ANNEX XXII

Alternative coaxial inserts for the interaction cavity of the European 170 GHz coaxial gyrotron for ITER*

K. A. Avramides
School of Electrical and Computer Engineering, National Technical University of Athens

INTRODUCTION

From the experimental results, regarding the pre-prototype 170 GHz coaxial gyrotron for ITER, existing at FZK, it is understood that the major competitor of the operating $TE_{34,19}$ mode is the $TE_{33,19}$ mode [1]. This mode is excited right after $TE_{34,19}$ during start-up, and its appearance at a beam voltage lower than predicted by the simulations, prevents the operating mode from reaching the desired power and efficiency. We investigate ways to suppress the competing $TE_{33,19}$ mode by introducing a different coaxial insert in the interaction cavity. We consider various down-tapered inserts with different radii, corrugation depths, and taper angles.

INSERTS AIMING AT REDUCING THE *Q*-FACTOR OF THE COMPETING MODE

The corrugation depth of the existing insert is $d = 0.44$ mm, corresponding to a ratio $d/\lambda = 0.25$ for the operating $TE_{34,19}$ mode (λ is the free-space wavelength of the mode). It is known that any depth in the region $0.2 < d/\lambda < 0.3$ is suitable for a design of a gyrotron operating at the fundamental cyclotron frequency [2]. For depths outside that region, there is a possibility that some competing modes can have enhanced quality factors due to a positive slope of their eigenvalue curve $\chi_{mp}(C)$ at the cavity $C = R_o/R_i$. For that reason we do not consider such depths in this study.

Since, for $0.2 < d/\lambda < 0.3$, the eigenvalue curves $\chi_{mp}(C)$ of the modes interacting at the fundamental cyclotron frequency exhibit negative slope, any increase in the down-tapered insert radius and/or in its taper-angle will result in decreased diffractive quality factors for those modes. This decrease gets larger as the caustic radii of the modes get smaller, since the influence of the insert gets stronger then. The caustic radius of the competing $TE_{33,19}$ mode is smaller than the caustic radius of the operating $TE_{34,19}$ mode by about 1.25 %. Consequently, the insert is expected to affect the $TE_{33,19}$ mode more than the operating $TE_{34,19}$ mode. It thus seems tempting to use an insert as thick as possible, in order to benefit from the different degree of decrease of the quality factors of the modes $TE_{34,19}$ and $TE_{33,19}$.

The insert radius is limited by ohmic loading considerations. The peak loading of the insert should not exceed 0.1 kW/cm^2 (ideal copper at 20°C) for CW operation. In the following, we considered an output power of about 2.2 MW and we determined the maximum radius R_i compatible with the ohmic loading limitation for every different insert. The results for several inserts in the cold-cavity approximation are shown in Table I. The insert IT1 of the first line is the existing coaxial insert of the pre-prototype tube. The peak ohmic loading for that insert is 0.04 kW/cm^2 for 2.2 MW output power. As a result, its radius could be further increased. This case is the I01 insert of the second line. For this thicker insert, as well as for the other five inserts below, the peak ohmic

TABLE I

Inserts compatible with ohmic loading considerations aiming at decreased $Q_{33,19}$

Insert	d (mm)	d/λ	R_i(*), (taper) (mm, deg)	$Q_{34,19}$	$Q_{33,19}$	Q_{com}/Q_{op} (%)	$f_{34,19}$ (GHz)	$f_{33,19}$ (GHz)	$f_{op} - f_{com}$ (GHz)
IT1	*0.44*	*0.25*	*8.00 (1°)*	*1639*	*1579*	*96.34*	*169.988*	*167.874*	*2.114*
I01	0.44	0.25	8.26 (1°)	1590	1502	94.47	170.000	167.895	2.105
I21	0.44	0.25	8.38 (2°)	1526	1390	91.09	170.001	167.898	2.103
I02	0.53	0.30	8.37 (1°)	1610	1528	94.91	169.995	167.887	2.108
I22	0.53	0.30	8.49 (2°)	1561	1442	92.38	169.996	167.888	2.108
I03	0.35	0.20	7.92 (1°)	1621	1547	95.43	169.992	167.882	2.110
I23	0.35	0.20	8.03 (2°)	1585	1480	93.38	169.993	167.883	2.110
Extreme insert geometries									
THICK	0.44	0.25	8.67 (2°)	1327	1134	85.46	170.036	167.957	2.079
THIN	0.44	0.25	5.00 (1°)	1666	1633	98.02	169.983	167.863	2.120

(*) At the beginning of the midsection of the cavity

* Work performed in co-operation with Forschungszentrum Karlsruhe (FZK).

