Installation and Test Results of a High-Power, CW Klystrode Amplifier at Los Alamos National Laboratory*

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Abstract

The Chalk River Laboratory (CRL) 1.25 MeV, 267 MHz CW radio frequency quadrupole (RFQ) project [1] has been moved to Los Alamos AOT Division as a collaborative effort between Los Alamos and Chalk River Laboratories. The RF part of this project includes two 267 MHz, 0.25 MW, CW klystrode transmitters. The klystrode is a relatively new type of RF source that combines the input structure from a conventional gridded tube and the output structure of a klystron. It is widely used within the UHF television band at reduced power (60 kW at peak of sync). However, this is the first application of a high power klystrode for a particle accelerator. This paper will describe the experimental configuration at Los Alamos, provide block diagrams of the klystrode transmitter, discuss the attributes of the klystrode which make it a desirable candidate for high efficiency CW accelerators, and present relevant test results.

Introduction

The klystrode [2] combines attributes from both gridded tube and klystron technology. The klystrode has a gridded input structure where a grid/cathode region produces a density-modulated beam whose energy is then converted to RF fields in a klystron-like output cavity. A schematic of the klystrode is provided in Figure 1. The primary klystrode market is UHF TV transmission where it provides up to 60 kW peak-of-sync output power at high efficiencies (> 70 %). Two high power klystrode developments have been undertaken in the last several years. The first high-power klystrode achieved in excess of 750 kW pulsed at a 10% duty factor at 425 MHz. The gain of the device was in excess of 20 dB and the efficiency was greater than 70 percent. The second high power klystrode development is the topic of this paper. The second high power klystrode was developed for a continuous wave (CW) accelerator application. The klystrode is to be used as a power source for a radio frequency quadrupole (RFQ) at Chalk River Laboratories in Ontario, Canada. This program has since moved to Los Alamos National Laboratory to serve as a test stand for high-average power accelerator applications. The high-power klystrode for this application is designed to provide 250 kW of CW power at 267 MHz with a gain in excess of 20 dB and an efficiency greater than 70 percent. The performance of this klystrode is the topic of this paper.

*Work supported by the Defense Nuclear Agency.

The schematic in Figure 1 illustrates the major components of the klystrode. The 250 kW klystrode is operated at negative 68 kV on the cathode with the grid bias several hundred volts below cathode. An external resonant circuit is attached to the grid/cathode region and the applied RF drive produces a density modulated electron bunch. The energy of this bunch is then converted into the RF field in an internal, output cavity. A magnetic focusing field is applied and the filament supply is also referenced to cathode.

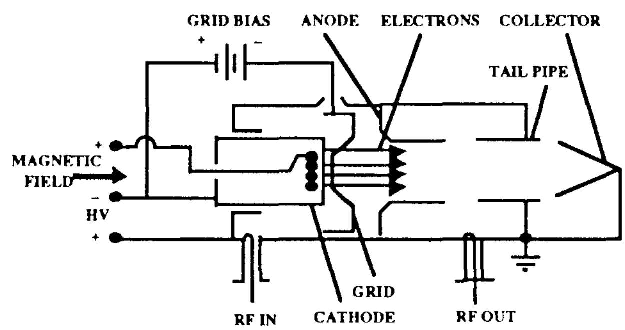

Figure 1. Klystrode schematic.

Our interest in the klystrode is motivated by its high efficiency and control characteristic. These attributes are described here and illustrated in the test results which follow. All high power klystrode developments to date have achieved an efficiency in excess of 70 percent. This efficiency is quite high when compared to the competing klystron and gridded tube technologies. Moreover, the klystrode has a soft saturation characteristic that allows the user to provide control over the output power while still achieving the full, saturated efficiency, and since the klystrode is essentially operated as a class B amplifier the degradation of efficiency at lower power levels is quite small when compared to klystrons.

