OPERATIONAL CHARACTERISTICS OF THE NRL GYROKLYSTRON AMPLIFIER*

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ABSTRACT

The high-energy physics community is considering the development of 1 TeV accelerators. Size and cost of such devices can be greatly reduced by operating at 10 GHz. Present tube technology seems incapable of meeting the power requirements at this frequency. A strong candidate for a drive tube to meet these requirements is a gyroklystron amplifier (GKA) due to its high gain, efficiency and power capabilities. The Naval Research Laboratory (NRL) is presently conducting GKA research to evaluate their performance characteristics. Operation of a 54 kW, 30% efficient, 4.5 GHz 3-cavity GKA is described. Experiments to evaluate the effects on the output phase of varying drive voltage, beam current, magnetic field and drive power and to examine phase-locked oscillator performance are discussed. The results of present GKA experiments serve to emphasize the applicability of the GKA to the next generation of linear accelerators.

INTRODUCTION

The microwave tubes required to drive an electron-position supercollider will have challenging characteristics.[1] For example, suggested microwave tube specifications[2,3] include average power of 25 kW, peak power of 300 MW, pulse width of 100 ns and frequency of 10 GHz. High gain (> 50 dB) and high efficiency (> 50%) are also important. Furthermore the source must be an amplifier or a phase-locked oscillator to allow each of the seperate drive tubes, and therefore accelerator sections, to be phase synchronized. It does not appear that the present SLAC klystron tubes can be easily extended to the required power or frequency.[3] A strong contender for the next generation accelerator drive tube is the GKA. The GKA is predicted to be a high efficiency, >50%, high gain > 40 dB, and high power device. Scaling the GKA to high frequency, > 10 GHz, is not difficult due to the simplicity of its fast wave circuit which avoids the small gaps of reentrant cavities or small periodic structures. Initial experiments have confirmed the desirable behavior of a GKA[4] and are elaborated in this paper.

GYROKLYSTRON DESIGN

A number of criteria were used in the design of the NRL gyroklystron amplifier shown in Figure 1. First, due to difficulties with spurious oscillations in previous experiments[5], the design was restricted to the fundamental cyclotron frequency operating in the dominant cavity mode, and the drift lengths were designed to be cut-off to the operating frequency. Second, due to the electron gun available for use, the design was constrained in magnetic field and, therefore, frequency. Third, rectangular cavities were chosen to allow easy tuning and to eliminate the dual polarization possible with a circular TE_{111} cavity. Fourth, a 40 dB gain was desired; calculations indicated that a three-cavity design would be capable of obtaining this gain.[6] Finally, a decision to use only conventional electromagnets was made. This was consistent with the frequency limitations imposed by the gun and allowed for greater experimental flexibility. Using these criteria the NRL GKLY-101 amplifier was designed, fabricated and is now under test.

As shown in figure 1, the GKLY-101 tube utilizes a magnetron injection gun to launch an annular electron beam into the rf interaction region, which consists of three cavities separated by radiation-free drift lengths. The gun was originally designed to provide a 5 A beam with an α (perpendicular velocity divided by parallel velocity) of 2 when operating at 60 kV. Testing has not exceeded 35 kV due to modulator limitations. At this voltage the α is closer to one based on both experimental evidence and computer simulation of the gun.

The rf circuit consists of three rectangular cavities in series operating in the TE_{101} mode at the fundamental cyclotron frequency. These cavities are separated by cylindrical drift lengths ($L=1.5\lambda$), which are cut-off to the operating frequency. The cavities are tunable by moving a foil membrane which forms one of the cavity walls. The first two cavities ($L=0.9\lambda$) are used to bunch the beam and have a cold loaded Q of 600. The third cavity ($L=1.1\lambda$) has a cold loaded Q of 235. All three cavities are matched to waveguide through a coupling hole in the side wall. This permits the drive signal to be introduced into the first cavity and the microwaves to be extracted from the third cavity. The waveguide on the second cavity can be used as a 3-cavity GKA diagnostic or to study 2-cavity GKA operation.

EXPERIMENTAL RESULTS

The NRL gyroklystron can be operated in three different modes: (1) amplifier, (2) oscillator, and (3) non-linear amplifier/phase-locked oscillator. We will describe all three but only discuss oscillator performance as a phase-locked oscillator.

