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Selectivity Properties of Coaxial Gyrotron Cavities with Mode Converting Corrugations

Zisis C. Ioannidis, Konstantinos A. Avramidis, and Ioannis G. Tigelis

***Abstract*—Longitudinally corrugated inserts have been proposed as an additional means to enhance the selectivity properties of coaxial gyrotron cavities. However, when increasing the frequency and the output power, the corrugated insert may not be sufficient to ensure mode stability. Vane loaded cavities with corrugated inserts seem to have the potential for superior mode-selectivity and could be employed to facilitate the development of multi-MW gyrotrons. In this work a numerical code based on the Spatial Harmonics Method is used to study the spectrum rearrangement of a typical coaxial cavity with corrugated insert in which additional wedge-shaped corrugations are introduced on the outer wall. A general design procedure for the upgrade of the mode selectivity is presented. Its merits are demonstrated for a 140 GHz gyrotron cavity.**

***Index Terms*—Gyrotron, coaxial cavities, corrugated waveguides, Spatial Harmonics Method.**

I. Introduction

GYROTRON oscillators are nowadays used in a variety of scientific and industrial applications that need a high-power high-frequency microwave source, although their development was primarily motivated by fusion related applications such as electron cyclotron resonance plasma heating [1], current drive [2], as well as suppression of plasma instabilities [3]. In all these applications the need to increase the output power and shorten the wavelength results in the increase of the interaction volume, leading to an extremely overmoded structure. Thus the issue of mode selection is of crucial significance for the successful design of a gyrodevice.

Usually, in gyrotrons, power is introduced in the tube in the form of a thin annular electron beam. A simple technique of mode selection is the proper positioning of the electron beam at the position where the coupling impedance between such a beam and a rotating non-symmetric $TE_{m,p}$ mode is maximized [4], [5]. This approach has proven to be quite effective for relatively low-frequency oscillators working with whispering gallery $TE_{m,p}$ modes and relatively small azimuthal and radial indexes [1]. However, working with higher-order modes this method becomes ineffective due to the density of the spectrum, which results in multiple modes with almost the same coupling factor.

Coaxial inserts have been proposed quite early in gyrotron development not only to significantly reduce the voltage depression of the electron beam [1], but also to selectively influence the competing modes. The inner conductor in the gyrotron cavity changes the eigenvalue spectrum by making the eigenfrequencies to depend on the outer to inner radii ratio $C = R_o/R_i$. This may rarefy the spectrum of the competing modes for specific C-values. Additionally, all the modes with caustic radius smaller that the insert radius are suppressed due to the increased ohmic losses on the inner conductor. Moreover, if the coaxial insert is properly tapered it results in a variation of the wave's group velocity along the cavity, which is directly related to the diffraction losses of the different modes. Thus, the introduction of an insert with progressively decreasing radius provides an additional means to selectivity by affecting the quality factor of the higher-order competing modes. The disadvantage of this method is that although it decreases the quality factor of the modes whose eigenvalue curves versus C exhibit a negative slope, it increases the quality factor of the modes having an eigenvalue curve with a positive slope. Such enhanced modes could impede the desired operation.

The selective properties of a coaxial cylindrical resonator can be further enhanced by the introduction of longitudinal corrugations on the inner conductor [6]–[8]. Choosing the corrugation geometric characteristics properly, all the eigenvalue curves $\chi(C)$ of the competing modes become monotonic with negative slopes. As a result, their quality factors become smaller and their starting currents increase. This means that by introducing corrugations on the insert, the parasitic modes can be easier suppressed by the operating mode during the mode competition, provided that the selection of the cavity C is made in a way that the negative slope of the operating mode's eigenvalue curve is sufficiently small.

An idea for even more enhanced mode-selectivity could be the additional introduction of a small number of corrugations on the outer wall [9], [10]. Selecting the total number of the corrugations and their dimensions properly it is possible to rearrange the eigenvalue spectrum of the cavity significantly [11], [12]. In this context, it could be possible to couple the major azimuthal competitors of the working mode with other low-order modes, decreasing in this way their diffractive quality factor, yet leaving the working mode almost unaffected.

In this work, we use the Spatial Harmonics Method in order to rigorously study and describe in detail the design procedure that could be followed in order to increase the mode

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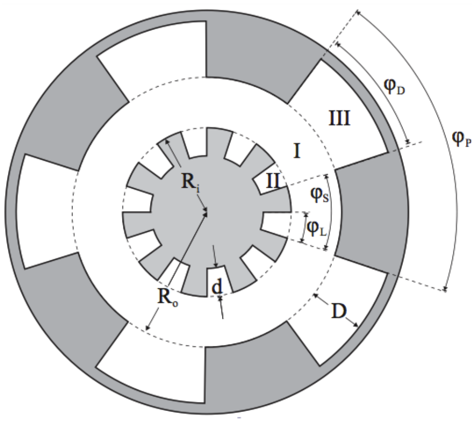

Fig. 1. Cross section of a coaxial cavity with wedge-shaped corrugations on the surface of both the inner and the outer wall.

selectivity of a coaxial gyrotron cavity with corrugated insert by introducing corrugations on the outer wall. Note that in contrast to [9], [10] our studies are based on a rigorous full wave method. In particular, in Section II we study the coupling mechanism of the outer corrugations in the presence of the inner corrugation in order to identify how both of them can work beneficiary together. In Section III, having in mind an actual coaxial gyrotron cavity with a corrugated insert, we search for a proper number of outer corrugations and study the rearranged eigenvalue spectrum that the corrugations evoke. Then, in Section IV we study how these corrugations affect the selectivity properties of the original cavity. Our conclusions are summarized in Section VI.

