Multi-Frequency Design of a 2 MW Coaxial-Cavity Gyrotron for DEMO

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***Abstract*—The Karlsruhe Institute of Technology (KIT) is working on a possible physical design of 2 MW coaxial-cavity gyrotrons for future fusion applications, initially considering a first demonstration fusion power plant (DEMO). One focus of the investigations is how successfully such gyrotrons can be operated at significantly different frequencies. The gyrotron design as presented here is optimized for operation at one very high order main cavity mode around 237.5 GHz, with secondary modes at 170.0 GHz and 203.8 GHz. The considered technical design restrictions as well as simulation results are presented.**

I. Introduction

Gyrotrons are the only high-power microwave sources for electron cyclotron resonance heating and current drive (ECRH&CD) of plasmas in future fusion power plants, particularly in the first demonstration power plants (DEMO). Assuming the 2012 baseline for DEMO (aspect ratio of 4.0, B_T>7 T), the operating frequencies for optimum ECCD are significantly above 200 GHz [1], while lower frequencies around 200 GHz and 170 GHz appear useful for plasma start-up and bulk heating or for other fusion applications, e.g. in the ITER tokamak which is currently under construction in Cadarache, France. The Karlsruhe Institute of Technology (KIT) is working on the design for a 2 MW coaxial-cavity gyrotron, which can operate with good performance at 237.5 GHz (cavity mode $TE_{49,29}$). As the result of an adequate mode-selection strategy considering output coupler and output window [2], the modes $TE_{35,21}$ (170 GHz) and $TE_{42,25}$ (203.8 GHz) were chosen as secondary modes; see Fig. 1 for illustration. The priority of initial studies was the optimization of the cavity [3] and of the triode-type magnetron injection gun (MIG) [4] with respect to the $TE_{49,29}$ main design mode, using rather simplified assumptions for the electron beam.

This work presents the imposed technical design restrictions, realistic assumptions for the electron emission and corresponding simulation results for all three operating modes. For interaction and MIG simulations, the European proprietary codes SELFT [5] and Euridice [6], and Ariadne [7] and ESRAY [8], respectively, were used.

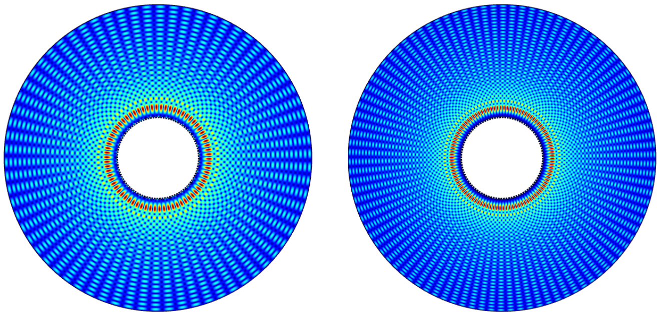

Fig. 1. Transversal profiles of the modes $TE_{35,21}$ and $TE_{49,29}$.

II. Assumptions

In the preceding study, the current density of the emitter was limited to 4 A/cm^2. With an emitter radius of 65 mm, a slant angle of 25° and an emitter width of 4.3 mm (3.9 mm width projected to the gyrotron axis), one can achieve 70 A of beam current. The beam energy for $TE_{49,29}$-mode operation is limited by the permitted ohmic loading on the cavity walls (2.0 kW/cm^2 at the outer wall and 0.2 kW/cm^2 on the coaxial insert) and was taken as the upper boundary for all three operating points. For $TE_{49,29}$-mode operation and with an appropriate MIG design (see Fig. 2), one obtains an RMS spread in the perpendicular velocity component ($\delta_{\beta,perp}$) of the electrons of around 1 % at the cavity entrance, which has no significant influence on the interaction. However, additional spread has to be considered from the emitter surface roughness [9] and from possible further non-uniform emission. In $TE_{49,29}$-mode operation, a typical emitter structure size of 2 µm leads to an increase of $\delta_{\beta,perp}$ to 3.4 %. For interaction calculations, $\delta_{\beta,perp}$=6 % was assumed, which means that less than 3 % spread may result from azimuthal variations of work function and heating temperature. These beam parameters allow obtaining 1.9 MW (33 % electronic efficiency).

The MIG is designed such that reflection and trapping of secondary electrons is avoided for all three operating modes. Despite its relative compactness, the electric field within the gun nowhere exceeds 7 kV/mm on its metallic surfaces.

An initial design for a 10.5 T magnet with 270 mm bore-hole diameter, supplied by an industrial manufacturer, has been used for the simulations.

The considered cavity has a radius of 31.78 mm and a length of 15 mm (straight middle section). The conical coaxial insert in this region has 100 longitudinal corrugations (each 0.3 mm × 0.3 mm) and a radius between 8.66 mm (cavity entrance) and 8.4 mm (cavity exit).

