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PHASE STABILITY OF LOCKED GYROTRONS*

J. McAdoo, M. Bollen,[a] V. L. Granatstein, R. Parker,[b] R. Smith,[c] G. Thomas,[c] A. McCurdy[d]

Laboratory for Plasma and Fusion Energy Studies
University of Maryland
College Park, Maryland 20742

Abstract

Phase measurements between a master oscillator and its slave gyroklystron have been made. The pulsed gyroklystron was operated both as an amplifier and as a phase triggered oscillator. As an amplifier, the phase jitter during the 3 μs pulse was 20^0; from pulse-to-pulse the jitter was 0.86^0. As a phase triggered oscillator the jitter of the firing point from shot-to-shot was $< 7^0$ even at input-to-output power ratios as large as 52 dB. The significance of these results for linear accelerator applications is discussed.

Introduction

As discussed in companion papers,[1,2] there is interest in using gyroklystrons to power linear accelerators. For this application there are tight specifications on the the phase coherence of the many gyroklystrons which would be used. One envisions a large number of these devices feeding rf power into the accelerator structure at intervals along its length. An electron bunch riding just ahead of the crest of the electric field from one gyroklystron must be handed to the field of the next, also just ahead of the crest. For this to happen, the phases of the fields from each gyroklystron must match. If the phases jitter with respect to each other, the electron bunch will sometimes join the succeeding fields behind the crests and will be lost. For good accelerator efficiency, the phase jitter must be small compared to the phase angle occupied by an electron bunch. Based on this, the gyroklystron must exhibit phase jitter of one degree or less.

Described here are phase noise measurements made on the gyroklystron at the Naval Research Laboratory. This 5 GHz, 50 kW device is specified in Ref. 1. and will not be redescribed in detail here. The gyroklystron can be operated as an amplifier, a phase triggered oscillator, or as a phase locked oscillator. In all cases, a continuous signal of low power is fed into the first stage of the gyroklystron amplifier, and the amplifier is then pulsed on for about 3 μs with a repetition rate of 60 Hz. The phase measurements consist of comparing the input signal with the output signal in a microwave Michelson interferometer. Measurements were made of the phase jitter between input and ouput both during the pulse and from pulse-to-pulse. The pulse-to-pulse measurements are important because they simulate the simultaneous operation of many gyroklystrons. We found 20 degrees of phase jitter during the pulse which we attribute to a 1% ripple on the high voltage pulse that drives the electron gun. Pulse-to-pulse jitter was $< 1^0$ when the gyroklystron was operated as an amplifier.

Experimental Set Up

Figure 1 shows how the gyroklystron is electrically connected to the interferometer. The gyroklystron starts with an electron gun G, then the three resonators are labeled R1-R3. The master oscillator is labeled M. There are two isolators preventing power generated in R1 from feeding back into the master oscillator and affecting its frequency. Immediately downstream from M is a switch that can disconnect the oscillator from the gyroklystron enabling one to view the diagnostic with and without the master oscillator hooked in. Ten percent of the master oscillator power is split off before the switch and sent to the interferometer. The electrical length of this path can be varied with a piece of coaxial cable fitted with a sliding short. The rf signal reflects from the short and is coupled to a variable attenuator and isolator to a mixer. Isolators reduce second order reflections between the attenuators and the mixer and thereby improve the sensitivity of the instrument. The mixer adds the vector fields from master oscillator and gyroklystron ouput and produces a dc signal proportional to the power of the combined fields. The mixer is "double balanced" which means that components of the signal which are not dependent on the phase angle between the two inputs are cancelled. As a result the mixer output signal, v, is proportional to the cosine of the phase angle:

$$v = SM(1 + \varepsilon)\cos(\phi + \delta) ,$$

where S is the amplitude of the field from the gyroklystron (slave) and M is the amplitude of the master oscillator field. ϕ is the phase angle between master and slave at the mixer; it is adjustable with the sliding short. δ is the the small amplitude phase jitter which we seek to measure, and ε is the amplitude noise.

If $\varepsilon \ll 1$ and $\delta \ll 1$, the above formula for the mixer output voltage breaks into two parts:

$$v = SM(1 + \varepsilon)\cos(\phi) + SM\delta\sin(\phi) .$$

When ϕ is adjusted to zero, the signal depends on the amplitudes and amplitude noise. At $\phi = \pi/2$, however, the signal is proportional to the phase noise δ and does not depend on the amplitude noise. Shot-to-shot noise is measured by looking at the mixer signal at a particular time after the start of the 3 μs pulse. The voltage level at this time is measured over many shots and the standard deviation is calculated with a digital processing oscilloscope. The shot-to-shot phase jitter is proportional to the standard deviation. During the pulse, the phase jitter can be directly observed as a small-amplitude modulation of the oscilloscope trace.