II. Discussion on Mode Coupling Mechanism

Fig. 1 presents the transverse cross-section of a coaxial cavity with corrugations on the inner and the outer wall. In particular, the inner radius of the cavity is R_i, whereas the outer radius is $R_o = C \cdot R_i$, with C being the outer to inner radii ratio. On the inner and the outer wall of the cavity there have been engraved N and M, respectively, wedge-shaped corrugations. The depth of those corrugations is D for the outer and d for the inner wall. Assuming that the ratio N/M is an integer number, the period of the structure is $\varphi_P = 2\pi/M$, defined by the number of corrugations on the outer wall. The angular corrugation parameter, defined as the ratio of the groove of the corrugation to the angular width of the unit cell of the corrugation, is φ_D/φ_P for the outer wall and φ_L/φ_S for the inner wall. Such a structure was studied in detail in [11], [12], where the Spatial Harmonics Method (SHM) was used to derive the characteristic equation for the eigenvalues of the TE modes and the effect of the corrugation properties on the spectrum was examined.

The way that the inner corrugations affect the TE modes eigenvalue spectrum of a coaxial gyrotron cavity with a smooth insert was presented in detail in [13]. It was then shown, by using an example, that due to the inner corrugations the modes of the smooth coaxial cavity couple between each other and consequently the eigenvalue spectrum of a TE mode family with azimuthal index m in a cavity with inner corrugations, is a mixture of slightly modified eigenvalue curves of a smooth coaxial cavity with azimuthal indexes equal to the azimuthal wavenumber $k_n = m + n \cdot N$, where $n = 0, \pm 1, \pm 2, \ldots, \pm n_{max}$. The total number of coupled modes that one should consider in order to have an adequately accurate representation of the spectrum in a specific C-value range, can be easily estimated by the inequality $|m + n \cdot N| < \chi$, where χ is the eigenvalue of the mode of interest [13].

Of course for a specific eigenvalue χ it is possible to select a large enough number for the inner corrugations in order to make the coupled modes appear high enough in the eigenvalue spectrum and rather away from χ. In this case the mode coupling in the χ-value range of interest is relatively weak and an adequately accurate representation of the spectrum can be obtained without accounting for the coupled modes. Although the azimuthal coupling is not very strong in this case, by choosing appropriately the corrugation depth, the shape of the eigenvalue curves of the smooth coaxial cavity changes significantly and they gain beneficial properties for the mode selectivity of the cavity. This is a common practice in coaxial gyrotron cavities with corrugated inserts where a large number of inner corrugations is used.

The outer corrugations work in a similar way with the inner ones. Actually, if we selected to have a corrugated outer wall and a smooth insert, the characteristic equation of TE modes for this type of corrugated cavity would be essentially the same as for the case of the cavity with inner corrugations only, and the coupling of azimuthal modes would be evoked in the same way. The presence, however, of corrugations on both walls makes things more complicated, since each of the surface corrugations couples a different set of mode families, which is defined by the total number of corrugations, namely N and M, that exist on each wall. If, indeed, the outer corrugations are relatively large and resemble to side cavities, the spectrum will be enriched by those cavities resonances and their harmonics too. In such a dense and complicated spectrum it would be difficult to find a convenient working point for the cavity.

Having in mind the above mentioned observation about weak azimuthal mode coupling in the cavity with smooth outer wall and an adequately large number N of inner corrugations, and in order to avoid working with an unmanageably dense spectrum, it is rather preferable to select N to be large enough so that all the coupled modes due to the inner corrugations are in a safe distance from the working mode. Then, the outer corrugations will effectively couple the slightly modified eigenmodes of the typical coaxial cavity with a corrugated insert, in a similar way with the one that the inner corrugations would couple the eigenmodes of a coaxial cavity with smooth walls. In particular, a relatively small number of outer corrugations M will couple both the working mode and its main azimuthal competitors with distant lower-order and higher-order modes of the cavity. The exact modes that will be coupled to each m-index are dictated and can be easily identified by the azimuthal wavenumber $k_n = m + n \cdot M$. Inversely, if the coupled modes of preference are known then the transverse wavenumber dictates the proper corrugation number M. In any case, these coupled modes will appear in the eigenvalue spectrum as almost straight lines that will force the eigenvalue curves of the working mode and its competitors to bend, since it is not possible for the curves of two coupled modes to cross each other. Our goal with the outer corrugation is to find a specific C-range where the coupled modes force the azimuthal competitors to bend but the working mode remains almost unaffected.

The aforementioned idea, first appeared in [9] can be better explained by example. For this reason in Section III we consider an already realized coaxial gyrotron cavity and we present the procedure that could be followed step by step to enhance the selectivity properties of a corrugated gyrotron cavity.

