OPERATION OF A HIGH-POWER CW KLYSTRODE WITH THE RFQ1 FACILITY*

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Abstract

A high-power klystrode rf system for the RFQ1 facility at the Chalk River Laboratories (CRL) has been manufactured by Continental Electronics Corporation (CEC), Dallas using klystrode amplifier tubes developed by Varian, San Carlos. The system consists of two units, each capable of 250 kW in pulsed or cw mode. The two units can be operated independently to drive two separate accelerator structures, or together in a master/slave combination to drive one structure. This system is the first high-power klystrode to power a cw accelerator, and is a significant step in high-power klystrode development, increasing the average power per tube by a factor of 5 (to 250 kW). Commissioning, initial operation of one unit of this system with the RFQ1 facility, and data obtained to date, is described.

I. INTRODUCTION

The RFQ1 facility [1] was the major component of a program at CRL to develop 100% duty factor accelerators for applications requiring high-current beams of protons or other light ions. The accelerator was first built for an energy of 600 keV (RFQ1-600), and later was rebuilt with new vanes to double the output energy to 1.25 MeV (RFQ1-1250). The rf system used for RFQ1-600 and the initial runs of RFQ1-1250 was a gridded-tube system based on an RCA 2054 triode. This system lacked flexibility and was becoming unmaintainable. Late in 1989, an order was placed with Varian to develop and supply a new system that would include two 250 kW cw klystrodes [2,3]. In 1992 February, AECL decided to terminate the cw ion linac development program, effective 1993 March 31. An arrangement was put in place to transfer the RFQ1 hardware to the Los Alamos National Laboratory (LANL), where it would be used to assist their program. Consequently, there was only time to install and commission one 250 kW module at CRL; the second module was delivered directly from CEC to LANL.

II. FINAL OPERATION WITH TRIODE

The output windows of klystrodes require protection from the effects of sustained high reflected power from a mismatched load. Varian's original design used a signal from a cavity-gap sensor (installed at a suitable spot in the output cavity) to decrease the rf drive via the output levelling loop if too high a reflected power level occurred. To provide further protection and facilitate conditioning of resonant structures, a 250 kW coaxial circulator was purchased. It was initially used on the RFQ with the triode system to obtain experience with a circulator.

Initial operation with the circulator up to 175 kW appeared no different from operation without it. However, attempts to increase the power level beyond 175 kW resulted in arcing in the RFQ, which shut down (tripped) the rf system. After each trip, the subsequent power level attainable decreased until the power could not be raised above 20 kW. Because the RFQ had been easily conditioned to over 200 kW cw without the circulator, it was apparent that adding the circulator either introduced a new problem or nullified some mechanism that had prevented damaging arcs. Further analysis indicated that, without the circulator, high reflected power from the RFQ at an arc caused the triode gain to decrease, thereby lowering the output power, allowing an arc to extinguish. With the circulator isolating the RFQ from the amplifier, the output power was unchanged. This level sustained the arc and sputtered a lot of copper onto the drive-loop ceramic window. A test arrangement using a storage scope, an analogue scope and a pulse generator was developed to sense high reflected power and remove the rf drive for a few microseconds, to allow the arc to extinguish. This arrangement allowed the RFQ to be reconditioned, and demonstrated the need for an arc suppression circuit for operation with the klystrode amplifier. An rf blanking module incorporating a similar control algorithm was subsequently developed for LANL, and was used during cw beam and rf experiments with the klystrode system (described in section V).

III. DESCRIPTION OF RF SYSTEM

A block diagram of a 250 kW module is shown in Fig. 1. Through three stages of amplification, the signal generator input of 10 mW is amplified to 250 kW with an overall gain of ~74 dB. The output of the solid-state amplifier, A2, is connected to the driver klystrode amplifier through a circulator and a directional coupler.

The EIMAC 2KDX15LA driver klystrode is a UHF TV tube rated for 15 kW peak power; however, in the modified circuit assembly, it supplies up to 4 kW cw. It is connected to the EIMAC 2KDX16LA final klystrode through directional couplers and a circulator. The final klystrode is connected to the load via a 15 cm coaxial transmission line that incorporates directional couplers and a variable coupler, E4.

