IMPROVED DESIGN OF A FREQUENCY-DOUBLING KU-BAND GYROKLYSTRON EXPERIMENT

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Abstract

At the University of Maryland, we have been investigating the use of gyroklystrons to drive advanced linear colliders. Recently, we produced over 75 MW of peak power at 8.57 GHz with a 3-cavity first harmonic coaxial system and about 27 MW at 17.14 GHz with a 3-cavity, frequency-doubling system. Based on these results, we have designed and tested a high-gain, 4-cavity second-harmonic tube that should enable us to use a phase-stable TWT driver. We have also designed an output waveguide system which transforms the power from the output waveguide and equally divides it into two standard rectangular waveguides. In this paper we present the results of our 4-cavity, frequency-doubling coaxial gyroklystron and we describe the details of our output waveguide system.

1 INTRODUCTION

At the University of Maryland, we have been exploring the possibility of using gyroklystrons to drive advanced linear colliders in X-band and above. We use a 460 kV, 540 A annular beam with a perpendicular-to-parallel velocity ratio (alpha) of 0.9-1.5, immersed in a magnetic field of about 5 kG, to excite a series in circular electric (TE_{0n}) coaxial cavities. With a 3-cavity first harmonic coaxial system we produced over 75 MW at 8.57 GHz [1] and with a 3-cavity, second-harmonic system we produced about 27 MW at 17.14 GHz [2]. In the former scheme, all of the cavities operate near the cyclotron frequency in the TE_{011} mode. In the latter scheme, the input cavity is driven near the cyclotron frequency in the TE_{011} mode, but the buncher and output cavities operate at twice the drive frequency in the TE_{021} mode. The output signal is extracted axially in the TE_{02} mode in overmoded circular waveguide.

Typical output pulses for the 3-cavity second harmonic system are shown in Fig. 1. The upper line is the beam current (about 540 A) and the lower line is the beam voltage (about 420 kV). The diamonds represent the microwave pulse, with a peak efficiency less than 14% and a peak power near 27 MW. The gain of both this second harmonic tube, and that of the first harmonic tube, was less than 30 dB.

The design value for the peak power for both tubes was about 80 MW, with an efficiency of about 32% and a gain near 50 dB. The results for the second harmonic tube fell well short of the design value, because the velocity ratio of the beam could not exceed a value of about 0.9, whereas the design value is 1.4-1.5. This results in a more than two-fold reduction in the perpendicular energy and a significant reduction in the output power. This trend is quantified in Fig. 2, where the efficiency is plotted as a function of drive power for a series of different values for alpha. The optimal result is for an alpha of 1.4, with a drive power of about 1 kW, and an output power of 80 MW. The curves stop at a drive power of 150 kW, because this is the maximum possible value for our magnetron input source. For an alpha of one, the maximum efficiency is about 12% at the maximum drive power, which is consistent with our experimental result.

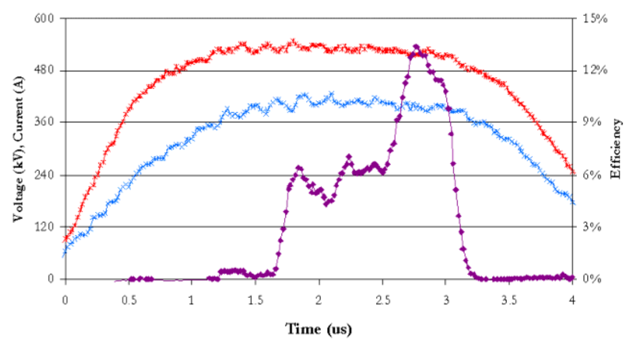

Figure 1: Sample experimental traces for the 3-cavity frequency-doubling gyroklystron.

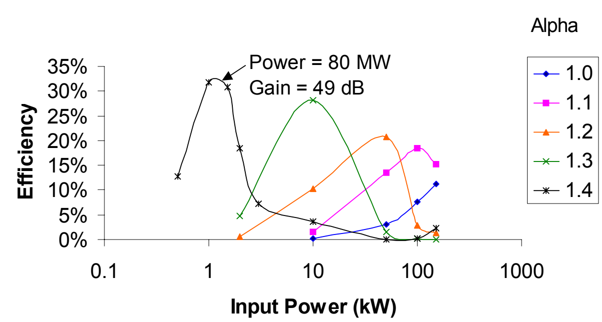

Figure 2: Sample theoretical curves of efficiency versus drive power and alpha for the 3-cavity frequency-doubling gyroklystron.

The reason for the reduction in alpha is that above this point there are instabilities near the input cavity. The onset of these instabilities was fairly rapid with increasing magnetic compression and dramatically interfered with the amplification process. The root cause of these instabilities appears to be a large inhomogeneity in the azimuthal beam density. This variation gives rise to local axial velocity spreads, which we believe result in a reduced start-oscillation threshold in the input cavity.

The variation in the current density from one extreme to the other has been measured to be more than 100%. There is a high correlation between this variation and the temperature variation that exists at the surface of our annular cathode. This variation in large part is due to a cold spot located near the entrance of the heater leads. The first harmonic tube's performance was much closer to the design values for two reasons. First, the roll-off in efficiency with decreasing alpha is less dramatic for the first harmonic. Secondly, the quality of the cathode has been slowly degrading with time. Our efforts to remedy this situation are described in the final section of this paper.

Experiments with the 3-cavity second harmonic system were terminated when the tungsten pin supports that hold the inner conductor in place broke due to beam erosion.