III. Cavity Design Procedure

We consider an already realized coaxial gyrotron cavity with the geometrical properties that are presented in Fig. 2. For this cavity the co-rotating TE$_{-28.16}$ mode (in our representation in [12] negative m-values correspond to co-rotating modes) with eigenvalue $\chi \approx 87.36$ was chosen as the working mode for operation at 140 GHz [14]. The main azimuthal competitors of the working mode are the co-rotating TE$_{-27.16}$ ($\chi \approx 86.04$) and TE$_{-29.16}$ ($\chi \approx 88.67$), with TE$_{-27.16}$ being the competitor that replaces the working mode at higher voltage and thus limits its stability range. The inner to outer radii ratio C in the middle section of the cavity, where the beam-wave interaction practically occurs, takes values in the range $3.66 < C < 3.83$. Our goal is to introduce M outer corrugations of proper dimensions in order to couple the azimuthal competitors with other low-order modes in the aforementioned C-range, but leave the working mode practically uncoupled in that C-range. It should be noted at this point that all the aforementioned competing modes are co-rotating and following the notation used in [12] they have a negative m-index. In this study, we prefer to continue using this notation, which means that every spatial term that has negative azimuthal wavenumber corresponds to a co-rotating coupled mode, whereas every spatial term with positive azimuthal wavenumber corresponds to a counter rotating coupled mode.

Prior to searching for the proper M-value, we should ensure that the already existing inner corrugations do not evoke azimuthal coupling of modes with eigenvalues in the area of the working mode. According to the strict criterion $N > |m| + \chi$ presented in [13], this can be ensured for eigenvalues up to $\chi \approx 90$ and for all the competing modes (higher azimuthal competitor with index $m = 29$) by having an insert with at least 119 corrugations. Thus, we increase the number of the inner corrugations from $N = 72$ to $N = 132$ or $N = 176$. The reason why we selected these values with be further justified in the manuscript when we will select the number of the outer corrugations M. In Fig. 3 we plot the eigenvalue curves of the modes TE$_{-28,\mathrm{p}}$ for $N = 72$ (black lines), $N = 132$ (blue dots) and $N = 176$ (red dashes), taking into account each time all the spatial terms needed for accurate calculations. In both cases, the increase of the corrugations number did not affect the eigenvalue curve of the working mode and additionally shifted the coupled modes higher in the spectrum, rarefying in this way the spectrum. The only change that may be observed is on the inner mode [6], which is not of interest for the operation of the cavity. Note that these coupled modes would not have been visible if we had used the Surface Impedance Model (SIM) [6] for the calculation of the eigenvalue curves and any estimation of the selectivity properties of the upgraded cavity would probably be less accurate for 72 corrugations.

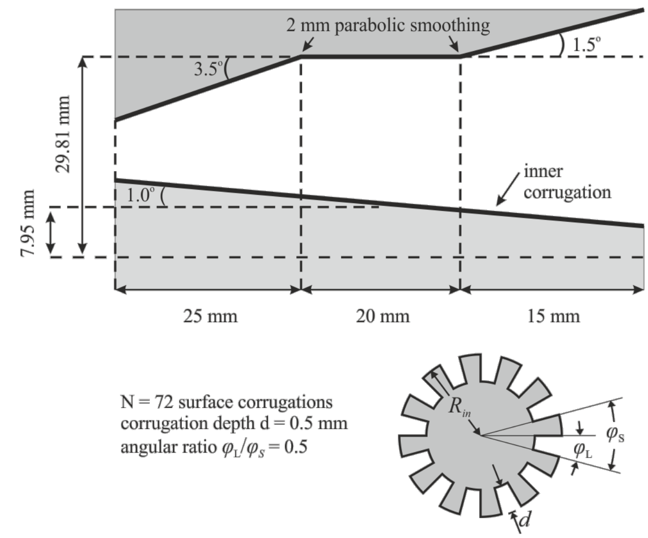

Fig. 2. Geometrical properties of the 140 GHz coaxial gyrotron cavity with corrugated insert [14] that is used as an example in Section III.

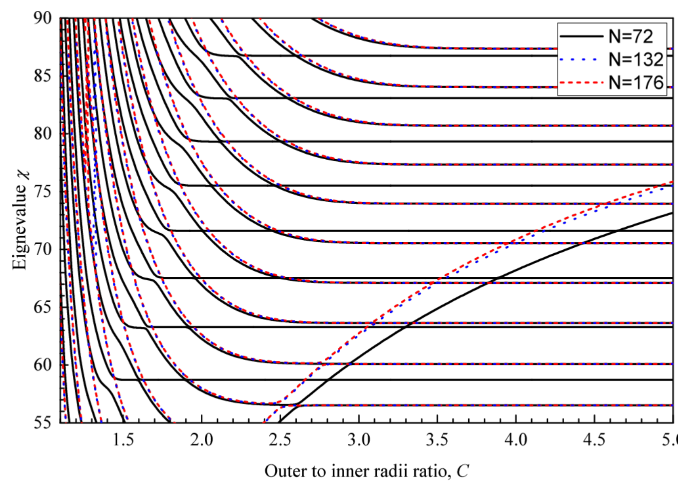

Fig. 3. Eigenvalues curves with azimuthal index $m = 28$ in a coaxial cavity with the number of the inner corrugations as a parameters. A large enough corrugation number ensures absence of mode coupling and mainly affects the inner mode.

