RECENT PROGRESS IN CW KLYSTRONS AT CPI

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Abstract

The need for super-power klystrons for particle accelerators has been growing in recent years. The key requirements for these devices are high efficiency and reliability. CPI has now delivered to four different applications around the world: 700-MHz, 1-MW-CW klystron for the Accelerator Production of Tritium (APT) project at Los Alamos National Laboratory (LANL), 499.76 MHz, 800-kW-CW for the Cornell Electron Storage Ring (horizontal orientation), 499.67 MHz, 800-kW-CW klystron for HERA at Deutsches Elektronen-Synchrotron (DESY) (vertical orientation), and 1.497 GHz, 100 kW CW klystron for the FEL Driver Accelerator at Thomas Jefferson National Accelerator Facility (TJNAF). Among the many-shared features on the super-power tubes are a six-cavity rf circuit (with one cavity tuned slightly below the second harmonic of the operating frequency), a single output window, and a modulating anode in the electron gun. The second-harmonic cavity is used to enhance efficiency. The 100-kW klystron incorporates a six-cavity rf circuit (no second harmonic cavity) and a diode gun. Computer predictions, performance specifications and operating results will be presented.

1 INTRODUCTION

CPI, formerly the Electron Device Group of Varian Associates, has a long history of building high-power UHF klystrons for many applications. In the early 1990's CPI worked with Stanford Linear Accelerator Center (SLAC) under a Cooperative Research and Development Agreement (CRADA) to develop a new 476-MHz, 1.2 MW CW source for the B-Factory [1]. CPI provided the electrical designs of the electron gun and rf circuit while SLAC led the effort on the mechanical design.

CPI was awarded its first contract to build a super-power klystron in late 1995 by LANL for the 700-MHz, 1-MW-CW klystron for the APT Project. Shortly after that orders were placed by both Cornell University and DESY for 500-MHz, 800-kW CW klystrons.

The order for three 100-kW CW klystrons for TJNAF was placed in June 2000. Although this tube is quite smaller than the super-power klystrons, it shared the same design approach and computer codes as the higher power devices.

2 DESIGN

2.1 Electrical Design

The electron gun design is primarily performed using XGUN, starting with the electrostatic beam optics. Once the performance is satisfactory, the beam optics are refined with magnetic field applied. Care is taken to evaluate and minimize the beam scallop down the drift tunnel. Analyses are performed at various operating conditions. The voltage gradients of the gun electrodes are analyzed with a goal of a maximum gradient of 60 kV/cm. Great care is taken to ensure a well-behaved beam is obtained.

The rf-circuits contain six cavities, including one tuned slightly below the second harmonic of the operating frequency. The designs are optimized to provide the required efficiency and gain without compromising bandwidth. The first two cavities are staggered around the operating frequency to provide the bandwidth. Next is the second-harmonic cavity followed by two inductively tuned cavities to optimize the electron bunching. The output cavity then extracts energy from the beam.

The rf-circuit is designed using 1-D and 2-D particle-in-cell codes developed at CPI. Many years of benchmarking the codes to measured results has lead to high confidence in the results. SUPERFISH is used for cavity design, while HFSS and MAFIA are used for the output cavity, coupling loop, and output window design.

2.2 Mechanical Design

The 700-MHz klystron was required to operate in a horizontal orientation. The approach was to design the klystron with sufficient mechanical integrity so that it could be loaded into the magnet horizontally. The rf-cavities are supported by six support rods that run from the base of the input cavity to the base of the collector. Each cavity has a support plate that was captured by the rods. A pivoting mechanism is placed at the collector base plate, which was very near the tube center of gravity, so the tube could be rotated from vertical to horizontal.

The two buncher cavities and the two inductively tuned cavities have stainless steel walls with copper endwalls, with cavities 4 and 5 copper plated to reduce resistive loss. The second harmonic and output cavities have OFE copper walls. All cavities, except the output, have one adjustable drift-tube tip and an adjacent flexible cavity endwall to allow for adjusting the tuning. The rf energy is extracted through a single coaxial window. The transition to waveguide is made through a T-Bar transition.

The collector is designed to dissipate the entire dc beam energy. It is made from thick-walled copper with grooves milled into the outer wall for the coolant to pass. The water-jacket bolts on with an o-ring seal and was proof tested at 200 psi (13.6 bar).

