

Theoretical Design of a 2-Megawatt Coaxial-Cavity Gyrotron for High-Power Operation at 238 GHz

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Abstract—This paper summarizes recent theoretical design work on a coaxial-cavity gyrotron for 238 GHz operation in a 10.5 Tesla superconducting magnet. The magnetron injection electron gun (MIG) and magnetic system are optimized to produce a stable electron beam that couples efficiently to the TE_{49,29} operating mode. The presented simulation results indicate that high-power operation is achievable and that the design is applicable for multi-frequency/multi-purpose operation at frequencies which fit to the window resonances of a CVD-diamond disk that is equivalent in thickness to the output window used for the EU 170 GHz ITER gyrotron.

Index Terms—gyrotron, multi-frequency, high-power

I. INTRODUCTION

In magnetic confinement fusion experiments, including Wendelstein 7-X and ITER, gyrotrons serve as high-power vacuum electronic sources for Electron Cyclotron Resonance Heating (ECRH). Gyrotrons are capable of delivering output powers in the megawatt range at operating frequencies in the millimeter-wave and sub-terahertz regimes, making them the only available source for efficient plasma heating.

With the development of next-generation high-field plasma fusion devices, there is a growing demand for gyrotrons operating at higher frequencies. In particular, ongoing research and development target gyrotrons suitable for high-field stellarators such as the quasi-isodynamic Stellarator Proxima Alpha which is considered to be the predecessor of Stellaris [1]. Higher operating frequencies are required to resonate with the increased magnetic field strength in the plasma.

Based on the transmission characteristics of the synthetic diamond output window with a dielectric constant of $\epsilon_r = 5.67$ and thickness of $d = 1.852$ mm developed for the ITER 1 MW gyrotrons [2], additional operating frequencies of 204 GHz and 238 GHz have been selected alongside the established 170 GHz frequency. A first theoretical design of a coaxial-cavity gyrotron capable of triple-frequency operation at 170, 204 and 238 GHz was presented in [3].

This work provides an overview of the practical implementation of such a multi-frequency concept based on the existing 170 GHz coaxial-cavity gyrotron currently available at KIT [4]. The primary objective is the realization of a new gyrotron designed for operation at higher frequencies, with a particular focus on achieving an output power of at least 1.7 MW at 238 GHz. This development is to be realized within a new 10.5 T superconducting magnet, which provides the

magnetic field strength required for high-frequency gyrotron operation.

II. ELECTRON BEAM PERFORMANCE AND WAVE INTERACTION

The selected cylindrical transverse electric (TE) modes for multi-frequency operation, with the TE_{49,29} mode at 238 GHz as the reference, are the TE_{42,25} mode at 204 GHz and the TE_{35,21} mode at 170 GHz. These modes fulfill the design requirements regarding the frequency match between the diamond window resonances and the respective mode cutoff frequencies. In addition, only minor deviations in the caustic radii are observed, with differences not exceeding 2 %, which is a key requirement for the design of a multi-mode, multi-frequency quasi-optical output system with almost the same direction of the millimeter-wave output beam.

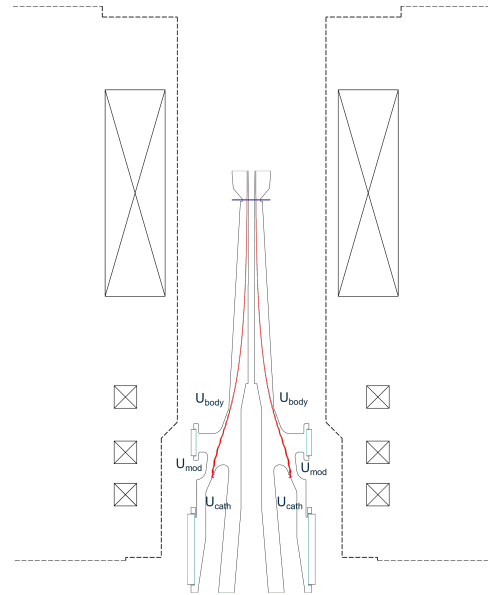


Fig. 1. Schematic of the experimental setup. Voltage levels are indicated on the corresponding components. The electron beam trajectory is shown in red, with the point at the cavity entrance where the beam parameters are evaluated marked in blue. Insulators are highlighted in light blue, and open boundaries are shown in green.