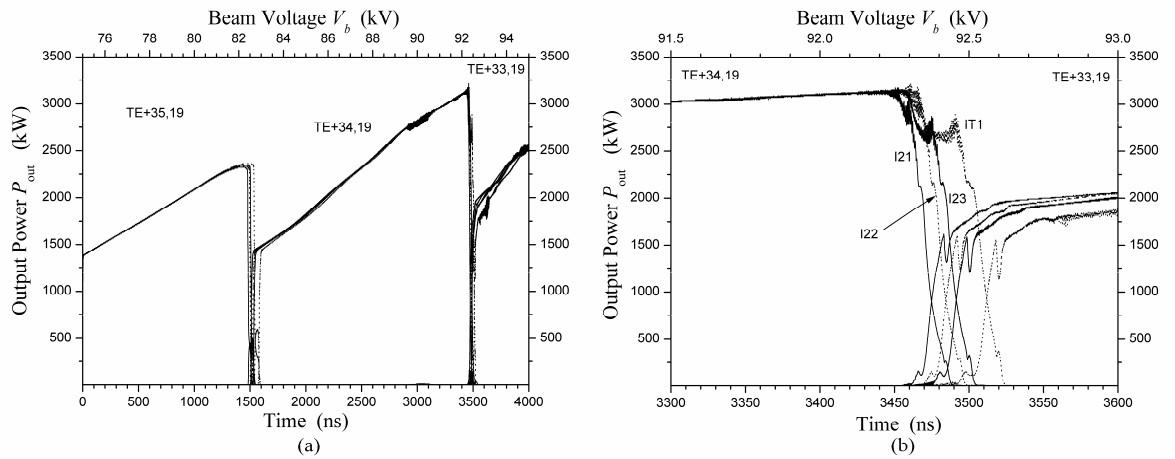


Fig. 1: Start-up simulations taking into account the modes $TE_{35,19}$, $TE_{34,19}$, and $TE_{33,19}$. (a) Excitation and detuning of the operating $TE_{34,19}$ mode for some of the insert configurations of Table I. (b) Detail of (a).

loading for 2.2 MW output power is 0.1 kW/cm^2. We considered 1° or 2° down-tapered inserts with corrugation depths d/λ = 0.2, 0.25, 0.3. In Table I, the cold-cavity values of the total quality factors and of the frequencies of the modes $TE_{34,19}$ and $TE_{33,19}$ are shown. In column 7, the ratio $Q_{33,19}/Q_{34,19}$ is also shown. This ratio expresses the degree of suppression of the competing $TE_{33,19}$ mode by the insert.

Regarding the different values of the corrugation depth, there is some kind of trade-off between the ohmic loading of the insert and its influence on the diffractive quality factor of the modes. In particular, when d/λ approaches 0.2, the ohmic loading increases and consequently the inner radius R_i should be smaller. However, the eigenvalue curves of the modes exhibit quite a steep negative slope and hence an insert of even a small radius can influence the diffractive quality factors to a significant degree. On the other hand, when d/λ approaches 0.3, the ohmic loading decreases and hence a larger R_i is feasible. However, in this case, the eigenvalue curves exhibit only a mild negative slope. As a result, although the insert radius can be larger, its influence on the diffractive quality factors remains at the same levels as in the $d/\lambda \to 0.2$ case. This can be seen in Table I. The case $d/\lambda \to 0.25$ is somewhere in-between and, as it turns out, it can offer the best suppression of $TE_{33,19}$.

It is apparent from column 7 of Table I, that every alternative insert seems to suppress the competing $TE_{33,19}$ mode better than the existing one. This is because the choice of R_i for those inserts was based on limiting ohmic loading. The best results are achieved by the 2° down-tapered inserts. In order to check whether a different insert will indeed improve the situation for the operating mode, we performed simulations for its excitation and detuning for the cases of the 2° down-tapered inserts I21, I22 and I23. An operating point of 90 kV, 75 A and α = 1.3, together with a magnetic field around 6.860 T were assumed. These values correspond to the value $\Delta \cong 0.453$ for the normalised frequency mismatch Δ of the operating $TE_{34,19}$ mode at the operating point. For the simulations, the self-consistent code *SELFT* [3] was used. The results are shown in *Fig. 1(a)*.