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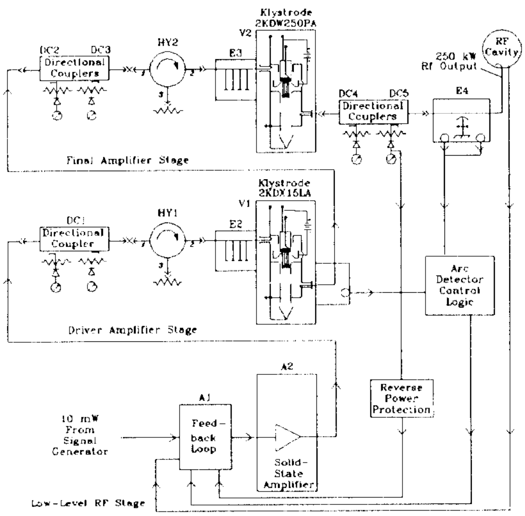

Fig. 1. RF block diagram of the system

The variable load coupler uses two Teflon slugs, which slide on the centre conductor of transmission line. It matches the load at the tuned frequency by reflecting a voltage of adjustable phase back into the output cavity of the klystrode. Optical detectors mounted on the line generate signals to activate a blanking circuit that reduces the gain by 40-60 dB. A coaxial transition (15 to 23 cm) follows the variable coupler. The connection to the circulator and the RFQ1 is via 23 cm transmission line.

The feedback loop, A1, is a dual control loop. It has an outer loop that senses the output power level and adjusts the input to the solid-state amplifier, to keep the output power constant within ±1%. The bandwidth of this loop is > 500 kHz, sufficient to remove amplitude modulation due to ripple on the high-voltage power supply. The faster inner loop protects the final and driver tubes by limiting the drive power if the operator (open-loop mode) or the outer loop (closed-loop mode) requests a drive power that would make the reflected power, output-window voltage, or driver-amplifier power exceed safe operating levels. The output-window power sensor signal has proved to be reliable and has replaced the cavity gap sensor originally used in the design.

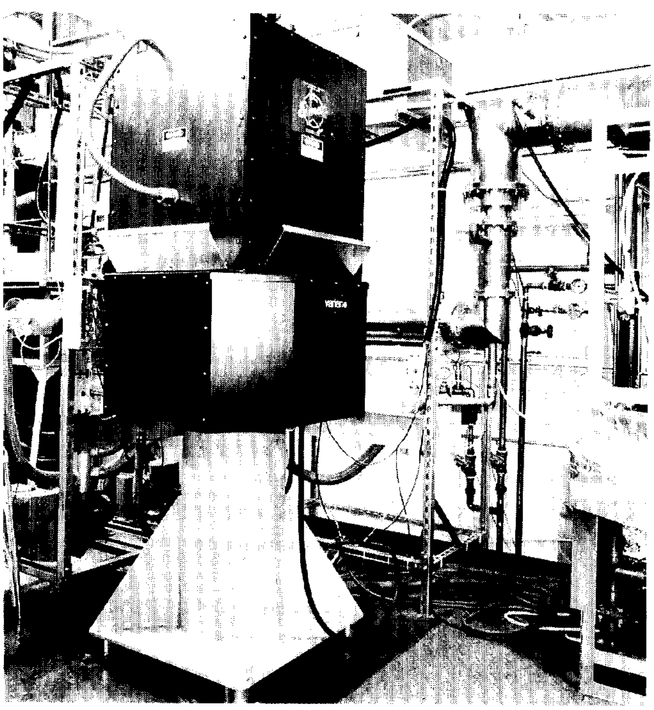

Fig. 2 Final klystrode amplifier

For operation into a resistive load, a forward-power-signal from a directional coupler can be used for the feedback signal for the outer loop. The loop parameters are optimized for a loaded Q range of 2000 to 20 000. A capacitor to simulate the cavity Q is placed on the rf feedback controller circuit board, to provide loop stability when controlling power to a resistive (low Q) load. The outer of the two feedback loops has been designed to allow operation of two 250 kW amplifiers in a "master/slave" configuration for a combined output of 500 kW.

