

DESIGN OF FOUR-CAVITY HIGH POWER GYROKLYSTRON AMPLIFIER*

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Abstract

In order to develop a high power Ku-band gyrokystron amplifier with high gain and efficiency for driving future linear colliders, a theoretical design of a four-cavity coaxial 17.1 GHz gyrokystron amplifier has been carried out. The X-band input cavity operates at TE₀₁₁ mode while the remaining three cavities (buncher, penultimate and output) operate at TE₀₂₁ mode, doubling the frequency of the input signal. The simulations show that both a very high efficiency of 45.6 % and a gain of 71 dB can be realized using a 500 kV, 700 A electron beam with a perpendicular-to-parallel velocity ratio of 1.5 and a parallel velocity spread of 6.4 %.

1 INTRODUCTION

Relativistic klystrons, gyrokystrons, magnicons and free-electron lasers are considered as the most promising candidates for driving future linear colliders. For TEV-scale linear colliders it is desirable to increase the electric field gradients which can be attained by increasing the radiation frequency. In recent experiments with a three cavity 1-1-1 coaxial gyrokystron carried out at the University of Maryland very high peak microwave powers of 75-85 MW at 8.6 GHz frequency were obtained [1]. The sequence 1-1-1 means that all three cavities, input, buncher and output, operate at the fundamental electron cyclotron frequency, so 1 is the cyclotron resonance harmonic number. To increase the frequency, the output cavity can be designed for operation at the second harmonic.

In previous computer simulations two-cavity and three-cavity frequency doubling gyrokystrons were studied (1-2 and 1-2-2 circuits) [2]. It was shown that introducing a second harmonic buncher cavity into a two-cavity 1-2 circuit (in this way a 1-2-2 circuit can be obtained) may increase the efficiency from 30 % to 41 % and gain from 26 dB to 49 dB; these results were obtained for a 500 kV, 700 A electron beam with a perpendicular-to-parallel velocity ratio (pitch-ratio) α of 1.508 and a parallel velocity spread of 6.4 %.

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To improve the device performance further we have undertaken a design of a four-cavity circuit, using the same beam parameters.

2 RESULTS FROM A POINT-GAP MODEL OF A FOUR-CAVITY GYROKLYSTRON

There exist at least four possible schemes of a four-cavity gyrokystron in which the input cavity operates at the fundamental and the output cavity – at the second cyclotron harmonic: 1-1-1-2, 1-1-2-2, 1-2-1-2 and 1-2-2-2. Here we may also add the scheme 1-2-4-2 where the third cavity resonates at the fourth harmonic frequency.

The design of each of these possible circuits requires a large consumption of computer time. In order to save this time we have first used a point-gap model (PGM) of the gyrokystron [3] to qualitatively estimate the performance of the five schemes. The PGM implies that the cavities lengths are much shorter than the drift spaces, thus electrons' energy is modulated in each cavity and this modulation causes electron phase bunching in drift regions. The three-cavity gyrokystron PGM developed in [3] was generalized for a four-cavity gyrokystron. The corresponding maximum efficiencies for the five schemes are given in Table 1. These values characterize the efficiency of electron bunching only but not the overall efficiency of the device. It is seen that the 1-2-2-2 circuit is the most efficient. Therefore detailed computer simulations were performed for this circuit.

Table 1: Maximum efficiencies calculated in the framework of PGM for 5 different circuits.

Circuit	Efficiency (%)
1-1-1-2	60.0
1-1-2-2	51.0
1-2-1-2	66.5
1-2-2-2	76.0
1-2-4-2	54.3

3 DESIGN OF 1-2-2-2 CIRCUIT

Our 1-2-2-2 circuit was based on the previously optimized 1-2-2 design [2]. The modification was done by inserting before the output cavity a second buncher (or penultimate) cavity with the same dimensions as the first buncher cavity. The geometry of the four-cavity

system is shown in Fig.1 and dimensions are tabulated in Table 2.

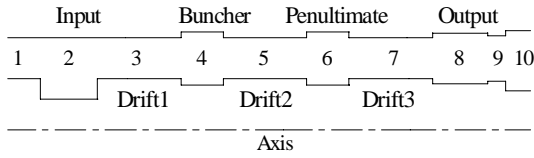


Figure 1: Geometry of the four-cavity 1-2-2-2 circuit

The operating modes are the TE_{011} mode for the input cavity and TE_{021} mode for the remaining three cavities. For operation in the 17.1 GHz frequency range, based on previous studies of a 1-2-2 design, the resonant frequencies of the input, buncher, penultimate and output cavities calculated by the scattering matrix code COAX [4,5] are 8.567 GHz, 17.136 GHz, 17.136 GHz and 17.063 GHz, respectively.

The large-signal code GYCOAX [6] was used for optimization of parameters to get maximum efficiency and gain. In the case of a four-cavity gyrokylystron it means a search in a 7-dimensional parameter space: 4 amplitudes (a_1, a_2, a_3 and a_4) and three relative phases (ϕ_2, ϕ_3 and ϕ_4) of the fields in each cavity – the phase ϕ_1 in the input cavity can be set to 0 without loss of generality.