What is particularly interesting is the point of detuning of the operating mode, shown in detail in *Fig. 1(b)*. According to column 7 of Table I, we can list the inserts from worse to better suppression of the competing $TE_{33,19}$ mode as follows: IT1, I23, I22, I21. However, according to *Fig. 1(b)*, the list from worse to better suppression of the $TE_{33,19}$ appears to be exactly the opposite, i. e. I21, I22, I23, IT1. There are two possible reasons for this discrepancy: In the sequence I21, I22, I23, IT1 the cold-cavity quality factor of the operating $TE_{34,19}$ mode becomes larger. Second, and most important, in that sequence the cold-cavity frequency separation between$TE_{34,19}$ and $TE_{33,19}$ also becomes larger (last column of Table I). We can thus deduce the following: In the present cavity and operating parameters, the point of detuning of the operating $TE_{34,19}$ mode probably depends more strongly on the value of its quality factor and on the frequency separation from the competing $TE_{33,19}$ mode, than on the quality factor of the latter. In other words, the fact that the inserts I23, I22, I21, achieve ratios $Q_{33,19}/Q_{34,19}$ more in favour of the operating $TE_{34,19}$ mode, is strongly offset by the fact that they reduce both $Q_{34,19}$ and the frequency separation of $TE_{34,19}$ and $TE_{33,19}$. As a result the existing insert IT1 performs better.

The calculations of the ohmic loading have been performed using the Surface Impedance Model (SIM) for the corrugated insert [2]. It is known that when the ohmic losses are calculated with a more accurate full-wave model [4], their value can be about half the value predicted by SIM. For that reason, in order to take advantage of the reduction of the ratio $Q_{33,19}/Q_{34,19}$ due to a thick insert to full extent, we also tried a 2° down-tapered insert of 8.67 mm radius exhibiting 0.2 kW/cm^2 peak ohmic loading for 2.2 MW output power (according to SIM). This insert is denoted as THICK in Table I. However, although $Q_{33,19}/Q_{34,19}$ = 85.46 % for this insert, its performance is even worse compared to the other inserts of Table I, as can be seen in the simulation of *Fig. 2*. The reason must be again the small frequency separation of $TE_{34,19}$ and $TE_{33,19}$ combined with the low $Q_{34,19}$. It is

thus understood that in the case of the 170 GHz coaxial gyrotron, the effort to suppress the competing $TE_{33,19}$ mode should focus rather on increasing the frequency separation between $TE_{33,19}$ and $TE_{34,19}$ than decreasing the ratio $Q_{33,19}/Q_{34,19}$. This frequency separation is maximum in a hollow cavity. For example, the insert denoted THIN in Table I, which has such a small radius that it has no effect on $TE_{34,19}$ and $TE_{33,19}$, results in the maximum frequency separation $\Delta f = 2.120$ GHz. A simulation with this insert (*Fig. 2*) indicates that it has the best performance regarding the beam-voltage value of detuning of the operating mode, despite the fact that the Q-factors of $TE_{33,19}$ and $TE_{34,19}$ are very close. In the following section we will consider inserts aiming at increasing the frequency separation between $TE_{33,19}$ and $TE_{34,19}$, without compromising though the suppression of the other competing modes, especially those with radial index $p = 20$.

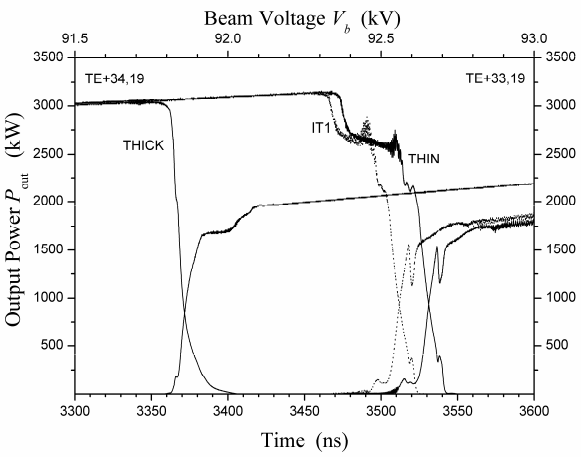


Fig. 2: Detuning of the operating $TE_{34,19}$ mode for the inserts THICK, THIN of Table I. The simulations take into account the modes $TE_{35,19}$, $TE_{34,19}$, and $TE_{33,19}$.

