MW Level 280 GHz 2nd Harmonic Coaxial Gyrotron Cavity with Variable Corrugation Depth

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Abstract

The demand for high-power gyrotrons at frequencies above 200 GHz is increasing. This is anticipated to provoke a growing interest in harmonic high-power gyrotrons. Interacting with the second cyclotron harmonic facilitates a doubling of the output frequency in gyro-devices using the same magnet system. Since the coupling of the electron beam with TE modes becomes inherently weaker, with increasing harmonic number, a suitable method must be found to suppress fundamental modes. The use of impedance corrugated inserts in coaxial gyrotron cavities has been presented in this regard. In order to increase the output power while maintaining the ohmic wall loading on the inner conductor at continuous wave compatible levels, we have devised a technique that enhances the efficiency of suppressing fundamental modes by employing a tapered corrugation depth on the inner conductor. This approach also increases the range of stable operation of the gyrotron and reduces the susceptibility of the operation to electron beam quality.

Keywords

electron tubes, gyrotrons, coaxial resonators, corrugated insert, second harmonic operation

INTRODUCTION

Gyro-devices operate based on the electron cyclotron resonance effect [1]. Thus, the generated microwave angular frequency ω is close to the electron cyclotron frequency Ω_c of the electrons or higher harmonics, thereof. The interaction condition between electrons and the electric field at any harmonic s can be expressed as

$$\omega = s\,\Omega_\mathrm{c} + k_\mathrm{z}\,v_\mathrm{z}\,, \tag{1}$$

where k_z denotes the axial wave number and v_z the axial electron velocity.

As Ω_c is proportional to the static magnetic field B, the output frequency can be increased with increased magnetic field. Notably, at the second harmonic of electron cyclotron frequency, only half the magnetic field is required for the same microwave frequency, simplifying and reducing costs for the magnet system, particularly for frequencies exceeding 200 GHz. Fusion gyrotrons, unlike harmonic gyrotrons for dynamic nuclear polarization [2–4], demand MW-level microwave output, utilizing highly overmoded cavities to minimize wall losses.

In this context, when targeting $s = 2$, competition arises from fundamental cyclotron frequency modes with low starting currents. To achieve efficient harmonic interaction, the cavity design must prevent these fundamental modes from being excited. This ensures optimal performance and MW output power level for fusion gyrotrons.

SUPPRESSION OF FUNDAMENTAL COMPETING MODES

It has been shown theoretically that the competing fundamentals can be suppressed, by use of a coaxial cavity with impedance corrugated insert [5–7], which is much simpler compared to the previously proposed injection locking approach [8,9].

In a coaxial gyrotron, the mode's eigenvalue, and hence its cutoff frequency and the diffractive quality factor of the cavity, depends on both the ratio of the outer to inner wall radius and the depth of the surface impedance corrugations on the inner conductor [10]. In this way, fundamental modes with caustic radii smaller than the operating mode can be suppressed. The corrugation depth of a suitable inner conductor is chosen between 0.4 and 0.6 times the free-space wavelength λ of the operating mode. To ensure that all competing modes are suppressed, the inner conductor must be significantly thicker than in fundamental gyrotrons. This leads to an increased ohmic loading ρ on the inner conductor and is especially problematic at high frequencies, since $\rho \propto f^{2.5}$ increases with frequency. For the suppression scheme to be effective, the electron beam must be guided close to the inner conductor.

This suppression scheme is enhanced via a linear taper of the corrugation depth and thus a specially designed adjustment of the surface impedance along the cavity axis. This allows the competing modes to be suppressed even more efficiently. Modes for which the corrugation depth is smaller than $0.2\,\lambda$ of their free-space wavelength exhibit a decrease in eigenvalue with increased wall radius ratio of the coaxial cavity. If the corrugation depth is now varied, so that the eigenvalue along the cavity is always in the decreasing slope part of the eigenvalue curve, the change in the eigenvalue of the competing modes can be increased, resulting in a further decrease of their quality factors. The radius of the inner conductor is selected such, that the operating mode is only slightly influenced by the inner conductor. Tapering of the corrugation depth enables more efficient suppression of the fundamental modes. This results in an extended range of stable gyrotron operation and makes it possible to reduce the radius and ohmic loading of the inner conductor.

