maximum obtainable efficiency in stable single-mode operation peaked at $L_2 = 18.5$ mm, whereas in the case of $\alpha = 1.4$ the maximum achievable efficiency reached saturation at $L_2 = 16.5$ mm. Based on these results the length $L_2 = 17.5$ mm was chosen for the new cavity design.

The maximum ohmic loading of the new cavity at excitation of the $TE_{22,8}$ mode is 3 kW/cm^2 which is higher than the typical value 2-2.2 kW/cm^2 used for CW operation of gyrotron cavities. However, this actual limitation depends on the type of cavity wall cooling and may be relaxed in future by advanced cooling concepts.

To further validate the new cavity with $L_2 = 17.5$ mm, additional, even more realistic multi-mode simulations were performed. The complete cavity plus non-linear up-taper geometry was simulated and the axial dependence of the magnetic field was taken into account. The beam parameters during the voltage ramp-up were taken from the beam optics code ESRAY [6]. ESRAY calculated also a spread of around 5% rms in pitch factor α, which was also considered in the multi-mode interaction calculations. The simulations showed a stable and improved performance of the new cavity. Results are shown in Fig. 2, where the power diffracted from the end of the cavity is plotted versus the cathode voltage for the case $\alpha = 1.42$.

The calculated performances of the original and the new version of the cavity with regard to the 140 GHz $TE_{22,8}$ mode for low and high electron velocity ratio α are compared in Table 1. As operating accelerating voltage for each case, a value which is around 2.5 kV lower than the accelerating voltage where the mode is lost is considered. The effect of the

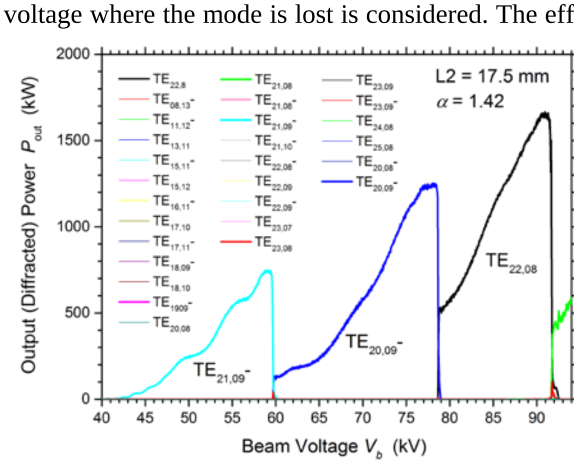

Fig. 2. Multi-mode simulations of the new version of the resonator: Dependence of the output power on the accelerating voltage. (A negative sign in the index denotes a counter-rotating mode.)

longer cavity is clearly visible in Table 1. The transverse efficiency $\eta_\perp = \eta_{\text{elec}}(1+\alpha^2)/\alpha^2$, where the interaction efficiency is defined as $\eta_{\text{elec}} = (P_{\text{out}} + P_{\text{ohm}})/(V_b I_b)$ is significantly increased. The output efficiency $\eta_{\text{out}} = P_{\text{out}}/(V_c I_b)$ is also shown. With the new version, an output efficiency enhancement by from 28.2 to 36.9 % for low α and from 34.5 to 38.0 % for high α has been predicted.

IV. Experimental Results

In Table 2 the measured output power, for all operating cavity modes and the corresponding frequencies and beam parameters are summarized. The excited mode was determined by measurement of the corresponding oscillation frequency.

The radius of the electron beam changes as ~ $f^{1/2}$ if the frequency f is increased from 124 to 169 GHz. A pair of gun coils is used to keep the pitch factor of the electrons at the desired value.

The highest output power of 1440 kW was measured for the $TE_{23,8}$ mode at 143.36 GHz with an increased beam current of I_{beam}= 54 A. In this case the efficiency is 38%.

It should be pointed out that all the modes in Table 2, oscillating at frequencies above 143.4 GHz (this frequency corresponds to the mode $TE_{23,8}$) were not taken into account in the numerical optimization procedure for the QOS. However, the measurements demonstrated that the modes are efficiently coupled out and that it is possible to operate the gyrotron using these cavity modes.

The operation of the gyrotron was optimized for each cavity mode. The limitation due to the diode operation of the MIG did not allow keeping the parameters of the electron beam optimal for all the operating modes. According to the ESRAY simulations the pitch factor of the electron beam varied in the range 1.0-1.5 for the different modes.

Mode	V_{acc} [kV]	U_b [keV]	R_b [mm]	I_b [A]	Freq. [GHz]	P_{out} [kW]	η [%]
$TE_{28,9}$	79.3	74.9	8.07	43.0	169.20	1150	35.7
$TE_{27,9}$	82.7	78.3	8.15	44.0	165.90	1070	31.1
$TE_{26,9}$	82.7	77.4	7.97	42.0	162.60	1200	36.9
$TE_{25,9}$	81.0	75.5	8.00	44.0	159.20	1093	32.9
$TE_{24,8}$	74.0	68.2	8.04	42.5	146.70	1200	41.4
$TE_{23,8}$	74.0	67.6	8.02	44.0	143.40	1210	40.7
$TE_{22,8}$	76.0	69.1	8.05	45.0	140.10	1150	37.0
$TE_{21,7}$	74.3	68.8	8.33	43.0	127.50	1035	35.0
$TE_{20,7}$	77.3	71.6	8.30	42.5	124.20	1004	33.0

Table 2. Experimentally measured output power and estimated interaction efficiency with corresponding parameters (accelerating voltage, beam energy, beam radius, beam current, frequency).

In order to estimate the interaction efficiency in the cavity the depression voltage of the electron beam in the cavity region must be taken into account. Additionally, the stray radiation and ohmic losses have to be considered. For instance, for the oscillation in the $TE_{23,8}$ mode at 143.36 GHz with 37 % output efficiency, according to the ESRAY code, for 74 kV cathode voltage, 44 A beam current and the actual magnetic field used in the experiment, the beam energy in the cavity is 67.6 keV. Therefore, taking that into account, we can estimate that the interaction efficiency must be at least 40% (here we have neglected stray radiation and ohmic losses). The corresponding beam energies for all considered modes are summarized in Table 2.

Due to a lack of time the experimental measurements for all the different cavity modes were performed at reduced cathode voltage of approximately 75 kV. A systematic measurement of the gyrotron performance in a wider range of parameters will be done in future.

V. CONCLUSIONS

Recent results on the improved performance (efficiency and the output power) of the step-frequency tunable 1 MW-class D-band gyrotron at IHM (KIT) are presented. The contour of the cavity was numerically optimized with respect to the highest efficiency. The gyrotron was operated in the frequency range from 124 GHz up to 169 GHz. The highest achieved output efficiency of the device is up to 38% (without depressed collector operation). For all the measured cavity modes a minimum output power of 1 MW has been demonstrated. In comparison to the previous shorter cavity configuration of the gyrotron the electronic efficiency is generally higher. For some modes the improvement in the output efficiency is up to 10 percentage units (from 27-28% to 37-38%). The results of measurements do not agree very well with the numerical simulations, most probably due to the unknown real parameters of the electron beam (pitch factor, velocity spread, trapped electrons, etc.) which are not measurable at the moment. They were obtained from numerical simulations using a static self-consistent code (ESRAY) only. The quantitative agreement with numerical simulations still must be improved.

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