Initial Operation of a High Power, K-Band, Harmonic Gyroklystron for Accelerator Applications*

J.P. Calame, H.W. Matthews, W. Lawson, B. Hogan, M.K.E. Lee, J. Cheng,
V.L. Granatstein, M. Reiser, and C.D. Striffler
Laboratory for Plasma Research and Electrical Engineering Department
University of Maryland
College Park, MD 20742

Abstract

Experimental studies of amplification and stability in a series of multi-megawatt, 19.7 GHz, second harmonic gyroklystron amplifier tubes suitable for driving future linear supercolliders are reported.* Four different two-cavity gyroklystron tubes have been constructed and tested, and each one has exhibited higher power, larger efficiency, and improved stability compared to its predecessor. The latest results include the production of peak output powers in excess of 29 MW, at an efficiency of 27% and a gain of 25 dB.

I. INTRODUCTION

The economical construction and operation of linear electron-positron colliders with center-of-mass energies in excess of 1 TeV will require the development of a new generation of high-frequency microwave amplifiers. Candidate amplifiers should be capable of producing approximately 100 MW, 1 μs pulses with an output frequency in the 10-20 GHz range. Pulse compression techniques would be employed to further increase the output power level to several hundred MW prior to injection into the accelerating structure. One promising candidate source for this application is the gyroklystron amplifier, a device which combines the energy extraction mechanism of the cyclotron resonance maser and the ballistic bunching approach of the klystron. Gyroklystrons can operate with overmoded cavities, which allows the production of high output powers with low current density beams and low cavity electric fields compared to those of klystrons and other conventional sources. Furthermore, the electron source usually employed in gyroklystrons (the magnetron injection gun or MIG) exhibits favorable scaling with frequency compared to linear beam guns. Over the past several years, we have developed a series of two- and three-cavity, 9.85 GHz gyroklystrons which ultimately produced 24-27 MW of output power for 1 μs at up to 33% efficiency [1-3]. These devices employed the TE_{011} mode in all of the cavities, and produced amplified power via a fundamental cyclotron wave interaction.

In order to increase the output power capability of a gyroklystron at any particular frequency, a larger diameter electron beam, drift tube, and output cavity must be employed. The greater degree of overmoding in these larger structures would almost certainly lead to increased mode competition problems. One way around this problem is to operate the output cavity at the second harmonic of the drive frequency. In this configuration the input and buncher cavities are designed to resonate at one-half of the desired output frequency. The output cavity extracts energy from the prebunched beam via an interaction of the cavity RF fields with the beam's second harmonic cyclotron wave. Further advantages of this device over purely fundamental systems are lower capital costs, simplified cooling, and reduced magnetic field levels. Alternatively, the harmonic gyroklystron can be viewed as a means of doubling the operating frequency with little or no decrease in output power capability compared to a fundamental gyroklystron.

To test the viability of the harmonic concept with our existing beam generation equipment, we have constructed a series of two-cavity, second harmonic gyroklystrons with TE_{011}, 9.85 GHz input cavities and TE_{021}, 19.7 GHz output cavities. The studies have culminated with peak powers in excess of 29 MW at 19.76 GHz, with 27% efficiency and 25 dB gain. In the following sections we will describe the experimental setup and detail the most recent results.

II. EXPERIMENT

The modulator, electron gun, magnet system, magnetron input source, and beam dump for the second harmonic experiment are the same as those used in the fundamental experiments. The electron gun produces a rotating, small orbit, annular electron beam which flows into the microwave tube under test. The present group of experiments generally employs beams in the 400-450 kV, 150-250 A range with computed α ($v_\perp/v_z$) values near 1.0. The 2nd harmonic gyroklystron tubes are modified versions of our 9.85 GHz two-cavity devices. The old 9.85 GHz, TE_{011} output cavities were replaced by TE_{021} cavities with resonant frequencies near 19.7 GHz. Cavities with gradual radial transitions were used to avoid mode conversion to the TE_{01} waveguide mode and help achieve a high forward-to-reverse power ratio. In addition, the intercavity drift space was modified to improve the attenuation to a 19.7 GHz, TE_{01} drift-tube mode while maintaining good attenuations to all other modes in the 6-13 GHz range. This was generally accomplished by modified placements of lossy dielectrics and the addition of resonant traps. A diagram of the third circuit tested is shown in Fig. 1.

