Amplification Studies of a Multi-Megawatt Two-Cavity X-Band Gyroklystron*

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I. INTRODUCTION

At the University of Maryland we are working to develop high power gyroklystron amplifiers with properties suitable for driving future electron-positron colliders[1]. Our initial experiments have involved a sequence of six different two-cavity configurations operating in the TE_{01} mode near 9.85 GHz. Each design was modified in accordance with it predecessor's performance to either improve tube stability or enhance amplifier operation (or both). The energy is derived from a rotating beam in 300–440 kV, 100–200 A, 1 μs pulses. With perpendicular-to-parallel velocity ratios ($\alpha = v_\perp/v_z$) near one, the studies have culminated in peak powers approaching 24 MW with efficiencies and large-signal gains of 33% and 34 dB, respectively. In the following sections, we will described the experimental setup and detail amplifier performance of the most recent configuration. Earlier results are reported elsewhere[2,3].

II. EXPERIMENTAL CONFIGURATION

A schematic of the overall system is shown in Fig. 1. A 500 kV, 400 A line-type modulator provides the required pulse to a Magnetron Injection Gun[4]. Eight coils are powered by four supplies to produce peak fields as high as 0.7 T and allow for considerable flexibility in magnetic field tapering. The nominal field at the cathode is 0.047 T. The beam is adiabatically compressed as it travels through the increasing axial magnetic field in the beam tunnel.

After leaving the gun, the beam travels through the circuit region. This region is shown in Fig. 2 for the sixth tube. The beam downtaper reduces the wall radius from 0.025 m to 0.015 m and is heavily loaded with lossy dielectrics (carbon-impregnated aluminum silicate) to suppress spurious oscillations. The length of the input cavity is 0.0173 m. In the various tubes, the input cavity quality factors range from Q=170 to Q=300. These Qs are achieved via a coupling slot on the radial wall and a thin lossy ring against the sidewall. A 2μs, 100 kW magnetron provides the input power. The drift section between cavities has a length of 0.109 m and contains nine lossy, tapered ceramic rings (80% B_eO and 20% S_iC) to stabilize spurious oscillations and isolate the cavities. The output cavity is 0.0240 m long and the Qs have varied from 145 to 225 as determined by the length of the coupling aperture. To prevent oscillations in modes near cutoff in the region after the output cavity, the output waveguide wall has a 2° taper.

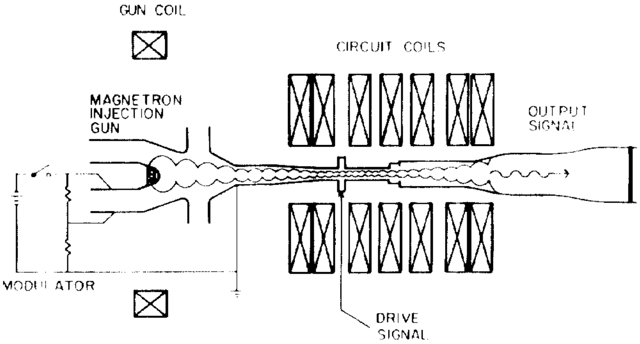

Figure 1: Schematic of the gyroklystron facility.

After leaving the circuit region, the beam and signal pass through a nonlinear tapered wall section to the beam dump. To reduce the peak electric field, the signal travels through a second tapered section to the half-wavelength output window.

Far-field measurements in an anechoic chamber are used to estimate power and mode purity. The receiving antenna is made from an open ended section of standard X-band waveguide and can be rotated by 90° and remotely swept radially more than one meter. Total pulse energy is measured with liquid calorimetry which consists of methanol flowing between two conical polyethylene pieces in a metal pipe with a 0.127 m diameter. A mode-selective directional coupler is used concurrently to provide the microwave power envelope and an additional peak power estimate. The waveguide is filled with sulfur-hexafluoride because the signal breaks down in air. The error estimates for power measurements in either system is approximately ± 0.6 dB.

Other microwave diagnostics include sampling forward and reflected power in the input waveguide, a C-band an-

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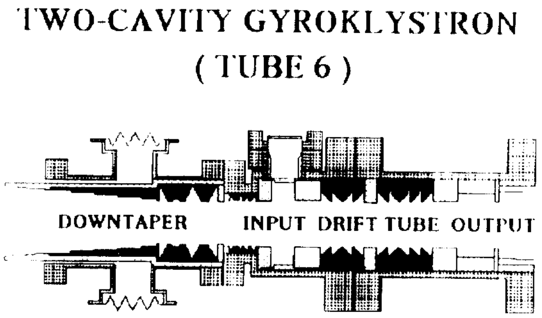

Figure 2: The two cavity circuit.

tenna looking at the back of the electron gun, and a spectrum analyzer which can obtain time-averaged frequency information from any of the probes.

III. Amplifier Results

The quality factors for the input and output cavities in Tube 6 are at the upper end of their respective ranges. For the experiment, beam voltage is limited to 440 kV due to intermittent modulator problems. The achievable velocity ratio is limited to about one due to instabilities in the downtaper region in the 7–8 GHz range. Given these constraints, parameter space is searched in beam voltage, beam current, velocity ratio, magnetic field, and drive power and frequency to achieve maximal amplification. Optimal efficiency in excess of 33% is found for a beam voltage near 425 kV and a current near 150 A. The optimal magnetic field profile results in a field strength of 0.540 T at the center of the input cavity and a field of 0.474 T at the output cavity center. The optimal drive frequency is roughly 9.870 GHz.