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[a] Mission Research Corp., Alexandria, VA 22312
[b] Naval Research Laboratory, Washington, D.C. 20375
[c] Varian Beverly Microwave Division, Beverly, MA 01915
[d] Applied Physics Section, Yale University, New Haven, CT 06520

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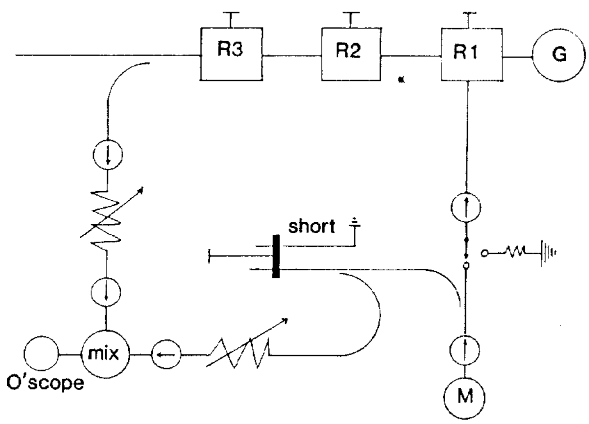

FIG. 1. Gyroklystron and interferometer schematic.

Results

Operating as an amplifier with 0.5 W input power from the master oscillator and 90 W out of the gyroklystron, shot-to-shot phase jitter was 0.86^0. However, the jitter during the shot was about 20^0. Amplitude jitter was checked to ensure that it was small compared to one. It measured 0.9%, thus vindicating our use of the approximations. From experiments on the effect of voltage changes in the gyroklystron's electron gun, it seems that the jitter in the pulse may be due to the 17 MHz, 1% ripple observed on the high voltage pulse. The ripple frequency of the phase jitter is half the high voltage modulation frequency. The reason for this is not yet understood.

As an oscillator the gyroklystron phase performance was unexpected. The oscillator was not locked but it was triggered by the master. In the short time available before publication deadlines, we were unable to find an operating mode whose frequency we could control with the master oscillator. We could, however, control the point on the master oscillator's phase at which the gyroklystron started to oscillate. This is important because it means that one could start any number of gyroklystrons in phase with each other. Then, using classic electromechanical feedback systems to control the oscillating frequencies, one could maintain the phase relations throughout the pulse. We measured the shot-to-shot phase jitter by comparing the phase relation between master and slave at the beginning of each pulse. The jitter is tabulated in the Table as a function of the ratio of master oscillator power to gyroklystron power.

This phase triggered oscillator appears to be frequency controlled by the tuning of R3 alone. The resonant frequencies of R1 and R2 can be tuned through many tens of MHz without affecting either the output frequency, or the amplitude. Radiation from R1 leaking into the driver circuit has the same frequency as the radiation output from R3. This suggests that the oscillations start in the third cavity, and a positive feedback path is then established backward through the cutoff waveguide (attenuation per section equals 30 dB). The master oscillator power affects the time between the beginning of the high voltage electron pulse and the beginning of the gyrolklystron oscillations. As the master oscillator power is decreased through two orders of magnitude the time delay increases by 0.5 μs. Apparently, the gyroklystron oscillator is slow to start up by itself, thus the start-up is influenced by any prebunching that might be achieved when the master oscillator signal is fed into the first resonator.

TABLE. Shot-to-shot jitter between master and slave for several ratios of master power to slave power. The slave gyroklystron is a phase triggered oscillator.

Gain (dB)	Phase Jitter
- 52	$7^0 \pm 15^0$
- 83	$39^0 \pm 15^0$
- 95	$50^0 \pm 15^0$

Conclusion

From the results reported here, it seems that the gyroklystron, operating either as an amplifier or as a triggered oscillator, would have sufficient phase coherence to function as an accelerator driver. More work is planned to determine how the triggering mechanism works in the oscillator. Although the last cavity of the gyroklystron appeared to be oscillating in this experiment, other cavities have been observed to oscillate under slightly different settings of the many variables under experimental control. Of immediate importance is the cataloging of the various oscillating modes. This will enable us to select the most appropriate mode for each application.

References

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