Amplifier: The NRL gyroklystron was designed for optimum operation as an amplifier[6] and best performance is obtained in this mode of operation. Measurements have been made of gain, output power and efficiency. Figure 2 shows typical small signal data with a gain of 26 dB. This data is taken with a uniform magnetic field and compares well with theoretical predictions of 30 dB small signal gain, for $\alpha \approx 1$ and $\Delta v/v_z \sim 10\%$ (experimental beam parameters). Larger small signal gains ($\approx$36 dB) have been observed with a shaped magnetic field.

The largest output power measured was 54 kW as shown in Figure 3 and was obtained using a shaped magnetic field. The corresponding large signal gain was 18 dB, the small signal gain was 22 dB, and the efficiency was 21%. Both the small signal gain and the efficiency are lower than the best values observed (36 dB, 30%). We speculate that this decreased performance is related to beam quality. The high power is obtained by increasing the current. This probably increases the space-charge effects and, therefore, the velocity spread. The shaped magnetic field profile used increases from the gun until the end of the second cavity and then decreases with a 30% variation from maximum to minimum field.

Bandwidth measurements have also been made for the GKLY-101 device. As previously discussed, the gun α is approximately 1. This corresponds to a theoretical bandwidth of 0.20% for a uniform magnetic field and a beam current of 6A. A bandwidth of .1% was observed. For lower current, 3 A, the bandwidth increased to .3%. Furthermore, the bandwidth increased to 0.4% with stagger tuning and magnetic field shaping. The stagger tuning is the dominant effect in broadening the bandwidth. For our device the bandwidths are limited by the cavity Q values. Without stagger tuning the limitation arises predominately from the drive cavity Q value. Since this cavity has a Q of 600 the expected bandwidth is 0.2%. For staggered tuning, the limitation is imposed by the output cavity with a Q value of 235 corresponding to an expected bandwidth of 0.4%. Clearly, lower Q cavities could be used to increase bandwidth. Overall gain could be maintained by increasing the number of cavities.

We have also examined the phase stability of the GKA. Initial studies show the following behavior: (1) $\Delta\phi_{B2} = 0.98$ rad/%; $\Delta\phi_{B3} = 0.22$ rad/%, (2) $\Delta\phi_V = -8.4 \times 10^{-2}$ rad/% (3) $\Delta\phi_I = 0.07$ rad/%, and (4) $\Delta\phi_P \sim 0.0$ rad/%, where $\Delta\phi_x$ is the change in phase angle between the input signal and the output signal, divided by the percentage change in parameter x (Bn = magnetic field near cavity n, v = beam voltage, I = beam current and p = drive power). The noise characteristics have been measured and are described in a companion paper.[7]

Non-linear amplifier performance: Operation of the gyroklystron amplifier as a non-linear amplifier/ phase-locked oscillator is also being examined. This mode of operation has been predicted for the gyroklystron.[8] The unique characteristic of this type of operation is the sharp transition from the linear amplifier region to the saturated locked-oscillator region. At the transition point a small increase in drive power excites and controls the phase of a powerful oscillation. This phenomenon has been observed experimentally. The drive curve is shown in Figure 4 and shows the same qualitative features as the theoretical prediction. The power locking ratio (10 log P_{osc}/P_{drive}) is 56.5 dB at the transition. In the phase-locked region the drive signal triggers the oscillation so that pulse to pulse the oscillation always starts at the same phase relative to the drive. The frequency of the oscillation may not be controlled by the drive. The phase diagnostic was set to examine only a narrow time window of the pulse. The diagnostic gave a polar oscilliscope display where the radial component corresponded to the product of the amplitudes and the angle from the x-axis, θ, was the relative phase difference between the two signals. For free oscillations pulse to pulse variations in the phase yield a circle. For phase-locked operation a stationary point results.