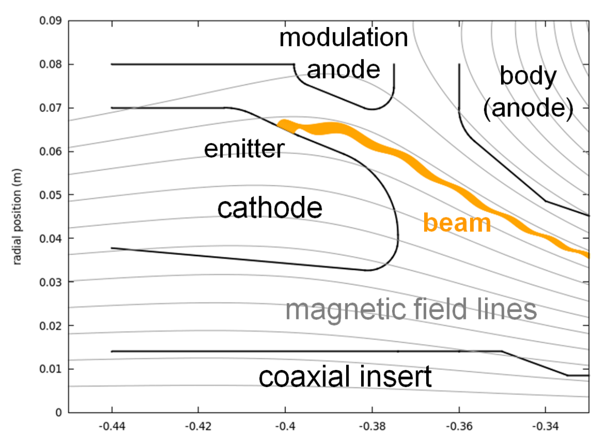

Fig. 2. MIG design of the gyrotron, including magnetic field lines and the electron beam for operation of the gyrotron at 237.5 GHz.

III. Results

Table 1 shows the operating points and simulation results for all three frequencies under consideration. These values have been found using self-consistent time-dependent startup simulations with at least ten modes each, taking into account the full guiding center distribution, velocity spread and voltage depression of the beam; see Fig. 3 for the $TE_{49,29}$ startup. While the optimum electron beam radius in the cavity is almost constant and likewise is the overall magnetic field profile, the modulation anode voltage has to be varied significantly to compensate the different magnetic field strengths at the emitter in order to obtain a reasonable pitch factor (ratio of perpendicular to axial electron velocity).

Due to its own space-charge, the electron beam experiences a voltage depression between emitter and cavity, but it is well known that this depression is significantly reduced by the coaxial insert. As one can see from Table 1, the voltage depression is only around 2 kV for all three operating points.

Table 1. Operating parameters of the three operating modes.

Window thickness in λ/2	5	6	7
Operating mode	$TE_{35,21}$	$TE_{42,25}$	$TE_{49,29}$
Mode eigenvalue	113.1	135.6	158.1
Frequency (GHz)	170.0	203.8	237.5
Magnetic field at emitter (T)	0.137	0.165	0.191
Accelerating voltage (kV)	85.6	87.9	87.4
Mod. anode voltage (kV)	53.7	46.6	37.5
Beam current (A)	69.4	70.0	69.3
Velocity spread by MIG	6.8 %	4.3 %	3.4 %
Magnetic field in cavity (T)	6.82	8.22	9.58
Beam voltage (kV)	83.4	86.0	85.6
Velocity spread (interaction sim.)	8 %	6 %	6 %
Guiding center radius at cavity (mm)	10.28	10.27	10.24
Pitch factor at cavity	1.27	1.25	1.22
Wavelength-to-beam-thickness ratio (in cavity)	6.2	5.1	4.4
Output power (MW)	1.8	1.9	1.9
Electronic efficiency (%)	31	32	33

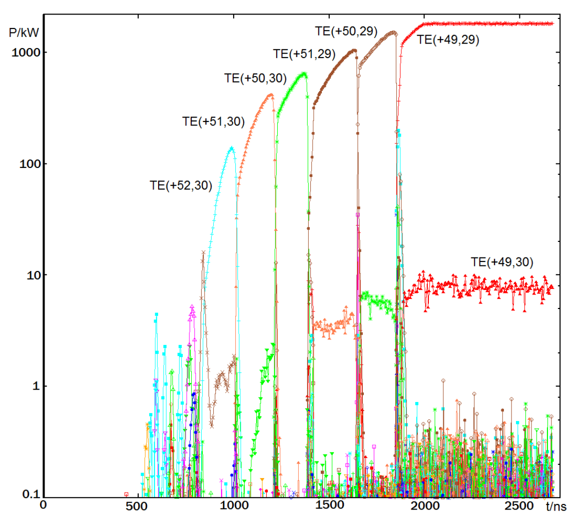

Fig. 3. Startup scenario for the $TE_{49,29}$ (137.5 GHz) operation. The voltages have been ramped up linearly, with the beam current following according to the Schottky effect. At t=2000 ns simulation time, the ramp-up was discontinued as the design values were reached. Simulations have been carried out using the HELIOS supercomputer at IFERC-CSC.

The peak ohmic loading of the coaxial insert for the different operating modes should be considered carefully, see Table 2: While the loading on the cavity wall decreases with decreasing operating wavelength at otherwise similar operating parameters, the loading on the insert increases. This is due to the broader mode maximum for lower-order modes.

Table 2. Peak loading for the three operating modes.

Mode	$TE_{35,21}$	$TE_{42,25}$	$TE_{49,29}$
Cavity wall loading (kW/cm²)	1.3	1.7	2.0
Insert loading (kW/cm²)	0.5	0.3	0.2

IV. Conclusion

The multi-frequency behavior of a coaxial-cavity gyrotron for DEMO has been investigated. While the MIG design for the three chosen operating points is promising and the interaction at the main mode $TE_{49,29}$ is robust, the ohmic loading of the insert increases for operation at the lower frequencies. An optimized coaxial-cavity multi-frequency gyrotron would thus require a thinner insert (which, however, might somewhat increase mode competition for $TE_{49,29}$) and/or should be operated at lower output power for the lower frequencies.

Acknowledgement

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