Table 2: Dimensions of the four-cavity 1-2-2-2 circuit

Cavity or Section	No.	Inner Radius (cm)	Outer Radius (cm)	Length (cm)
Inlet	1	1.825	3.325	5.000
Input	2	1.100	3.325	2.286
Drift 1	3	1.825	3.325	3.328
Buncher	4	1.610	3.520	1.691
Drift 2	5	1.825	3.325	3.328
Penultimate	6	1.610	3.520	1.691
Drift 3	7	1.825	3.325	3.328
Output	8	1.620	3.520	1.712
Output	9	1.760	3.360	0.693
Outlet	10	1.400	3.550	5.000

Exploration of such a multidimensional space is almost hopeless without certain optimization procedure. For this reason a subroutine which varies all a 's and ϕ 's according to the Hooke-Jeeves method [7] and looks for the maximum efficiency was written and successfully embedded into the code GYCOAX. A further improvement of the optimization procedure was made by incorporating in the subroutine additional 3 parameters I_1, I_2 and I_3 , which correspond to the currents in three sets

of coils creating the guide magnetic field. Thus, the parametric space becomes 10-dimensional. In this way, however, we merge into one optimization procedure two previously separate procedures: first, optimization of the a 's and ϕ 's and second, optimization of the guide magnetic field.

The improved large-signal code was first applied to the configuration, presented in Fig. 1 where all drift spaces have the same length – 3.328 cm (see also Table 2). Both very high efficiency of 43.2 % and gain of 71 dB were calculated (compare with 41.1 % and 49 dB for the three-cavity 1-2-2 gyrokylystron design [2]).

Additional simulations were performed to further increase the efficiency by: 1) optimizing the drift space lengths and 2) stagger tuning (ST) [8,9] of the last two cavities.

At the first step, there exists an experimental setup constraint: the distance between the input cavity exit and the output cavity entrance have to be kept constant. For that reason, only the buncher and the penultimate cavities were moved. The results are presented in Table 3. In its first two rows 0 means that the cavity is in the same position as in Fig. 1, while +1 or –1 means that the corresponding cavity is displaced by 1 cm on the right or on the left, respectively. The efficiency for each configuration is given in the last row. The best result is obtained when the buncher cavity position is unchanged while the penultimate cavity is displaced 1 cm on the right (see fifth column in Table 3). For all five considered cases the gain is approximately 71 dB.

Table 3: Displacements of the buncher and penultimate cavities in cm and corresponding efficiencies

Displacement of the Buncher cavity	0	+1	–1	0	0
Displacement of the Penultimate cavity	0	0	0	+1	–1
Efficiency (%)	43.2	43.0	40.7	44.2	43.4

At the second step, ST was applied to the penultimate and the output cavities for the case of the highest efficiency at the previous step. The results are shown in Table 4. By small changes in their dimensions, the penultimate and the output cavities resonant frequencies were slightly modified. This leads to an essential efficiency increase – from 44.2 % before ST to 45.6 % after ST.

Table 4: Cold-cavity frequencies (in GHz) and efficiency without and with stagger tuning.

	Penultimate cavity	Output Cavity	Efficiency (%)
Without ST	17.136	17.063	44.2
With ST	17.070	17.086	45.6

The study of the stability of operation performed by using the code QPB [10] shows that the input, the buncher and the penultimate cavities are stable. However, the starting currents (approximately 600 A) for the output cavity operating TE_{021} mode and parasitic TE_{131} mode are lower than the beam current of 700 A, i.e. the output cavity is not zero-drive stable. Zero-drive stability of the output cavity was demonstrated at $\alpha = 1.4$. The efficiency decrease to 43.1 % for this α -value but is still very high. Since the pitch-ratio can be varied experimentally between approximately 1.0 and 1.5 the dependence of the efficiency on α is also studied (see Fig. 2). It is evident that the efficiency differs by a factor of about 2 for the end values of the examined α -range.

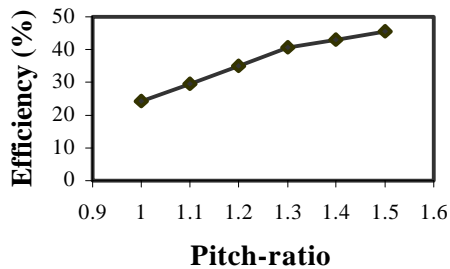


Figure 2: Efficiency dependence on pitch-ratio

4 CONCLUSION

A four-cavity coaxial gyrokystron amplifier design for the 17.1 GHz frequency range was presented in this paper. The simulations were performed for a circuit in which the input cavity operates at the fundamental frequency, while the buncher, penultimate and output cavities operate at the second harmonic of the cyclotron frequency (1-2-2-2 circuit). Calculations based on the point-gap model show that this is the most efficient scheme among the schemes with input and output cavities operating at first and second harmonic, respectively.

In order to accelerate the finding of the optimum device parameters with respect to the efficiency and gain a subroutine using the Hooke-Jeeves optimization method was embedded into the large-signal code GYCOAX. Additional optimization of the drift spaces and stagger tuning of the last two cavities were carried out. The simulations predict both very high efficiency and gain of 45.6 % and 71 dB, respectively, for the 1-2-2-2 gyrokystron, using an electron beam with 500 kV voltage, 700 A current, perpendicular-to-parallel velocity ratio of 1.5 and parallel velocity spread of 6.4 %. Even if we restrict ourselves to a zero-drive stability of the output cavity (at $\alpha \leq 1.4$) the efficiency of the studied four-cavity gyrokystron decreases slightly to 43.1 % but

it could deliver output microwave power of up to 150 MW.

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