INSERTS AIMING AT INCREASING THE FREQUENCY SEPARATION

As it was mentioned above, any corrugation depth $0.2 < d/\lambda < 0.3$ is, in principle, suitable for operation at the fundamental cyclotron frequency. As it was pointed out in [2] though, the choice $d/\lambda \cong 0.2$ is safer regarding possible competition from modes interacting at the second cyclotron harmonic. Consequently, we will first consider inserts with $d/\lambda = 0.2$ (i. e. $d = 0.35$ mm). In Table II, several such inserts are shown. Only 2° down-tapered inserts are presented, because the performance of all the tested 1° down-tapered inserts was inferior. For each insert configuration, the starting currents of the basic triplet $\{TE_{35,19}, TE_{34,19}, TE_{33,19}\}$ together with the starting currents of the competing triplet $\{TE_{-33,20}, TE_{-32,20}, TE_{-31,20}\}$, are depicted in *Fig. 3*. (We use a negative azimuthal index to denote a counter-rotating mode.)

The first insert I24s of Table II keeps the frequency separation between $TE_{33,19}$ and $TE_{34,19}$ the same as in the existing cavity ($\Delta f = 2.114$ GHz), but it suppresses better the competing modes with radial index $p = 20$ (*Fig. 3*). According to simulations and experiment though, these modes do not seem to be important competitors, so the advantage of this insert is not of much importance. The second insert I24b achieves the best frequency separation (2.120 GHz), equal to that in the hollow cavity. However, according to *Fig. 3*, it suppresses less the competitors with radial index $p = 20$. Multi-mode simulations are needed to determine whether the modes with radial index $p = 20$ cause problems or not. Finally, the radius of the insert I25 was chosen in order to suppress the modes with radial index $p = 20$ at least as effectively as the existing insert IT1. As it turns out, this insert is better than the existing one: They both have almost equal performance in suppression of the modes with radial index $p = 20$ (I25 is even better), they both have the same $Q_{34,19}$ and ratio $Q_{33,19}/Q_{34,19}$, but the frequency separation between $TE_{33,19}$ and $TE_{34,19}$ is better with I25. Furthermore, as it has been said before, the insert I25 eliminates the possibility of competition from modes interacting with the beam at the second cyclotron harmonic. We have also tested inserts with $d/\lambda = 0.25$ ($d = 0.44$ mm)

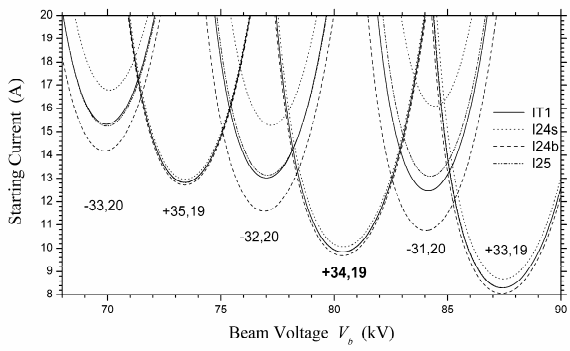


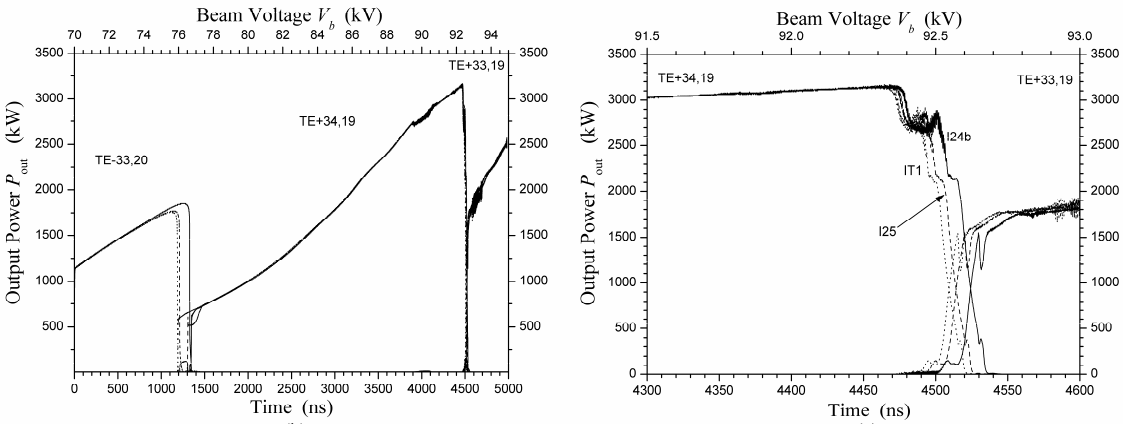
Fig. 3: Starting currents versus the beam voltage for the insert configurations of Table II.