Figure 3 reveals the time structure of the output power signal at the optimal parameters. The solid line represents the data as unfolded from a crystal detector response assuming a TE_{01}, 9.870 GHz signal in the anechoic chamber. The dashed line indicates the beam voltage pulse. The signal onset corresponds to the onset of drive power and the signal fall coincides with the end of the beam voltage flat top. Calorimetry measurements at the optimal point yield consistent power estimates (0.08 dB higher). The angular distirbution of radiated power indicates that the output energy is purely TE_{01}. Tube 6 represents a 10% increase in peak power over Tube 5.

Figure 4 shows the effect of magnetic field variations. If the output field is held fixed at 0.474 T and the input field is varied, the peak amplifier response follows the solid curve. If instead the input cavity field is fixed at 0.540 T and the output cavity field is varied, the response follows the dashed line. Note that the amplifier is more sensitive to input cavity variations. We believe that this is because the tube is gain limited and performance is strongly dependent on input cavity bunching. Previous theoretical calculations[3] were in good agreement with the experiment and support this conclusion.

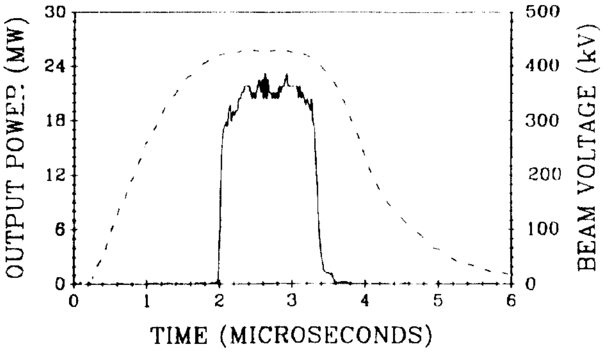

Figure 3: Time evolution of the amplified pulse at the optimal parameters.

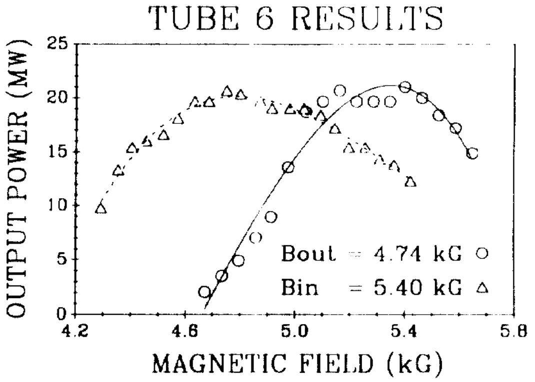

Figure 4: Peak power as a function of magnetic field tapering.

Peak power and efficiency are plotted as a function of beam current in Fig. 5. The drive power, frequency, and magnetic field are held constant. Maximal efficiency occurs at 150 A and maximal power occurs at 170 A. There are several factors contributing to the fall off at high currents. First, the drive frequency is no longer optimal. Second, velocity spread increases at higher currents. Finally, instabilities limit the velocity ratio to lower values. By increasing the frequency to 9.874 GHz, peak powers of 24 MW are achievable at 190 A.

The final figure compares curves of output power versus input power for the last two tubes. The main difference in the tubes was the input cavity Q, with the higher value resulting in the higher gain by 7 dB. Further increases in Q are not possible due to start oscillation limits in the input cavity.

Conclusion

In summary, the two-cavity experiments have expanded the state-of-the-art in output power for gyroklystrons by nearly two-and-a-half orders of magnitude and have established the gyroklystron as a viable RF driver candidate

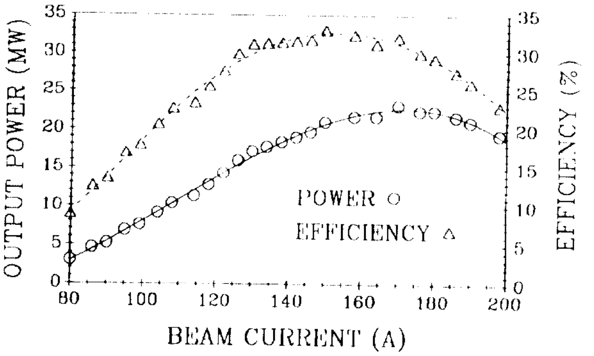

Figure 5: Peak power and efficiency measurements as a function of beam current.

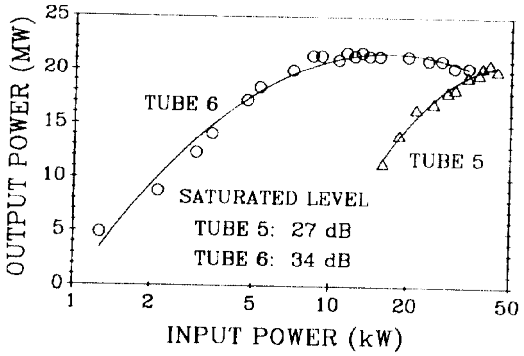

Figure 6: A comparison of gain for tubes 5 and 6.

for electron-positron colliders. Initial experiments with intermediate bunching cavities also appear promising[5]. Future work involves 20 GHz designs both at the fundamental cyclotron frequency and at harmonics[6].

IV. REFERENCES

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