To better understand the advantage of the soft saturation characteristic comparison to the klystron is helpful. The power transfer characteristic of a klystron actually becomes flat and then rolls over when the klystron is driven into saturation. Unfortunately, the klystron provides its maximum efficiency only at saturation. We cannot rapidly control the accelerating cavity field level to compensate for beam induced disturbances by varying the drive power to the klystron in saturation because of the flat power transfer characteristic. Therefore, with a klystron it is necessary to provide a control margin (the control margin is the amount we must operate the klystron below saturation in order to achieve cavity control requirements). Typically we assume a 10 to 20% control margin will be sufficient; however, this translates to a 10 to 20% decrease in klystron efficiency. In contrast, the soft saturation characteristic of the klystrode provides a power transfer function which flattens out as saturation is approached but still has a positive slope. With this characteristic, we can exercise control over the accelerating cavity fields without paying the efficiency penalty required for the klystron.

When a klystron is operated at a power level less than the saturated-output power, a significant efficiency penalty is paid. Unfortunately in accelerator service the accelerating cavity power requirements are different from cavity to cavity but one klystron type is typically purchased (to minimize development costs) to provide power to a number of accelerating cavities with variable power requirements. This results in some klystrons being utilized at power levels much below saturation and a significant degradation in efficiency. Techniques like the adjustment of modulating-anode voltage to vary beam current from klystron to klystron can be used to minimize the loss in efficiency as the klystrons are operated at power levels below maximum, but the efficiency penalty is still high. In contrast the test data presented below illustrates that the klystrode provides excellent efficiency over a broad range of output power. This is consistent with what we expect from a class B amplifier.

The klystrode is also smaller in size and lighter in weight than klystron technology at low frequencies (<500 MHz). It is however limited in gain. The high power klystrode developments have provided on the order of 22 dB of gain which is much smaller than the 50 - 60 dB achievable with klystrons. The peak and average power of the klystrodes is also less than that achievable with klystrons. It is questionable if current klystrode technology can provide in excess of 500 kW of average power because of RF heating of the cathode by the drive power.

Transmitter Design

The klystrode transmitter was designed by Continental Electronics. It is a three stage transmitter capable of operating either pulsed or CW. The transmitter is equipped with circuits that maintain a constant power output and protect from overload conditions.

The input signal to the transmitter drives a solid state amplifier capable of providing up to 50 watts of output power. The solid state amplifier drives a driver klystrode power amplifier which has approximately 23 dB of gain but under nominal operating conditions provides less than 3 kW of drive to the final klystrode stage. The final power amplifier then raises the output to the rated 250 kW. A voltage sample of the field in the RFQ cavity is monitored by a feedback loop which amplitude modulates the drive to maintain a constant cavity field. A sample of the reflected power is also monitored and excessive reflected power causes RF excitation to be removed from the system. A block diagram of the transmitter is included in Figure 2.

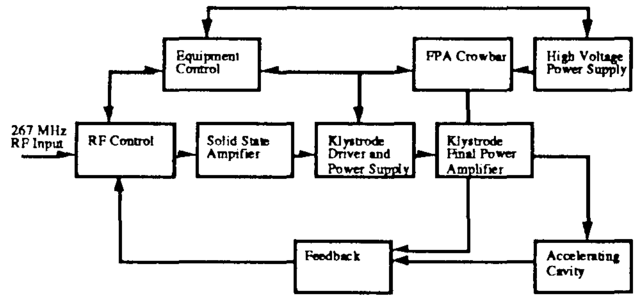

Figure 2. Klystrode transmitter block diagram.

Test Results

Test results are provided below. Figure 3 illustrates the power transfer curve of the high power klystrode amplifier. The soft saturation characteristic can be observed in this figure. Figure 4 presents the efficiency of the klystrode as a function of output power. It is observed from Figure 4 that the efficiency is greater than 70% from 160 kW to the maximum output power. Figure 5 illustrates the klystrode bandwidth. It is observed from the figure that the 1 dB bandwidth is approximately 1.4 MHz.