The spent electron beam and output radiation pass through a nonlinear uptaper and the beam dump, and the radiation continues through a second non-linear uptaper and

* Work supported by the U.S. Department of Energy.

a λ-resonant window into either an anechoic chamber or a large directional coupler/liquid calorimeter. New nonlinear tapers which preserve the TE_{02} output mode were employed in these experiments. In addition, the pickup antenna system in the anechoic chamber and the directional coupler were modified for K-Band operation. Peak power measurements obtained with each of the three measurement systems (anechoic chamber + crystal detector, directional coupler + crystal detector, and liquid calorimetry differential thermal measurements + coupler/crystal detector waveform shape) were found to agree within 7%.

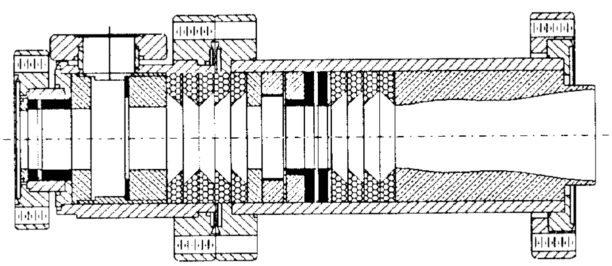

Figure 1. Section view of harmonic gyroklystron Tube 3.

III. RESULTS

The first tube employed a long (5 cm) high-Q (650) output cavity and was plagued by severe instabilities that prevented amplification at the second harmonic. The instabilities resulted from fundamental cyclotron interactions in the output cavity region. A second tube was constructed using a shorter (3 cm) output cavity with a somewhat lower Q (500) and a fairly rapid post-cavity radial uptaper. It also employed an improved set of drift tube traps. This circuit produced peak amplified powers near 12 MW at 19.74 GHz with an efficiency of 15%. However, performance continued to be limited by a variety of instabilities. These included a group of 1-4 MW, TE_{11}-like modes at 6-7 GHz which coexisted with the amplified signal, and a 6.9 GHz oscillation which would "cut" into the amplified signal as the beam α and/or current were increased.

Based on the assumption that the output cavity region continued to be the source of the instabilities, a third tube with a lower Q (350) and a somewhat steeper post-cavity uptaper was constructed. It produced peak powers in excess of 21.5 MW at 19.76 GHz, with 21% efficiency and 23 dB gain [4]. These results were obtained with a 437 kV, 232 A, $\alpha \approx 0.9$ electron beam. In addition, at the point of peak power production the amplified signal strongly suppressed the 6-7 GHz background instabilities. Power production and the range of stable beam parameters were still limited by the onset of instabilities at 6.9 and 12.7 GHz Working on the possibility that the 19.7 GHz resonant trap section of the drift tube was creating reflections at these frequencies, a fourth tube was created by removing the traps from Tube 3 and replacing them with extra lossy dielectric. The change eliminated the instabilities over a broad range of beam parameters. To date we have obtained output powers in excess of 29 MW at 19.76 GHz, with an efficiency of 27% and a gain of 25 dB. These optimal results were obtained at 455 kV and 238 A, with an α of about 1.