TABLE II

Inserts with $d = 0.35$ mm aiming at increased frequency separation between $TE_{34,19}$ and $TE_{33,19}$

Insert	d (mm)	d/λ	R_i(*), (taper) (mm, deg)	$Q_{34,19}$	$Q_{33,19}$	Q_{com}/Q_{op} (%)	$f_{34,19}$ GHz)	$f_{33,19}$ (GHz)	$f_{op} - f_{com}$ (GHz)
IT1	*0.44*	*0.25*	*8.00 (1°)*	*1639*	*1579*	*96.34*	*169.988*	*167.874*	*2.114*
I24s	0.35	0.20	7.92 (2°)	1614	1529	94.73	169.989	167.875	2.114
I24b	0.35	0.20	7.50 (2°)	1659	1615	97.35	169.984	167.864	2.120
I25	0.35	0.20	7.75 (2°)	1640	1579	96.28	169.986	167.869	2.117

(*) At the beginning of the midsection of the cavity



(a) *(b)*

Fig. 4: Start-up simulations considering the modes $TE_{35,19}$, $TE_{34,19}$, $TE_{33,19}$, $TE_{-33,20}$, $TE_{-32,20}$, and $TE_{-31,20}$. (a) Excitation and detuning of the operating $TE_{34,19}$ mode for some of the insert configurations of Table II. An initial power of 1 *MW was assumed for the mode* $TE_{-33,20}$ *at* V_b = 70 *kV. (b) Detail of (a).*

and $d/\lambda = 0.3$ ($d = 0.53$ mm) in the same manner as described above. The results, however, were identical to those of the inserts with $d/\lambda = 0.2$ ($d = 0.35$ mm). Consequently, since the choice $d/\lambda = 0.2$ is preferable regarding competition from the second cyclotron harmonic, there is no need to consider using a corrugation depth different than $d/\lambda = 0.2$.

As it turned out, the most promising inserts are I24b and I25 of Table II. In order to check their performance, regarding also the suppression of modes with radial index $p = 20$, we performed multi-mode start-up simulations with the code *SELFT*. The results are shown in *Fig. 4(a)*, together with a similar simulation for the existing insert IT1. In order to support more the unwanted scenario of the excitation of a mode with radial index $p = 20$ at the operating point, we assumed that the mode $TE_{-33,20}$ is already excited at $V_b = 70$ kV. Still, the operating $TE_{34,19}$ mode is always excited afterwards (and not suppressed by $TE_{-32,20}$ or $TE_{-31,20}$) and reaches the operating point. According to *Fig. 4(b)*, both inserts I24b and I25 of Table II have better performance than the existing insert IT1. In addition the choice of their corrugation depth eliminates the possibility of competition from modes interacting at the second cyclotron harmonic. However, such competition has not been observed up to now, even with the existing insert, and the gyrotron performance with the inserts I24b and I25 is marginally improved compared to that with the existing insert. It is thus questionable whether just an insert replacement worth the effort.

SUMMARY AND CONCLUSIONS

The experimental results indicate that the $TE_{33,19}$ mode is the most dangerous competing mode in the coaxial cavity of the European 170 GHz gyrotron designed to operate in the $TE_{34,19}$ mode. An extended investigation of the use of an alternative coaxial insert in order to improve gyrotron performance, revealed the following: Attempts to suppress the $TE_{33,19}$ mode by reducing its quality factor using a thicker insert fail, because this reduction is always accompanied with a decrease in the frequency separation between $TE_{34,19}$ and $TE_{33,19}$. Consequently, the effort should be oriented towards the increase of this frequency separation. Thinner inserts seem to succeed in that, without compromising the suppression of the rest competing modes. It turns out that best results are achieved with a 2° down-tapered insert, with corrugation depth $d = 0.35$ mm and radius between 7.50 mm and 7.75 mm (inserts I24b and I25 of Table II). Furthermore, these inserts secure elimination of the possibility of competition from modes interacting at the second cyclotron harmonic. However, it seems that the improvement of the performance of the existing gyrotron with the use of just an alternative insert is marginal. Probably, a new design of the whole coaxial cavity is needed for more noteworthy results.

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