Phase-locked oscillator performance: By proper adjustment of the magnetic field profile, beam voltage, and current the GKLY-101 tube will operate as an oscillator. Then by application of a drive signal, the oscillator frequency and phase may be fixed. This is the classical "driven oscillator". The phase correlation diagnostic and a spectrum analyzer were used to measure both phase and frequency locking. Figure 5 shows the output signal observed using a crystal diode. For this case the oscillator frequency is not locked and the beat frequency seen in Figure 5 is the difference between the drive frequency and the oscillator frequency. Using a spectrum analyzer seperate frequency peaks were measured with a difference corresponding to the observed beat frequency. This beat signal is observable since the drive signal is triggering the phase of the oscillation. As the drive signal is increased the frequency locks to the drive frequency. The locking bandwidth, ΔF, was 1.9 MHz. Adler[9] has developed a simple model for determining the drive power required to lock an oscillator:

$$\Delta F = \frac{2F_o}{Q_L}\left(\frac{P_d}{P_o}\right)^{1/2} \qquad (1)$$

where, F_o is the free running frequency, Q_L is the loaded Q of the oscillator cavity, P_d is the drive power and P_o is the output power. For our case, the oscillations occur in the first cavity and the signal is amplified in the next two cavities. Thus, P_o is then the output power divided by the gain of the amplifier ($\approx$20dB). Using equation (1) we calculate that the power locking ratio should be 17.8 dB. Adding 20 dB to this we obtain a predicted locking ratio of 37.8 dB which compares well with the experimentally observed value of 35.8 dB.

CONCLUSIONS

The gyroklystron has been shown to be a high gain, high efficiency device. With the additional ability to scale to high frequencies the gyroklystron seems an ideal drive tube for the next generation of high-energy accelerators. Phase stability measurements agree well with theoritical predictions and suggest that, with care, the stringent accelerator requirements for phase stability can be met.

REFERENCES

* Work Supported by the NAVELEX.
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1. P.B. Wilson, Proc. 12th Int. Conf. on High Energy Accelerators, SLAC-PUB-3227 (1983).
2. R.B. Neal, Stanford Linear Accelerator Center Report SLAC/AP7, (1983).
3. V.L. Granatstein, Int. J. Electronics 57 p. 787 (1984).
4. W.M. Bollen, A.H. McCurdy, B. Arfin, R.K. Parker, and A.K. Ganguly, submitted to the IEEE Trans. on Plasma Physics (1985).
5. R.S. Symons and H.R. Jory, in Adv. Electron. Elec. Phys., 55, p. 1, Academic Press, NY (1981).
6. B. Arfin and A.K. Ganguly, Int. J. Electron., 53, p. 709 (1982).
7. J. McAdoo, M. Bollen, V. Granatstein, R.K. Parker, R. Smith, G. Thomas, and A. McCurdy, this proceedings.
8. W.M. Bollen, A.K. Ganguly, B. Arfin, M. Nagurney, and F.N. Wood, Proc. IEEE Plasma Sciences Meeting (1984).
9. R. Adler, Proc. of the IRE, 34, 351 (1946).