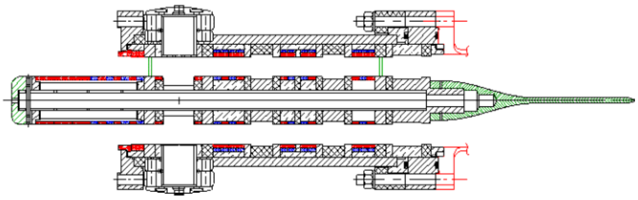

Figure 3: A schematic of the 4-cavity, frequency-doubling microwave tube.

2 FOUR CAVITY CIRCUIT

Based on the results of the first two 3-cavity systems, we have designed and tested a 4-cavity frequency-doubling system with high theoretical gain. The schematic for this tube is shown in Fig. 3. An additional gain cavity was added, and while the lengths of the drift regions were somewhat shortened, the overall length of the circuit was increased by about 2.3 cm. The shape of the inner conductor taper was also modified to reduce the amount of mode conversion to the TE_{01} mode to under 0.1%.

The inner conductor is defined by an indentation on the inner conductor. The quality factor (Q) is about 55 and the resonant frequency of the operating mode is near 8.585 GHz. The remaining cavities are defined by (nominally) symmetric transitions on the inner and outer walls in order to minimize mode conversion to the TE_{01} mode. The two intermediate cavities are identical with Qs near 390 and resonant frequencies near 17.136 GHz. The output cavity has a reduced Q (310) and a reduced frequency (17.115 GHz), to stabilize the cavity and optimize the amplification. The additional buncher cavity increases the large-signal gain by about 12 dB to over 60 dB (at the design alpha of 1.4). The predicted efficiency also improves, but only to about 34%.

Unfortunately, the same electron gun / emitter was used, and so the performance of the 4-cavity tube was only comparable to that of the 3-cavity system. As before, the principle problem was traced to low-frequency (X-Band) instabilities that were generated in or near the input cavity. This resulted in a low maximum alpha, and a maximum output power of about 20 MW, with a full-width half-maximum of 500 ns, and gains and efficiencies in-line with the previous tube.

The inner conductor supports were relocated to a region of low current density, and this tube operated many times longer than the 3-cavity tube without significant damage to these support pins. Operation was stopped to effect the repairs described in the final section.

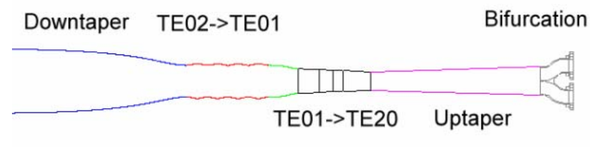

Figure 4: The output waveguide.

3 OUTPUT WAVEGUIDE

A schematic of the output waveguide is shown in Fig. 4. The output of the gyroklystron is a TE_{02} mode in 5 inch circular pipe (due to peak electric field considerations at the output window). To use this power to energize an accelerator section, we need to convert the power into the fundamental mode in rectangular waveguide. This is done in a sequence of sections, described while moving left to right in the figure.

First, a nonlinear taper reduces the circular guide radius so that only the first two radial modes can exist. Then, a periodic rippled-wall converter with four ripples converts the second radial mode into the first radial mode. A second small nonlinear downtaper brings the radius to that required for a circular-to-rectangular converter that was designed by S. Tantawi of SLAC at 11.424 GHz, [3] and scaled by us to Ku-Band. The output of this converter is TE_{20} (rectangular) in a waveguide that is nearly square. A linear taper is used to transform the waveguide dimensions to the height of standard Ku-Band, but twice the width of the standard. A bifurcation then converts this configuration to two standard Ku-Band waveguides.

For ideal performance, the mode conversion is more than 99.5% perfect. All aspects of this system have been cold-tested individually and work well; the final construction of the vacuum-compatible components is well under way.

4 SUMMARY

We have a two-prong approach to resolve the problem of input cavity instabilities and asymmetry in the azimuthal beam current. First, we are redesigning the input cavity to have a quality factor of about 40 in the operating mode, which represents a 20% reduction in the original Q. The previous input cavity is shown in Fig. 5. The lossy Q is currently derived from ceramics just outside the cavity. An additional ceramic will be inserted in the center of the cavity to selectively attenuate spurious modes.

Second, we have developed a number of changes to the design and manufacturing of large annular cathodes and are working with the manufacturer to realize these changes. The results of all of these changes will be evaluated in the upcoming months.

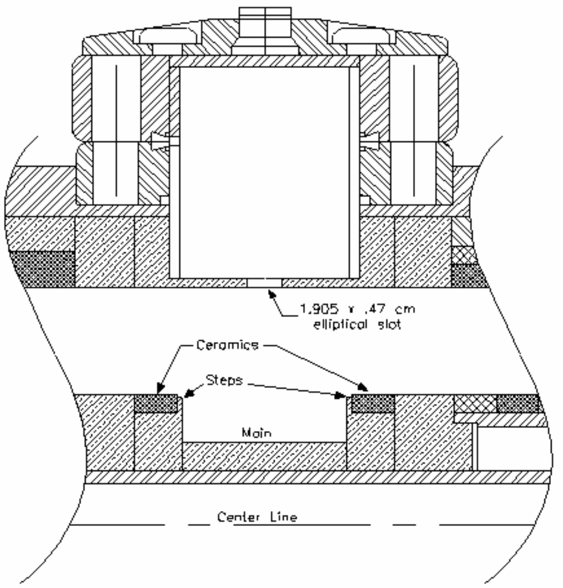

Figure 5: An enlargement of the input cavity.

5 REFERENCES

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[2] M. Castle, Ph. D. Thesis (March 2001, University of Maryland).

[3] S. Tantawi, private communication.