In order to excite the selected modes, the electron beam parameters must be compatible with the magnetic field configuration of the new 10.5 T superconducting magnet. To

allow for increased flexibility in adjusting the electron beam parameters, a triode-type MIG as described in [5] is employed. In order to match the magnetic field profile, the beam tunnel has been extended in length by 60 mm. A schematic of the resulting setup is shown in Fig. 1.

The electron beam trajectory, shown in red in Fig. 1, is calculated using the particle-in-cell simulation code ESRAY [6] and is constrained by the voltage limits of the respective electrodes as well as by the current limitations of the magnetic field coils. The electron beam parameters, including their standard deviations, are evaluated at the spacer position, indicated in blue, which corresponds to the voltage ramp-up region of the cathode voltage, and are presented in Fig. 2. At the nominal operating point, the electron beam exhibits a kinetic energy of 90 keV, a current of 75 A, and a pitch factor of 1.3 at the center of the cavity.

These beam parameters are subsequently used as input for the electron beam–wave interaction simulations in the cavity, which are performed with the time-dependent, self-consistent multimode code ROCK [7]. The simulations account for 42 competing modes and include the effect of voltage depression. At the selected operating point, an output power of 2.45 MW is obtained, corresponding to a 36.3 % efficiency of the energy transfer from the electron beam to the microwave. The complete startup scenario is shown in Fig. 3.

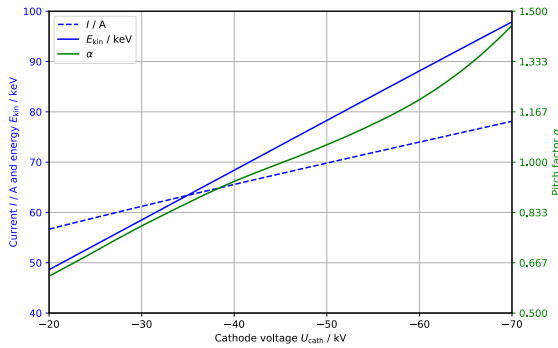


Fig. 2. The electron beam parameters energy (blue), current (dashed, blue) and pitch factor (green) as a function of the cathode voltage ramp-up.

The same design and simulation approach can be applied to the other selected operating frequencies, demonstrating that the coaxial-cavity gyrotron can achieve high-power operation with controlled beam dynamics and robust mode excitation across all targeted frequencies. These results confirm the feasibility of multi-frequency electron cyclotron resonance heating in the 10.5 T superconducting magnet, with future work focusing on experimental validation and optimization of the quasi-optical output system.

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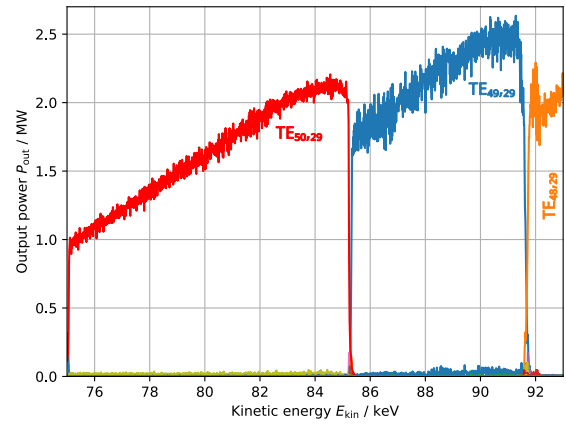


Fig. 3. Excitation of the TE_{49,29} mode (blue) during startup.

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