Having selected the N-value properly we can proceed to the selection of the M-value. Since we suppressed the inner corrugation coupling, we expect the outer corrugations to couple the slightly modified eigenvalue curves of the cavity with the corrugated insert. In this context we calculate the eigenvalue curves of all TE modes in a coaxial cavity with inner corrugations for azimuthal indexes up to $|m| = 90$. Then, we overlay these eigenvalue curves in sets of three sequential m indexes over the eigenvalues of the main azimuthal competitor triplet, i.e. the modes with azimuthal indexes $m = -27, -28, -29$, in order to gain insight of how the corresponding spectrum is rearranged. For example in Fig. 4 we examine the coupling of modes $\mathrm{TE}_{-28,\mathrm{p}}$ with modes $\mathrm{TE}_{-13,\mathrm{p}}$, where $p = 1, 2, ...$ is the radial index of each mode. Taking into account that the azimuthal wavenumber is $k_n = m + n \cdot M$, $n \in \mathbb{Z}$, it is easy to understand that this coupling scheme could be evoked by introducing $M = 15$ corrugations on the outer wall, since $k_{-1} = 28 - 1 \cdot 15 = -13$. Similarly, the azimuthal competitors $\mathrm{TE}_{-27,\mathrm{p}}$ and $\mathrm{TE}_{-29,\mathrm{p}}$ would couple with the low-order modes $\mathrm{TE}_{-12,\mathrm{p}}$ and $\mathrm{TE}_{-14,\mathrm{p}}$ respectively. In the same figure the range $3.66 < C < 3.83$, which corresponds to the C-values of the middle section of the cavity, has been grayed out. It can be seen that in the aforementioned range the working mode $\mathrm{TE}_{-28,16}$ would probably couple strongly with the low-order mode $\mathrm{TE}_{-13,20}$, whereas the competitors are unaffected by their coupled modes. Consequently, this kind of outer corrugation would strongly degrade the quality factor of the working mode and should be avoided. Note that all the above mentioned eigenvalue curves refer to a coaxial cavity with corrugation only on the insert and they have been calculated taking into account all the necessary spatial terms.

Fig. 5 presents the possible coupling of $\mathrm{TE}_{-28,\mathrm{p}}$ modes with the counter rotating modes $\mathrm{TE}_{16,\mathrm{p}}$. Obviously, this coupling scheme could be achieved by introducing $M = 44$ corrugations on the outer wall and would evoke coupling of the competitors $\mathrm{TE}_{-27,\mathrm{p}}$ and $\mathrm{TE}_{-29,\mathrm{p}}$ with the low-order mode counter rotating sets $\mathrm{TE}_{17,\mathrm{p}}$ and $\mathrm{TE}_{15,\mathrm{p}}$, respectively. In difference to the previous M selection, it seems that with $M = 44$ the working mode remains almost unaffected along the middle section of the cavity $3.66 < C < 3.83$ (grayed out region in the graph), whereas both of the azimuthal competitors couple strongly with the aforementioned low-order mode sets. In particular $\mathrm{TE}_{-27,16}$ is sturdily coupled with $\mathrm{TE}_{17,19}$ in a similar manner that $\mathrm{TE}_{-29,16}$ is coupled with $\mathrm{TE}_{15,20}$.

Of course in the previous calculations we took into account just the nearest coupled mode set. In other words in the identification of the possibly coupled modes using the azimuthal wavenumber $k_n = m + n \cdot M$, we considered only the coupled modes that correspond to the $n = -1$ spatial term. In order to have a clearer image of the rearranged spectrum, all the coupled mode sets defined by the wavenumber k_n and the criterion $|m + n \cdot M| < \chi$ with $n = 0, \pm1, \pm2, \ldots, n_{max}$ should be taken into account. Fig. 6 presents all the modes that would possibly couple in the eigenvalue range $85 < \chi < 90$ due to the 44 outer corrugations, taking into account all the spatial harmonics up to $n_{max} = \pm 2$. According to this figure the modes $\mathrm{TE}_{-28,\mathrm{p}}$ are coupled not only with the $\mathrm{TE}_{16,p}$ mode set but additionally to the higher-order mode sets $\mathrm{TE}_{-72,\mathrm{p}}$ and $\mathrm{TE}_{60,\mathrm{p}}$. This means that the expected spectrum will probably be quite more complex than the approximated in Fig. 5. Correspondingly, the coupling scheme of the azimuthal competitors is more complex. For example in the C-range of interest, the higher located competitor $\mathrm{TE}_{-29,16}$ is coupled not only with the distant $\mathrm{TE}_{15,20}$ mode, but with the higher-order $\mathrm{TE}_{59,6}$ mode too. The latter mode would have not be visible if we had addressed the coupling problem using a surface impedance

