DESIGN OF THREE-CAVITY COAXIAL GYROKLYSTRON CIRCUITS FOR LINEAR COLLIDER APPLICATIONS*

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In this paper we consider the preliminary designs of three-cavity microwave circuits for coaxial gyroklystrons. These tubes are predicted to produce over 100 MW of power in 1 μs pulses in X- and Ku-Band for linear collider applications with efficiencies exceeding 40% and gains above 50 dB. In particular, we examine the effect of first and second harmonic buncher cavities on the efficiency and gain of both first and second harmonic microwave circuits. We also examine the necessary conditions to contain the axial field profile of overmoded buncher and output cavities. Performance is contrasted with current two-cavity designs. [1]

I. INTRODUCTION

At the University of Maryland, we have been exploring the suitability of gyroklystrons as drivers for the next generation of linear colliders. When our investigation began, the state-of-the-art was represented by a 52 kW, 4.5 GHz 3 cavity gyroklystron at NRL [2]. As an intermediate step to the 100+ MW microwave power levels anticipated to be necessary for a 1 TeV collider, we designed 30 MW, 10 and 20 GHz, first and second harmonic gyroklystrons, respectively. These tubes utilized the interaction of a 450 kV, 160-260 A, 1 μs (flat top) beam with a series of circular electric mode cavities separated by heavily loaded drift regions. The ratio of the velocities perpendicular and parallel to the axial magnetic field hovered near one in all experiments. Likewise, all tubes utilized a simple TE_{011} input cavity with radial wall input coupling and a lossy ring to lower the quality factor. [3,4]

We have just completed modifications to the gyroklystron test bed that should enable us to exceed the 100 MW level for output power. The modulator voltage was upgraded to 500 kV and the current capability was increased to 800 A by adding additional pulse-forming networks in parallel with the existing hardware. A new single-anode magnetron injection gun that can take advantage of the new modulator capabilities has been designed, constructed, and delivered. The minor modifications to the magnet system that are required by the new gun have been completed.

To increase the flexibility of the magnet system and to enhance the compatibility of our system to other current experimental investigations, we have decreased the drive frequency to three times the current SLAC frequency. Our magnetron drive hardware has been modified to accommodate this change. Detailed designs of two-cavity systems employing first and second-harmonic output cavities have been designed, are currently under construction, and have been described in a companion paper in these proceedings. [1]

A recent theoretical effort [5] has indicated that, in addition to improved gain, a buncher cavity can also enhance the maximum gyroklystron efficiency of several configurations. In this paper we use our partially self-consistent, large-signal code [6] to investigate the effects of a buncher cavity on the performance of coaxial gyroklystrons (which are always driven by first-harmonic input cavities). First, we present the design of abrupt-transition TE_{02} second harmonic cavities that minimize TE_{01} mode conversion. Then the large signal performances of fundamental output circuits with fundamental and second harmonic buncher cavities are described. The results of a second harmonic buncher/output gyroklystron are then analyzed. We close with a preliminary discussion of a three cavity design which has a second-harmonic buncher cavity and a fourth harmonic output cavity.

II. ABRUPT-TRANSITION OVERMODED CAVITIES

A schematic of the three cavity design with second-harmonic buncher and output cavities is given in Fig. 1. The length and the inner and outer radii of the TE_{021} buncher cavity have been selected to minimize mode conversion to the TE_{01} mode and subsequent leakage of fields into the drift regions. This is typically achieved by forming the cavity with equal radial transitions from the drift tube radii. The diffractive quality factor of this cavity, according to our scattering matrix code is over 750,000. The required quality factor for optimal efficiency will be achieved by the insertion of lossy ceramics into the cavity. Similar criteria are used to design the output cavity, though the quality factor is achieved solely through diffractive coupling at the output end. The cavity parameters are given in Table I. The drift radii given correspond to the regions downstream from the respective cavities.

