Design of a Second Harmonic MW-Level Coaxial Gyrotron Cavity

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***Abstract*—An optimized second harmonic cavity for a 170 GHz 1.3 MW fusion gyrotron is presented. The suppression of the competing modes at fundamental frequency is achieved solely due to a specific design of the coaxial cavity with corrugated inner conductor and does not require e.g. the injection of an external signal. The design is verified by self-consistent multimode simulations. The results show an excellent suppression of the competing fundamental modes.**

***Index Terms*—electron tubes, gyrotrons, coaxial resonators, corrugated insert, second harmonic operation**

I. Introduction

Since the operating principle of gyro-devices is based on the electron cyclotron resonance effect [1], the oscillation angular frequency ω of the radio frequency (RF) wave is close to the electron cyclotron frequency Ω or higher harmonics thereof. Thus, the condition for the interaction between electrons and the electric field at any harmonic s can be stated as follows:

$$\omega \approx s\,\Omega - k_{\mathrm{z}}\,v_{\mathrm{z}}\,. \tag{1}$$

The RF frequency is detuned by the so-called Doppler term and, therefore dependent on the axial wavenumber k_{z} and the axial particle velocity v_z. Since Ω depends mainly on the static magnetic field B, it is clear that ω increases with an increased magnetic field. Likewise, it is evident from (1) that for the same RF, only half the magnetic field is required if the interaction takes place at the second harmonic of electron cyclotron motion. This allows the magnet system to get significantly simpler and cheaper if one targets for operating frequencies above 200 GHz. In contrast to the widely deployed harmonic gyrotrons for dynamic nuclear polarization applications, fusion gyrotrons require RF output power levels in the MW range and therefore highly overmoded cavities are used to keep the wall losses low. Especially, at $s = 2$, there are always competing modes at the fundamental cyclotron frequency which have a low starting current. Since the fundamental modes couple to the electron beam more efficiently than the harmonic modes, the resonator design must prevent those fundamental modes from oscillating, otherwise the harmonic interaction is suppressed.

II. Suppression of Fundamental Competitors

One possibility to prevent the fundamental modes from oscillating might be the use of coaxial gyrotron cavities with corrugated inserts. This is a common technique in high-power gyrotrons to suppress competing modes, and the basic possibility for harmonic operation of impedance-corrugated coaxial cavities has already been theoretically considered at medium power levels [2].

Compared to the typical utilized hollow gyrotron cavities, the cutoff frequency f_{c} of the mode depends in the coaxial cavity on the radius of the outer and the inner conductor.

If the cutoff frequency of the mode decreases along the cavity axis, its diffractive quality factor also decreases. This leads to an increase of the beam current required for oscillation.

Consequently, modes which are unaffected by the inner conductor are preferred. By introducing axial corrugations into the inner conductor, competing modes can be suppressed even more effectively. If the width of the corrugations is chosen smaller than half the free space wavelength at cutoff frequency λ_{c} of the TE mode, the mode conversion at the corrugations is negligible. The corrugations can be described as a change in the effective surface impedance of the inner conductor in this case [3]. If the corrugation is chosen between 0.3 and $0.5\,\lambda_{\mathrm{c}}$ of the second harmonic operating mode, the cutoff frequency of the competing fundamental decreases strongly, if the outer to inner radii ratio increases, as shown in Fig. 1. Consequently, the fundamental modes can be suppressed by a down tapered inner conductor with proper radius. The inner wall radius and the taper angle have to be chosen in such a way, that the eigenvalue curve of the most critical fundamental modes decreases strongly within the cavity midsection, where the main interaction takes place.

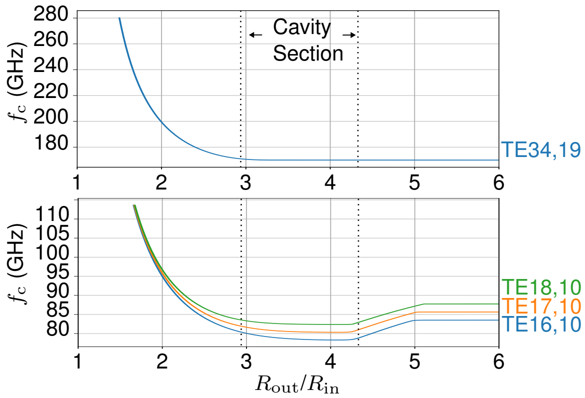

Fig. 1. Cutoff frequency of operating mode $TE_{34,19}$ and the strongest competing fundamental modes $TE_{16,10}$, $TE_{17,10}$ and $TE_{18,10}$ for an outer radius of 29.55 mm and a corrugation depth of 0.4 λ_c

III. Optimized Second Harmonic Cavity

The simulation results for, a 170 GHz 1 MW second harmonic cavity design are presented. The $TE_{34,19}$ mode is selected as the operating mode to meet the wall loading requirements and to match the existing KIT electron gun and launcher system, so that the cavity can be installed in the existing KIT 2 MW coaxial gyrotron [4]. To ensure second harmonic interaction, the fundamental competitors have to be identified. For the optimization, all fundamental competitors with a coupling factor higher than 0.5 of the coupling factor of the operating mode were taken into account. The identification of the most critical competitors can be performed by linearized starting current calculations [5]. Due to the fact, that the coupling between electron beam and the second harmonic mode is decreased, compared to fundamental interaction, the interaction length has to be increased.