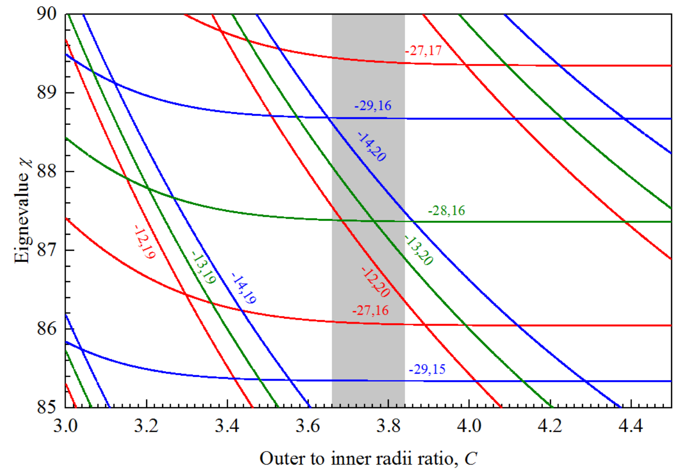

Fig. 4. Possible coupling of the working mode $\mathrm{TE}_{-28,16}$ with mode $\mathrm{TE}_{-13,20}$. The competitors $\mathrm{TE}_{-27,16}$ and $\mathrm{TE}_{-29,16}$ would couple with $\mathrm{TE}_{-12,20}$ and $\mathrm{TE}_{-14,20}$, respectively.

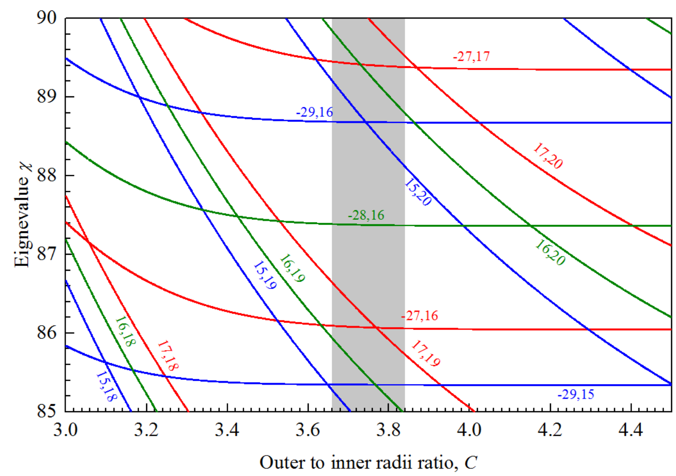

Fig. 5. Possible coupling of the working mode $\mathrm{TE}_{-28,16}$ with mode $\mathrm{TE}_{-16,20}$. The competitors $\mathrm{TE}_{-27,16}$ and $\mathrm{TE}_{-29,16}$ would couple with $\mathrm{TE}_{17,19}$ and $\mathrm{TE}_{15,20}$, respectively.

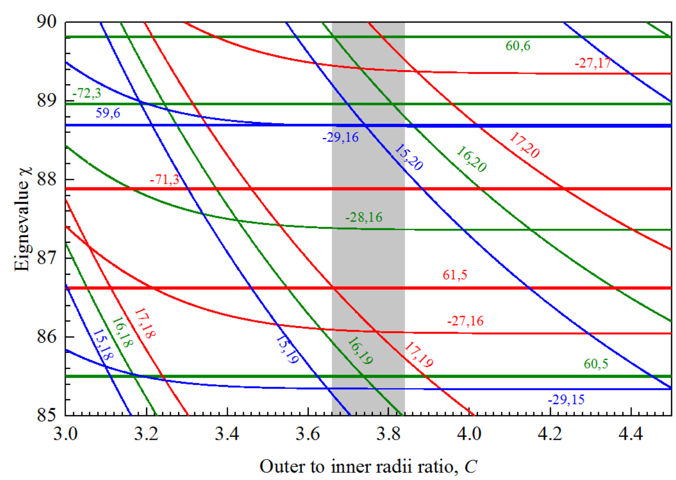

Fig. 6. Complete coupling scheme of $\mathrm{TE}_{-28,16}$ and its azimuthal competitors $\mathrm{TE}_{-27,16}$ and $\mathrm{TE}_{-29,16}$. All the possibly coupled modes in the range $85 < \chi < 90$ have been taken into account.

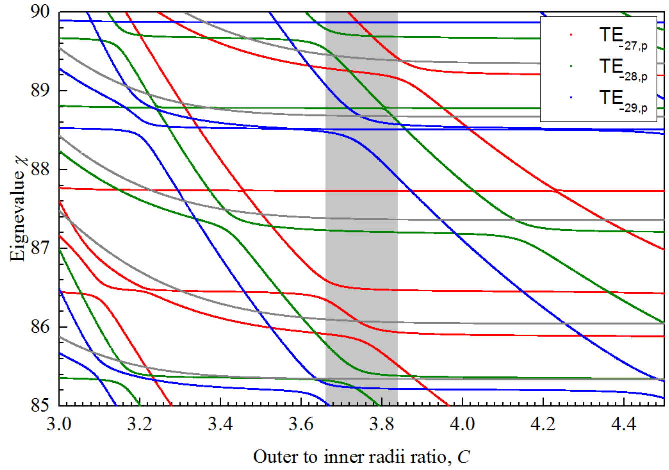

Fig. 7. SHM calculated spectrum for the three competing modes in the modified cavity with $N = 176$ and $M = 44$ outer corrugations of depth $D = 0.1$ mm.