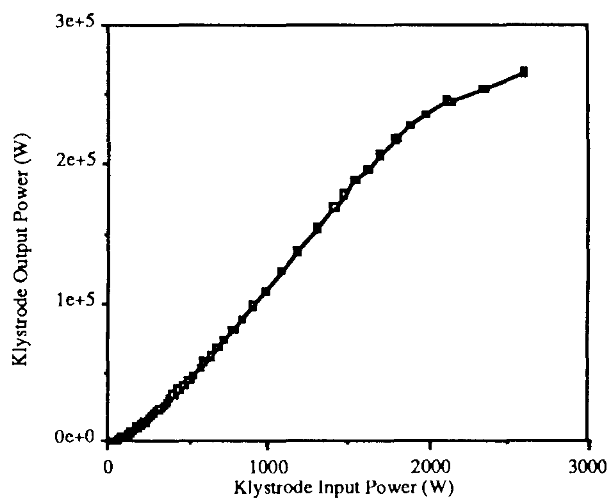

Figure 3. Klystrode power transfer curve.

Conclusion

The test results demonstrate that for some accelerator applications the klystrode has significant advantages over a klystron. These advantages include size, weight, and efficiency. Applications where klystrode technology can provide performance enhancements include frequencies from 200 to 700 MHz in applications where the peak and average power is less than 500 kW. Testing is continuing at Los Alamos and is concentrating on characterizing the phase response of the klystrode and evaluating the impact of optimizing the output cavity tuning and loading on the peak efficiency if performance is optimized at power levels below the design output power. It is expected that the klystrode will be providing RF power to the RFQ before the end of the fiscal year.

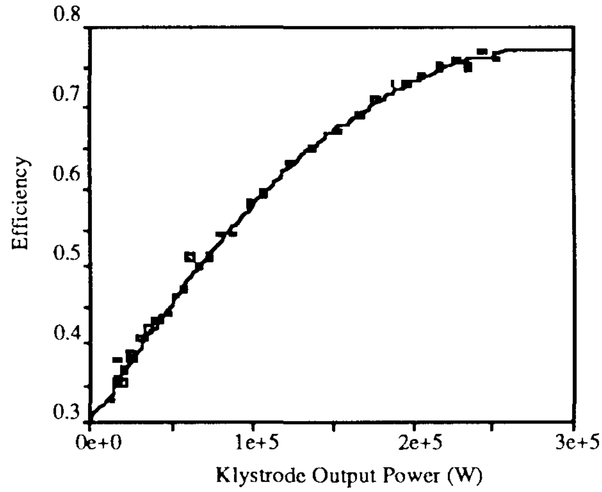

Figure 4. Efficiency vs. output power.

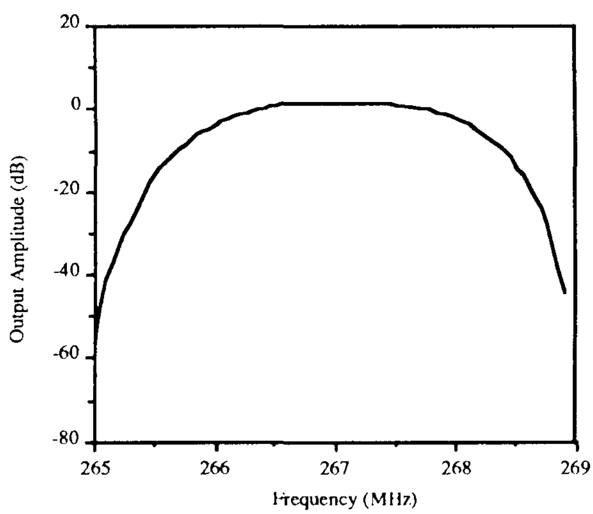

Figure 5. Klystrode frequency response.

References

[1] J. Y. Sheikh, A. D. Davidson, G. E McMichael, L. W. Shankland, and B. H. Smith, "Operation of a High-Power CW Klystrode with the RFQ1 Facility", in Proceedings of the 1993 Particle Accelerator Conference, IEEE Catalog No. 93CH3279-7, 1175 (1993)

[2] D.H. Priest, "The Klystrode-An Unusual Transmitting Tube with Potential for UHF-TV," IEEE Trans. on Electron Devices, Vol. 70, No. 11, p. 1318 (1982).