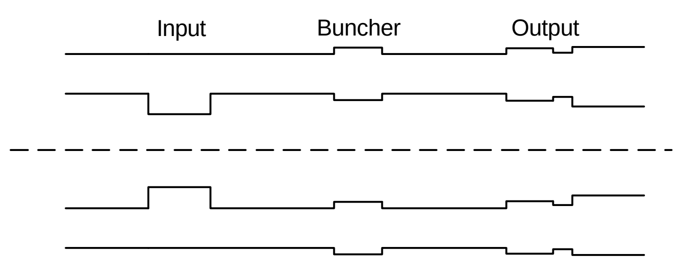

Figure 1. The second-harmonic output three cavity design.

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The buncher cavity's azimuthal electric field profile (in arbitrary units) at the first radial maxima in the cavity is given in Fig. 2 as a function of axial location. The tails of the field are negligible after about 2 cm. The start oscillation curves in the magnetic field range of interest for relevant circular electric modes is given in Fig. 3. This figure assumes that the lossy dielectrics load all modes equally. The operating mode is completely stable for currents below 780 A but the TE_{01} mode is highly unstable at the upper range of the magnetic field. Consequently, if the method for loading the cavity cannot preferentially load the lower radial mode, the cavity length will have to be shortened to push the unstable range to higher magnetic fields. The start currents for modes with azimuthal indices between 1 and 3 were also evaluated, but they were all at least as stable as the TE_{02} mode.

Table I. Abrupt transition harmonic cavity dimensions.

Parameter	length (cm)	
	buncher	output
Inner drift/lip radius	1.83/-	1.40/1.75
Inner cavity radius	1.62	1.61
Outer drift/lip radius	3.33/-	3.55/3.35
Outer cavity radius	3.54	3.50
cavity axial/lip length	1.63/-	1.7/0.7

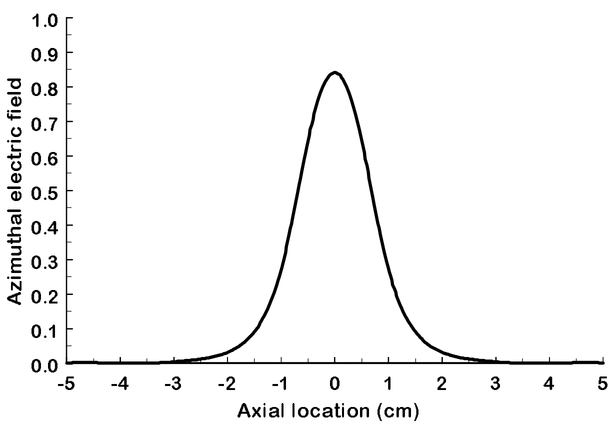

Figure 2. Field profile of the second harmonic buncher cavity.

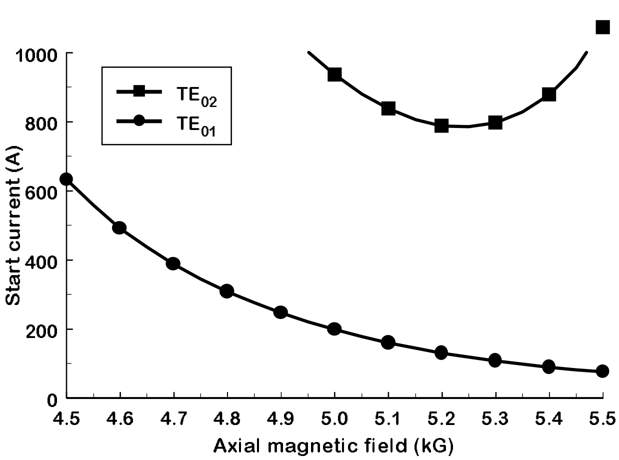

Figure 3. Start oscillation curve for the second harmonic buncher cavity.