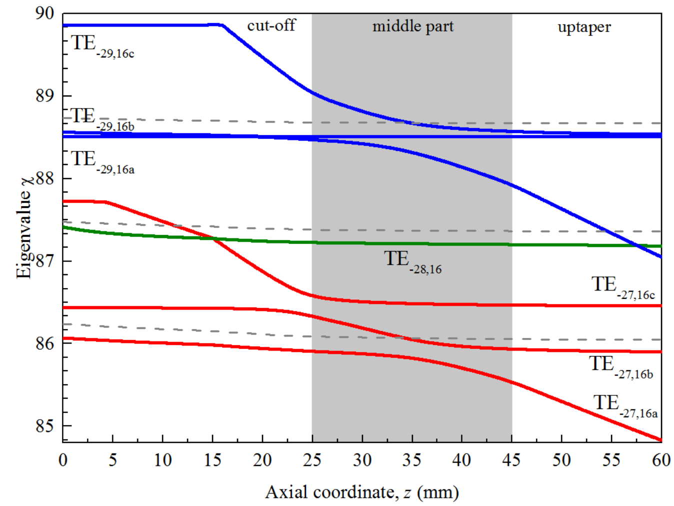

Fig. 8. Eigenvalue curves of the competing modes in the upgraded cavity with respect to the axial coordinate z. Lines with different color correspond to different azimuthal indexes and do not intersect between each other.

method and thus the necessity for considering the extra spatial terms in the representation of the field distributions becomes now clear.

Up to now we used the characteristic equation of the coaxial cavity with corrugated insert and smooth walls in order to find the proper number of outer corrugations and gain insight on how the rearranged spectrum will approximately be. In order, to calculate the actual full-wave eigenvalue spectrum we have to define the geometrical properties of the outer corrugations and solve the characteristic equation of the complex cavity. In this way we will also account for the ”inner” mode that could appear due to the presence of the outer corrugations, which was definitely not visible with the simplified procedure that we followed. For simplicity we select the angular ratio of the corrugation unit cell to be $\varphi_D/\varphi_P = 0.5$ and the relatively small depth $D = 0.1$ mm (approximately 0.05λ with λ being the free space wavelength for 140 GHz), so that the spectrum is not rearranged massively. The number of the outer corrugations is $M = 44$, whereas the number of the inner corrugations is $N = 176$. Note that for simplicity reasons the SHM approach presented in [12] accounts for integer N/M ratios, without this affecting, though, the generality of the method. This assumption justifies why in Fig. 3 we presented the eigenvalue curves for $N = 132$ and $N = 176$ inner corrugations.

Fig. 7 presents the full-wave spectrum taking into account spatial terms up to $n_{max} = 5$. For comparison reasons in the same figure we present with dark gray lines the eigenvalue curves of the basic azimuthal competitor triplet ($\mathrm{TE}_{-27,16}$, $\mathrm{TE}_{-28,16}$ and $\mathrm{TE}_{-29,16}$) in the cavity without outer corrugations. Although this figure is quite similar to the approximation presented in Fig. 6, one could observe that the working mode $\mathrm{TE}_{-28,16}$ appears with a slightly lower eigenvalue than before due to the increase of the resonating volume of the cavity. On the other hand the spectrum in the area of the azimuthal competitors has been so massively rearranged that the quality factor of these modes should drop rapidly. The change of the resonance properties of the competing azimuthal modes is studied in Section IV.

TABLE I
QUALITY FACTORS OF THE UPGRADED CAVITY

Cavity	Mode	Frequency (GHz)	Diffractive Q
initial	$\mathrm{TE}_{-27,16}$	137.866	1458
upgraded	$\mathrm{TE}_{-27,a}$	137.474	412
	$\mathrm{TE}_{-27,b}$	137.802	505
	$\mathrm{TE}_{-27,c}$	138.541	1219
initial	$\mathrm{TE}_{-28,16}$	139.948	1603
upgraded	$\mathrm{TE}_{-28,16}$	139.694	1533
initial	$\mathrm{TE}_{-29,16}$	142.036	1708
upgraded	$\mathrm{TE}_{-29,a}$	141.385	279
	$\mathrm{TE}_{-29,b}$	141.767	1727
	$\mathrm{TE}_{-29,c}$	142.012	554

IV. SELECTIVITY PROPERTIES

We consider the coaxial cavity with the geometrical parameters presented in Fig. 1 with the modified number of inner corrugations. Additionally, we suppose $M = 44$ slots on the outer wall with depth $D = 0.1$ mm and angular ratio $\varphi_D/\varphi_P = 0.5$. For this cavity we calculated the eigenvalue curves of the TE modes with azimuthal indexes $m = -27, -28, -29$ with respect to the axial coordinate z. For representation reasons in Fig. 8 we present only those eigenvalue curves that are located near the ones of the competing modes of the original cavity, which are also shown in the figure with gray dashed lines. Regarding the names of the modes, we retained the notation $\mathrm{TE}_{-28,16}$ for the working mode, since this mode is almost unaffected from the mode coupling corrugations of the outer wall. For the competitors $\mathrm{TE}_{-27,16}$ and $\mathrm{TE}_{-29,16}$ we add the subscripts a, b and c to show that these modes originate from the initial competitor that is coupled with those modes that the spatial harmonics indicate. Recall that the coupled modes has been presented in detail in Fig. 6.