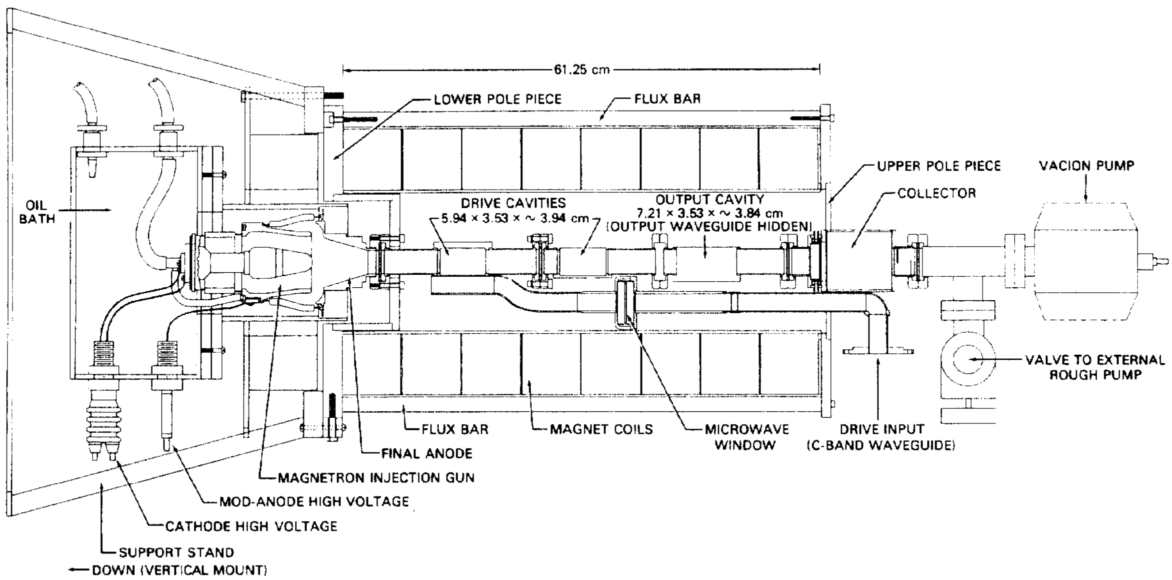

Fig. 1. Drawing of the NRL gyroklystron amplifier.

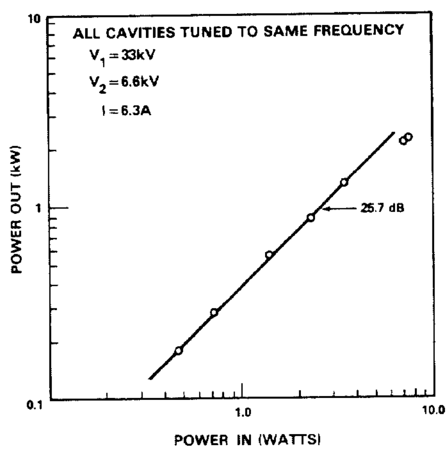

Fig. 2. Small signal gain in a uniform magnetic field.

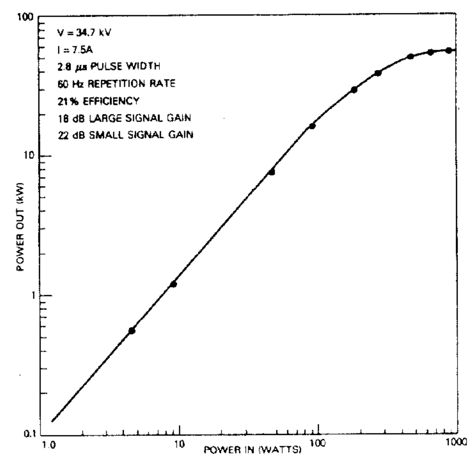

Fig. 3. Amplifier drive curve with shaped magnetic field to optimize power.

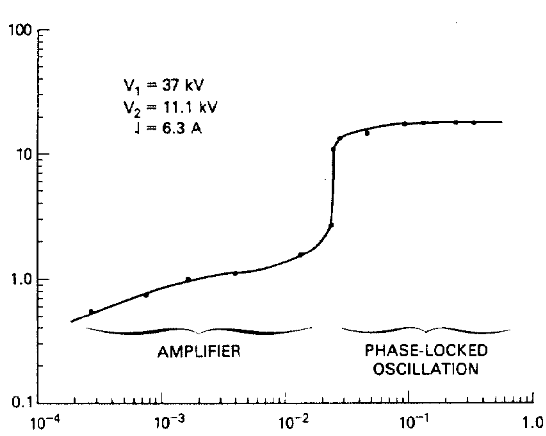

Fig. 4. Drive curve for non-linear amplifier.

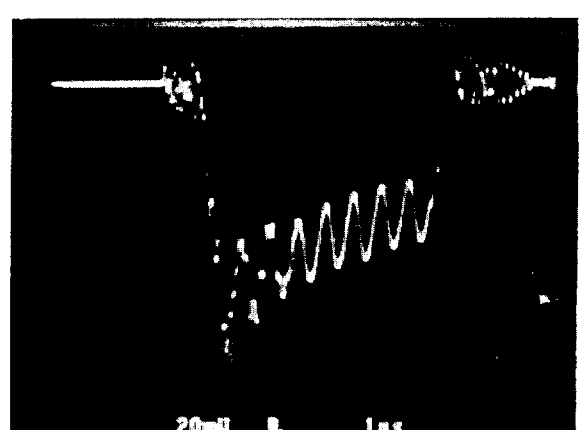

Fig. 5. Beating of oscillator power with drive power.