III. LARGE-SIGNAL OPERATION

The single anode Magnetron Injection Gun is designed to produce a 500 kV, 500 A beam with an average perpendicular-to-parallel velocity ratio of 1.5 and an axial velocity spread of 6.4%. [1] The velocity spread remains below 10% for currents up to about 800 A. Optimizations of the three-cavity designs were carried out at the nominal beam parameters and efficiency was subsequently characterized as a function of velocity spread.

The drift tube lengths and the cavity quality factors for the three basic designs are indicated in Table II. The three digit sequence that identifies the particular design indicates the expected amplified harmonic in each of the cavities. The same basic TE_{011} input cavity is assumed for all designs, though the required Q varies somewhat. The cavity is formed by decreasing the inner radius of the drift tube to 1.1 cm for a distance of about 2.29 cm and is stable to all modes at the nominal operating parameters. The length is chosen to correspond to the broadwall length of the X-band waveguide that will couple the input power to the cavity via two radial wall slots that are 180° apart. All first harmonic cavities resonate at 8.568 GHz in the TE_{011} mode and all second-harmonic cavities resonate at 17.136 GHz in the TE_{021} mode. For simplicity, the fundamental buncher cavity in the 1-1-1 design has the same dimensions as the input cavity. The fundamental output cavity in the first two designs was taken from the planned two-cavity experiment. [1] The dimensions of the buncher and output cavities of the 1-2-2 design are given in Table I.

Table II. The three-cavity design parameters and performance characteristics.

Parameter	Design		
	1-1-1	1-2-1	1-2-2
Input cavity Q	80	119	70
Drift 1 length (cm)	4.5	5.5	4.5
Buncher cavity Q	65	727	389
Drift 2 length (cm)	6.5	5.0	4.5
Output cavity Q	124	124	322
Efficiency (%)	41.7	38.8	41.1
Large signal gain (dB)	51	31	50

The optimal efficiencies and gains at the nominal operating parameters are also given in Table II for the three designs. Both designs for which the buncher and output cavity harmonics are the same achieve efficiencies above 41%, which corresponds to an output power exceeding 100 MW. The large signal gain in both cases is about 50 dB. The first harmonic output cavity is quite stable at the design parameters, but the second harmonic output cavity is only marginally stable and requires further work. The fundamental output design with a second harmonic buncher has considerably lower gain and somewhat lower efficiency than the other designs. Furthermore, the required buncher cavity quality factor is unrealistically high.

In spite of its potential drawbacks, the 1-2-1 design is still of interest because of the dependence of efficiency on velocity spread. This dependence is indicated in Fig. 4 for both first harmonic output designs. The 1-2-1 design has a strong dependence on velocity spread but achieves a theoretical efficiency of nearly 50% with zero spread. The 1-1-1 design has a weak dependence on velocity spread and achieves a maximum value above 45% with zero spread. This performance is consistently about 2% higher than the simulated two-cavity first harmonic design. [1]

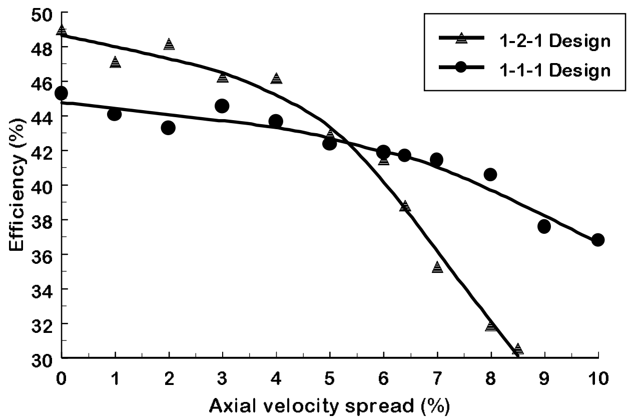

Figure 4. Simulated efficiencies of the first-harmonic output circuits.

The dependence of efficiency on velocity spread for the 1-2-2 design is indicated in Fig. 5. The decrease in efficiency with spread is fairly weak up until about 6%. From zero velocity spread up until this point, the second harmonic efficiencies are only about 1% lower than the corresponding first harmonic efficiencies. The three-cavity second harmonic efficiency is over 6% higher than the corresponding two-cavity design. [1] This represents a significant improvement. A 1-1-2 design was attempted during this investigation, but zero spread efficiencies were limited to about 30%.