The eigenvalues curves depicted in Fig. 8 are then used to calculate the resonance frequency and the corresponding diffractive quality factor of each new or modified mode. As it was previously mentioned, the eigenvalue curve of the working mode $TE_{-28,16}$ retains the beneficial properties that the corrugations of the insert provide and is almost unaffected from the outer corrugations, having a quite high diffractive quality factor, i.e. 1533, that only dropped by approximately 4% as shown in Table I. A similar drop is observed in the resonance frequency of the mode, which is of course expected, since the introduction of the outer corrugations increases the resonance volume of the cavity. Fig. 9 presents the magnitude of theE_{φ} component of $TE_{-28,16}$ field distribution. It is quite visible that the mode pattern has not changed significantly compared to the original $TE_{-28,16}$ field distribution. The main difference is that there is a slight modulation of the magnitude of the field in the φ coordinate that follows the outer corrugation.

On the contrary, the mode $TE_{-27,16}$, which was the most intense one among the competitors and would follow $TE_{-28,16}$ in the excitation sequence with respect to the accelerating voltage, has been modified significantly. $TE_{-27,16}$ transformed into three coupled modes that have quite reduced quality factors compared to the initial one. In detail, the modes with the largest $TE_{-27,16}$ content, i.e. $TE_{-27,16\mathrm{a}}$ and $TE_{-27,16\mathrm{b}}$, exhibit very low quality factors 412 and 505, respectively. The third mode $TE_{-27,16\mathrm{c}}$, which has relatively higher quality factor comparing to the two previously discussed modes, namely 1219, consists mainly of the low radial index mode $TE_{61,5}$, which is not expected to couple with the beam since it has caustic radius $R_c = |m| R_o/\chi \simeq 21.0$ mm, which is quite far away from the beam radius $R_b = 10.0$ mm [14] that is selected to fit to the caustic radius of $TE_{-28,16}$. Of course the caustic radius definition is probably used abusively here, since the field distribution of $TE_{-27,16\mathrm{c}}$ is not a pure $TE_{61,5}$ distribution. However, Fig. 10 that presents the magnitude of the E_{φ} component of the mode, approximately at the center ($z = 35$ mm) of the middle part of the cavity, verifies that the maximum of the field distribution is rather away from the beam's position.

The case is quite similar for the higher azimuthal competitor $TE_{-29,16}$ too. The latter mode is also transformed to three new ones. $TE_{-29,16\mathrm{a}}$ and $TE_{-29,16\mathrm{c}}$ that have relatively high $TE_{-27,16}$ content exhibit quite low diffractive quality factors, 279 and 544, respectively. On the contrary, $TE_{-27,16\mathrm{b}}$ has a quality factor that is comparable to the one of the working mode, i.e 1727. This was rather expected, since the eigenvalue curve of the mode is almost a straight line. Of course $TE_{-29,16\mathrm{b}}$ consists mainly of $TE_{59,6}$, which has caustic radius $R_c \simeq 19.9$ mm and for this reason is not expected to be a strong competitor. Fig. 11 presents the magnitude of the E_{φ} component of the $TE_{-29,16\mathrm{b}}$ mode, which verifies that the field in the region of the electron beam is rather weak.

At this point it is worthwhile to mention that the coupled modes $TE_{-27,16\mathrm{c}}$ and $TE_{-29,16\mathrm{b}}$ correspond to the second nearest spatial harmonic of their main azimuthal index and they would not be visible in the eigenvalue spectrum if a simpler approach, such as the Surface Impedance Model, was

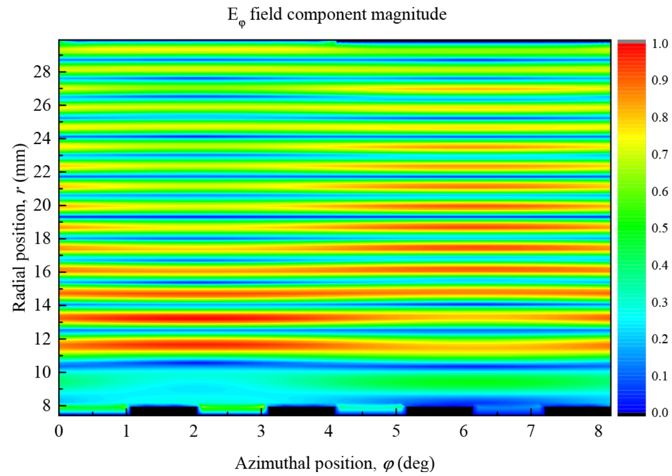

Fig. 9. $TE_{-28,16}$ mode contour plot of the magnitude of the E_{φ} field component (a.u), calculated at the middle of the cavity ($z = 35$ mm). The field distribution retains the properties of the corresponding mode in a cavity with smooth outer wall.