IV. INSTALLATION & SYSTEM PERFORMANCE

Both of the 250 kW rf systems were acceptance tested at CEC. The first completed system was shipped to CRL. Installation began on 1993 January 04 and was completed, with first rf power out of the final amplifier, by 1993 February 02. An overview photograph of the installed amplifier is shown in Fig. 2. The system was tuned to 267 MHz and initially operated into a 300 kW resistive load. The signal from the output-window sensor was found to be somewhat larger during operation at CRL than it had been at both Varian and CEC. The upper limit of 500 mW allowed for this signal was reached at an output power of only 237 kW, whereas previously the observed signal was less than 400 mW at an output power of 300 kW. The time allowed for tests of the amplifier was too short to allow a detailed investigation of this

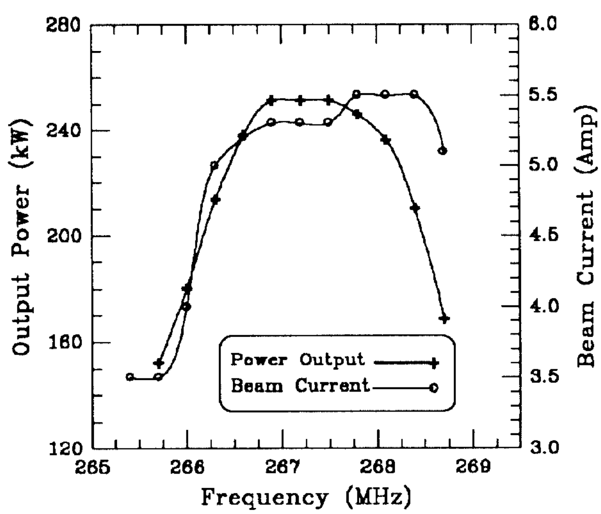

Fig. 3 System bandwidth with system tuned at 267 MHz

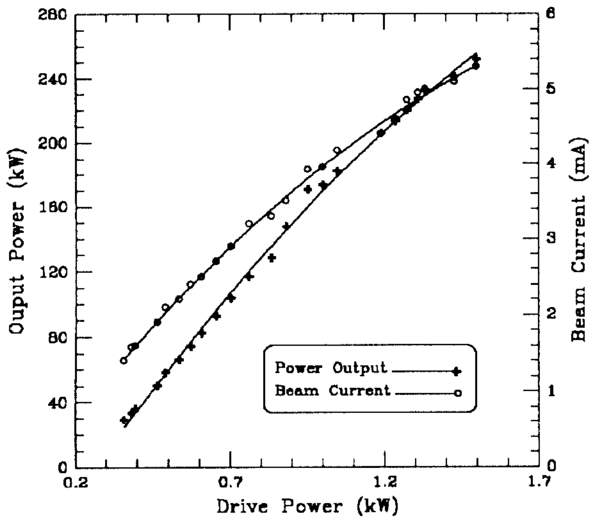

Fig. 4 System linearity at 267 MHz

discrepancy, and since the power obtainable was sufficient to meet the needs of the beam experiments with RFQ1, the problem was not resolved. Tuning errors that were initially suspected now appear unlikely, leaving instrumentation differences as the most probable explanation. Varian now believes that the 500 mW limit is conservative, and has reviewed increasing this limit if similar readings are obtained following recommissioning of the system at LANL. The bandwidth and linearity of the rf system observed during the acceptance tests are shown in Figs. 3 and 4.

V. OPERATION WITH RFQ

Prior to first operation with the klystrode system, the RFQ had been left unpowered but under vacuum for over four months. Some reconditioning was required, but with the pulsing capability of the new system it was much easier to break through multipactor and to condition for high, cw power. Beam acceleration was attempted immediately after the RFQ would accept the design 150 kW cw power. Within three days, a cw proton beam of > 50 mA was accelerated from 50 keV to 1.25 MeV without incident. As expected, transmission and emittance were similar to that observed previously with the triode amplifier [4]. During the very limited time available for experiments before the 1993 March 31 shut down, minor incompatibilities between the level controller and the rf-blanking module prevented closed-loop RFQ-field control during beam acceleration. These incompatibilities were identified and necessary modifications checked out at the module level prior to shut down; none appear to present serious long-term concerns.

VI. CONCLUSIONS

The beam operation was similar to that with the triode system. Closed-loop beam operation was not achieved, but no "show-stoppers" are expected. The pulse capability of the rf system significantly eased and shortened RFQ conditioning. Coarse tuning adjustments to change the amplifier frequency are easy; however, considerable fine tuning is required to achieve best efficiency (>70%) and final-amplifier gain (>22 dB). The high, output-window, sensor-power problem is not yet resolved, but should not limit operation at LANL. Cavity-gap sensor readings were inconsistent; output-window probe readings proved much more useful as input to the protection circuit.

The successful tank and beam operation has demonstrated that a klystrode is a suitable rf amplifier for accelerator cavities, and thus deserves serious consideration as the power source for the next generation of high-power cw or pulsed accelerators in the 0.2 to 1 GHz frequency range.

VII. ACKNOWLEDGEMENTS

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