DESIGN OF A 280 GHZ GYROTRON CAVITY

Based on this approach, a 280 GHz $\mathrm{TE}_{36,20}$-mode cavity was designed for second harmonic operation. The primary

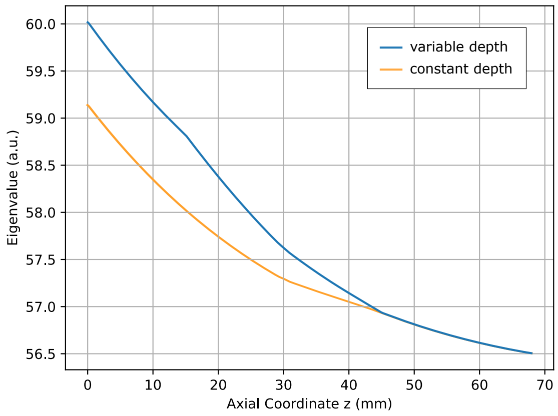

Figure 1. Eigenvalue of the most critical fundamental competing mode $TE_{-17,12}$ with constant and with variable corrugation depth.

competing modes that need to be suppressed are the counter rotating $TE_{-16,12}$, $TE_{-17,12}$ and the co-rotating $TE_{18,11}$, and $TE_{19,11}$ modes.

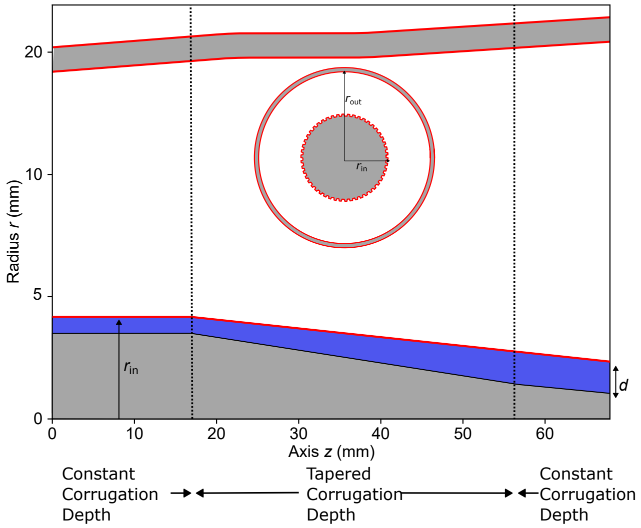

Figure 2. Schematic of the coaxial cavity with tapered impedance corrugations.

With this geometry, presented in Fig. 2, interaction simulations were performed using the self-consistent multimode code EURIDICE [11]. First, the geometry was simulated with a constant corrugation depth and then compared to the results with a tapered corrugation depth. The cavity was designed for an output power of 800 kW and an electronic efficiency of 17.6%. Due to improved competing mode suppression, the radius of the inner conductor could be reduced from 5.7 mm to 4.5 mm without the fundamental competing modes prevailing. Consequently, the ohmic loading on the inner conductor could be reduced from 0.35 kW/cm^2 to 0.20 kW/cm^2 while maintaining the same output power. However, it should be noted that the inner conductor radius cannot be arbitrarily small to provide suppression of the competing modes. In addition, with smaller inner conductor radii, considerations regarding mechanical stiffness and bending due to the thermal loading on the inner conductor need to be taken into account. The inner conductor profile was kept simple, allowing fabrication using disk or groove cutters. The reduced inner conductor loading is intriguing because the output power of the gyrotron can be increased with equal cooling capabilities. This also allows the efficiency of the gyrotron to be increased, with increase in effective interaction length and therefore the quality factor of the cavity.

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