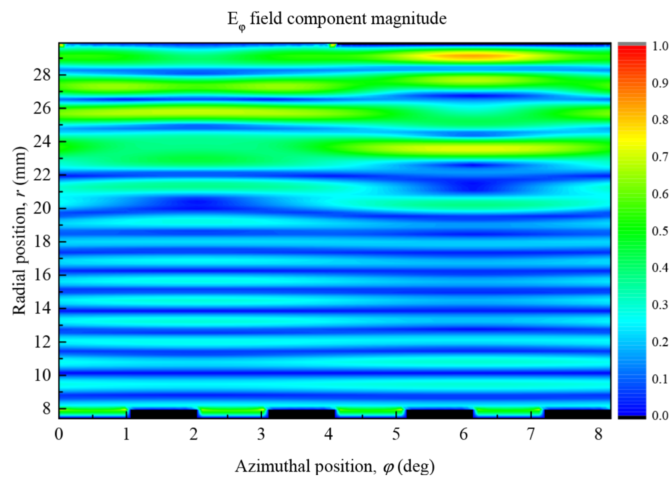

Fig. 10. $TE_{-27,16\mathrm{c}}$ mode contour plot of the magnitude of the E_{φ} field component (a.u.), calculated at $z = 35$ mm. The maximum of the field appears near the caustic radius of $TE_{61,5}$.

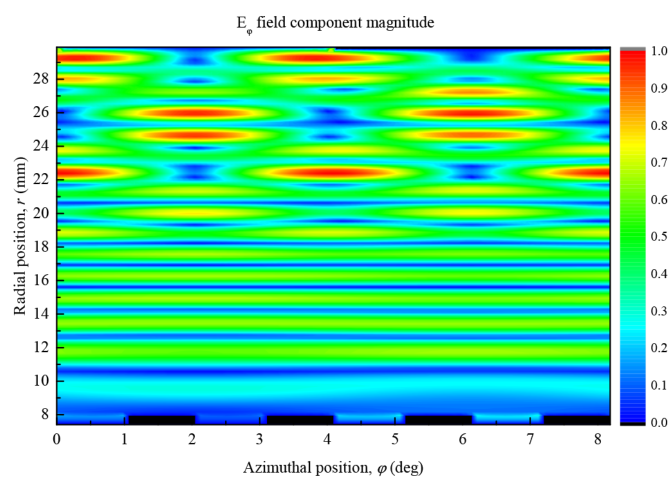

Fig. 11. $TE_{-29,16\mathrm{b}}$ mode contour plot of the magnitude of the E_{φ} field component (a.u.), calculated at $z = 35$ mm. The maximum of the field appears near the caustic radius of $TE_{59,6}$.

employed.

V. Ohmic Loading of the Walls

A limiting factor for the design of a coaxial corrugated cavity is the ohmic loading of the corrugated walls. Assuming a typical cooling system, a rule of thumb for the cavity design is to keep the ohmic loading of the outer wall less than 2 kW/cm^2 and the loading of the inner wall approximately ten times lower.

Supposing that the conductivity of the walls is $\sigma = 1.4\times10^7$ S/m (accounting also for the effects of high operating temperature and surface roughness on the conductivity of copper) and that the RF power generated in the cavity is $P = 1.5$ MW, the peak ohmic loading of the outer wall is $p_o = 1.03$ kW/cm^2 whereas the peak loading of the inner wall is $p_i = 0.28$ kW/cm^2. In the original cavity without the outer corrugations the peak losses density for the outer and the inner wall is $p_o = 0.93$ kW/cm^2 and $p_i = 0.21$ kW/cm^2, respectively. Thus, in the upgraded cavity the loading of the outer wall is increased by approximately only 10%, whereas the loading of the inner wall by 33%.

It should be noted, however, that the loading of the insert could be easily decreased by reducing the number of the surface corrugation and by slightly decreasing its radius.

VI. Summary and Conclusion

In this work we examined in detail how the introduction of a relatively small number of corrugations on the outer wall of a coaxial cavity with a corrugated insert can be beneficial for its selectivity properties. The enhanced selectivity properties of the cavity originate from the fact that the outer corrugation couples the azimuthal competitors of the working mode to other ones having either lower of higher azimuthal indexes, whereas the working mode remains almost unaffected. For this reason a full-wave method was used.

A procedure for the design of the outer corrugations was outlined. In particular, focusing on the example of an already designed and manufactured 140 GHz coaxial gyrotron cavity, a high-enough number of inner corrugations was selected to ensure absence of mode coupling due to the inner corrugations. Then, a relatively small number of corrugations was selected ensuring that the coupled modes that the outer wall brings on affect only the azimuthal competitors. The eigenvalue curves of the modified modes were consequently used in order to calculate the resonance frequencies and the corresponding diffractive quality factors. Calculations with a SHM based numerical code showed that most of the modified azimuthal competitors have lower quality factors than the slightly modified working one. In the cases where the modified competitors had higher quality factor, the field distribution of the modes was used to ensure that the interaction with the beam will be probably weak, since the most of the field content is located away from the beam radius.

As an extension of this work the actual beam-wave interaction should be examined in such a complex cavity. We are already working towards this goal by creating a common interface between the SHM based cold-cavity approach numerical code and the self-consistent interaction code package EURIDICE [15]. In this way the SHM eigenvalue curves and the transverse field structure of the modified competitors will be introduced to the EURIDICE interaction code and different start-up scenarios will be studied.

It should be noted that although the presented methodology was illustrated by the 140 GHz coaxial gyrotron cavity example, it is quite evident that it is general and it can be used in any other gyrotron case.

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