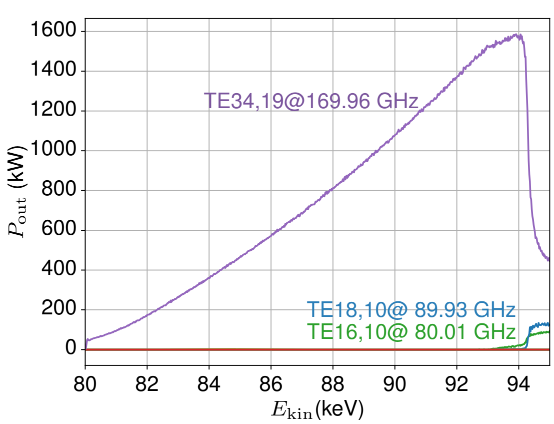

Fig. 2. Multimode start-up simulation of the $TE_{34,19}$ operating mode with all fundamental competing modes with a coupling factor > 0.5

The interaction between electrons and the transversal electric TE Modes inside the cavity is simulated with the self-consistent, time-dependent, multimode code EURIDICE [6]. As shown in Fig. 2, an output power of 1.33 MW can be achieved with this cavity at the operating point with a kinetic entry energy of the electrons of 91.5 keV, a beam current of 75 A, a pitch factor α of 1.2 and an applied magnetic field of 3.5 T. The electronic efficiency at this operating point is 19.4 %. A spread of the kinetic input energy of 0.3 %, the pitch factor of 5.0 % and a guiding center spread of 2.0 % were considered in the simulations. This promises a total efficiency of over 50 % using a multistage depressed collector [7]. The operating point was chosen 1.5 keV below the point of mode loss to ensure operational margin. The simulations show a maximum electronic efficiency of 21.96 %. The ohmic loading of the inner wall is kept below 250 W cm^{-2} and 2 kW cm^{-2} on the outer wall.

IV. Conclusion

A gyrotron cavity optimized for second harmonic interaction and operation at an output power in the MW range has been presented. The proposed method, for the design of the inner conductor, has been verified in self-constant multimode simulations. For this purpose, a 170 GHz cavity at second-harmonic interaction was designed. Due to the optimized inner conductor, the cavity design is capable of generating 1.33 MW. The ohmic loading requirements on the outer and inner cavity walls are both fulfilled. The proposed suppression scheme can now be extended for harmonic fusion gyrotron designs with frequencies above 200 GHz.

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Part of the simulations were performed on the EUROfusion High Performance Computer (Marconi-Fusion).

References

[1] V. Flyagin *et al.*, "The Gyrotron," *IEEE Trans. Microw. Theory Techn*, vol. 25, no. 6, pp. 514–521, Jun. 1977, number: 6.
[2] K. Avramides, C. Iatrou, and J. Vomvoridis, "Design Considerations for Powerful Continuous-Wave Second-Cyclotron-Harmonic Coaxial-Cavity Gyrotrons," *IEEE Trans. on Plasma Sci.*, vol. 32, no. 3, pp. 917–928, Jun. 2004, number: 3.
[3] C. Iatrou, S. Kern, and A. Pavelyev, "Coaxial cavities with corrugated inner conductor for gyrotrons," *IEEE Trans. Microw. Theory Techn.*, vol. 44, no. 1, pp. 56–64, 1996, number: 1.
[4] S. Ruess *et al.*, "KIT coaxial gyrotron development: from ITER toward DEMO," *Int. J. of Microw. and Wireless Technologies*, vol. 10, no. 5-6, pp. 547–555, Jun. 2018.
[5] E. Borie and B. Jödicke, "Comments on the linear theory of the gyrotron," *IEEE Trans. on Plasma Sci.*, vol. 16, no. 2, pp. 116–121, Apr. 1988, number: 2.
[6] K. A. Avramides, I. G. Pagonakis, C. T. Iatrou, and J. L. Vomvoridis, "EURIDICE: A code-package for gyrotron interaction simulations and cavity design," *EPJ Web of Conferences*, vol. 32, p. 04016, 2012.
[7] B. Ell *et al.*, "Mechanical design of the short pulse E×B drift two-stage depressed collector prototype for high power gyrotron," in *Proc. IEEE Int. Vacuum Electronics Conf. (IVEC)*, 4 2021, pp. 1–2.