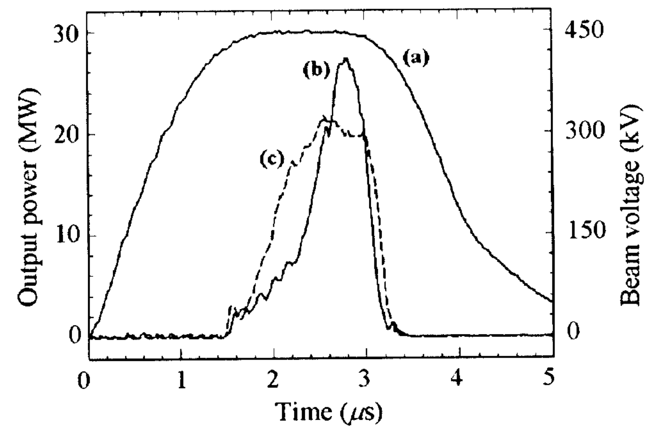

Figure 2. Typical waveforms from Tube 4; (a) voltage, (b) example of a fairly narrow, high power pulse, and (c) a wider, moderate power pulse.

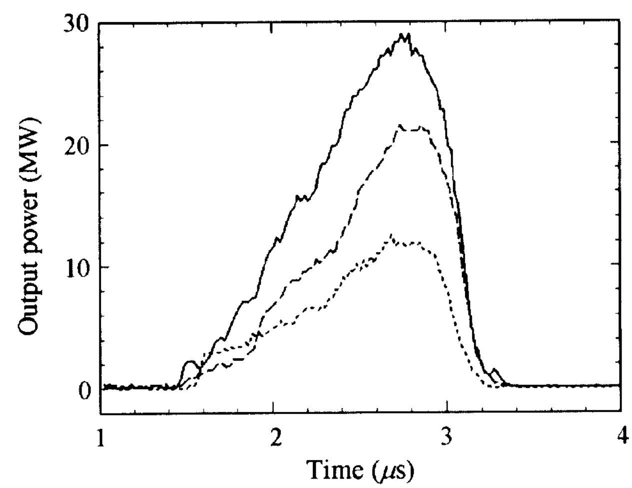

Figure 3. Power vs. time waveforms from Tube 2 (dotted), Tube 3 (dash), and Tube 4 (solid).

Typical output power vs. time waveforms from Tube 4 are shown in Fig. 2. The wider, lower power pulse (c) was obtained by adjusting the magnetic field profile to over-bunch the beam in the input cavity. Fig. 3. shows the highest reproducible peak power waveforms from each tube. In all cases the power builds up slowly over time. This results from a gradual increase in beam α over the duration of the flattop of the voltage pulse [1]. This effect, due to compensation problems in the resistive divider that drives the modulation anode in the gun, combines with the strong sensitivity of second harmonic gyroklystrons to changes in α to produce the triangular pulses observed.

Systematic studies of output power as a function of beam voltage, beam current, and drive frequency in Tube 3 are shown in Figs. 4, 5, and 6, respectively (similar studies at the

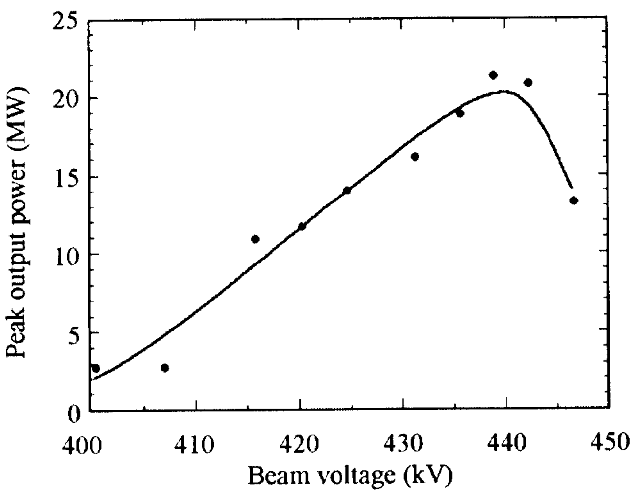

Figure 4. Effect of beam voltage on output power in Tube 3.