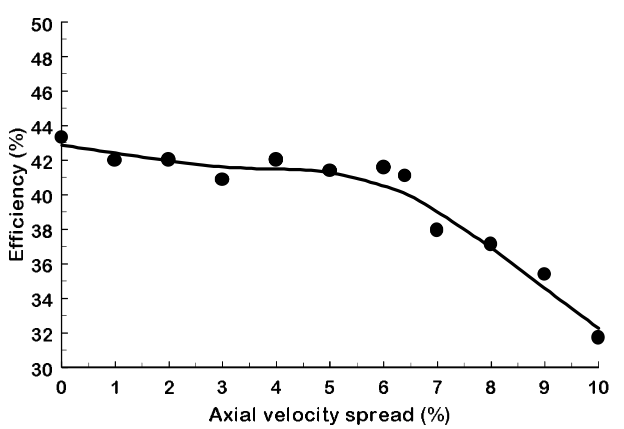

Figure 5. Efficiency of the second-harmonic output circuit.

A 1-2-4 design has also been attempted for which the abrupt transition output cavity would operate at 34.272 GHz in the TE_{041} mode. This design was again motivated by earlier work [5] and would represent a device with extremely attractive properties for a variety of applications. The output cavity designed for this simulation has a quality factor of 625, an axial length of 1.3 cm and a lip length of 0.3 cm. The wall radii were again selected to minimize mode conversion to lower radial modes. The output power is predicted to be 94.5% in the TE_{04} mode. The amount of power flowing back into the drift tube is about 0.2% of the total output power. Unfortunately, our best results to date have produced efficiencies of only about 13%.

V. SUMMARY

This theoretical investigation represents a first look at the design of three-cavity coaxial gyroklystrons and the results are somewhat preliminary. Nonetheless, these results appear to be quite promising for first and second harmonic designs. Efficiencies of 40% and gains of 50 dB appear to be achievable with realistic beam parameters. The abrupt transitions of the second harmonic TE_{021} cavities enable quite compact drift regions to be utilized. This is a distinct advantage over previous circular waveguide tubes which required smooth radial wall transitions to minimize mode conversion. The large-signal gains of the three-cavity systems are significantly better than the corresponding two-cavity designs. The improvement in efficiency is moderate for first harmonic tubes but dramatic for second harmonic design.

Additional work needs to be done to determine and improve the stability of the second harmonic cavities to first harmonic modes. Also, the effect of lossy ceramics on the harmonic buncher cavities needs to be examined. Finally, the performance limits of 1-2-4 designs need to be understood to determine if high efficiency circuits are possible.

V. REFERENCES

[1] J. P. Calame, *et al.*, "Design of 100 MW, two-cavity gyroklystrons for accelerator applications," in these proceedings.

[2] W. M. Bollen, *et al.*, "Design and performance of a three-cavity gyroklystron amplifier," IEEE Trans. Plasma Sci., **PS-13**, 424 (1985).

[3] W. Lawson, *et al.*, "Performance characteristics of a high power X-Band two cavity gyroklystron," IEEE Trans. Plasma Sci., **20**, 216 (1992).

[4] H. W. Matthews, *et al.*, "Experimental studies of stability and amplification in a two cavity second harmonic gyroklystron," IEEE Trans. Plasma Sci., **22**, 825 (1994).

[5] G. S. Nusinovich and O. Dumbrajs, "Two-harmonic prebunching of electrons in multicavity gyrodevices," Phys. Plasmas, **2**, 568 (1995).

[6] P. E. Latham, W. Lawson, and V. Irwin, "The design of a 100 MW, Ku-Band second harmonic gyroklystron experiment," IEEE Trans. Plasma Sci., **22**, 804 (1994).