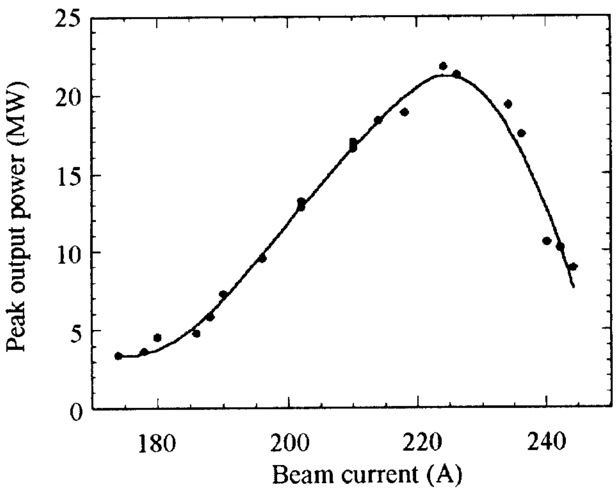

Figure 5. Effect of beam current on output power in Tube 3.

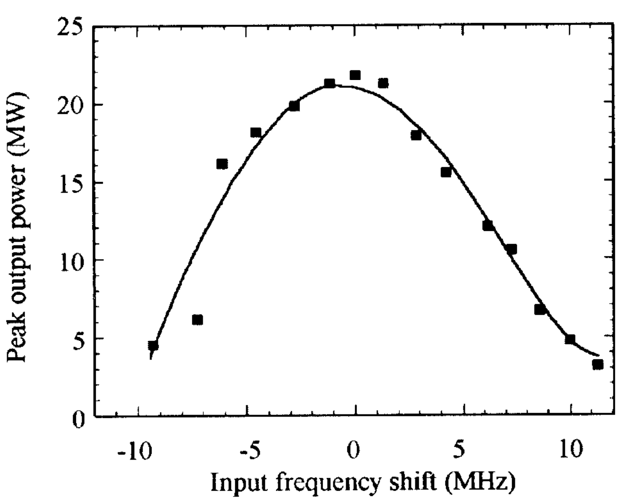

Figure 6. Effect of a shift in drive frequency on output power in Tube 3.

29 MW level in Tube 4 are just getting under way at the time of writing). In each study, only the parameter of interest is allowed to change from the optimal value; the other parameters and the circuit magnetic field profile remain fixed. However, at each point on the graphs the magnetic compression (beam α) was adjusted to just maintain stability and therefore maximize power. In the voltage study, the power falls off on either side of the optimal value (440 kV) as the beam-wave interaction slips out of resonance. In the beam current study, the power initially rises as the current increases, due to the existence of additional beam energy. However, at high currents the power falls off for a variety of reasons, including a decrease in beam quality (due to space charge effects), beam-induced detuning of cavity resonances, and the onset of instabilities (which we suppress by reducing α, and thus the amplified power decreases). In the frequency study, the observed FWHM bandwidth of 14 MHz is only slightly smaller than the value expected on the basis of the cavity Qs ($\approx$17 MHz).

IV. SUMMARY

The results of this proof-of-principle experiment indicate that second harmonic gyroklystrons can produce large amounts of output power with reasonable efficiencies. The powers measured in the latest second harmonic tube are actually higher than those obtained in our earlier two-cavity fundamental experiments (although the efficiency is somewhat lower). These results suggest an advanced capability for driving future linear supercolliders. Future experiments will include studies of harmonic output cavities with discrete radial transitions and experimental measurements of beam α. A 100 MW output power, 17 GHz, second harmonic experiment with a new electron gun and an upgraded modulator is also under construction [5].

V. REFERENCES

[1] J.P. Calame *et al*, "Experimental studies of stability and amplification in four overmoded, two cavity gyroklystrons operating at 9.87 GHz," J. Appl. Phys. 70, 2423 (1991).

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

[3] S. Tantawi *et al*, "High power X-band amplification from an overmoded three cavity gyroklystron with a tunable penultimate cavity," IEEE Trans. Plasma Sci. **20**, 205 (1992).

[4] W. Lawson *et al*, "High power operation of a K-band second harmonic gyroklystron," submitted to Phys. Rev. Lett. in March 1993.

[5] W. Lawson *et al*, this conference.