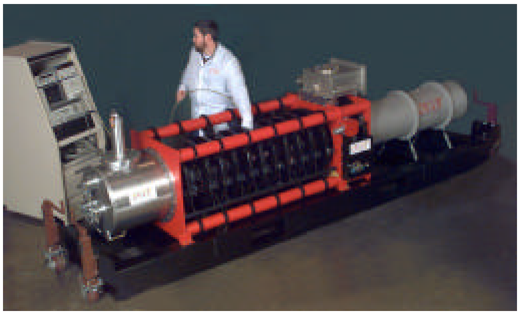

Figure 1: VKP-7952A Klystron for APT

The 700-MHz APT klystron and the 500-MHz Cornell tube were both designed for horizontal operation and had the described mechanical design. The tube for DESY operates vertically with the gun up and did not need a full power collector. The electron gun was to operate in air. The tube was shipped in the magnet horizontally and was then tipped to a vertical position at the customer site during installation.

3 TEST RESULTS

3.1 700-MHz, 1-MW CW Klystron

The basic power, efficiency, gain, and bandwidth all met the specification. Additionally the klystron had to demonstrate stable performance and achieve 85% of its rated power at six equally spaced positions of a 1.2:1 mismatch. Figure 2 plots the output power, body power, and mod anode current as a function of mismatch position.

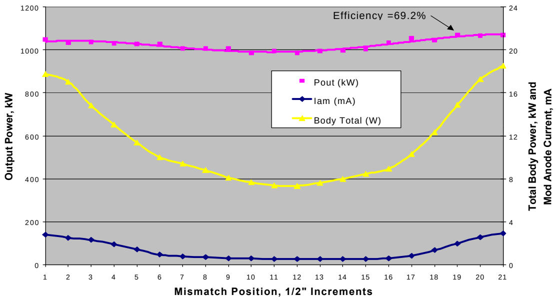

Figure 2: VKP-7952A Performance into 1.2:1 VSWR

3.2 500-MHz, 800 kW CW Klystrons

On the 500-MHz klystron for Cornell University (VKP-7957A), the gain was characterized at various beam operation. At a constant beam voltage of 76 kV, the beam current was adjusted by varying the mod anode voltage. The gain decreased at the lower beam powers. However if the beam impedance is kept constant, the gain at saturation is fairly constant at all beam powers. Figure 3 shows the various transfer curves at constant beam impedance.

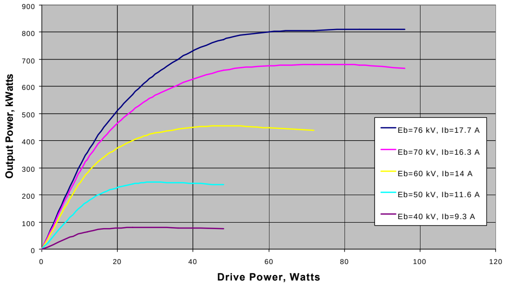

Figure 3: VKP-7957A Transfer Curves at Beam Impedance

Table 1 summarizes the key measured data on the 3 different super-power klystrons developed by CPI. The specification requirements were met in all three cases. Even at high efficiency, each tube performed without a hint of instability under various operating conditions.

	VKP-7952A	VKP-7957A		VKP-7958A	
Frequency, MHz	700	499.76		499.67	
Cathode Voltage, kV	92	76	63	74	62
Mod Anode Voltage, kV	75.5	54	52.7	56.5	56.3
Beam Current, Amps	16.8	17.7	17	18	17
Output Power, kW	1,020	822	608	826	611
Efficiency	66%	61%	57%	62%	58%
Drive Power, watts	51	70	36	18	8.2
Gain, dB	43	40.7	42.3	46.6	48.7

Table 1: Measured Data of Super Power Klystrons

4 100-KW KLYSTRON

4.1 Introduction

Although the 1497 MHz, 100-kW CW klystron does not push the energy levels of the super-power devices, the development still presented numerous challenges. The key customer desire was a robust, reliable klystron. The efficiency request was for a modest 50%, with a gain of 48 dB and a bandwidth of 5 MHz. Additionally, the tube had to tolerate a 1.35:1 mismatch at any phase. The gun was to be a diode type and the collector had to be capable of dissipating all of the beam power.

4.2 Electrical Design

The same codes and design processes used on the super power tubes were used for this klystron. The rf circuit consists of six cavities; no second harmonic cavity is incorporated. The first three cavities are staggered around the operating frequency to provide the bandwidth. Next are two inductively tuned cavities to optimize the electron bunching. The output cavity then extracts energy from the beam.

4.3 Mechanical Design

The frequency and relatively low output power led to a reasonable size device. The klystron will operate vertically with the gun down. It is shipped separate from the electromagnet and the two are integrated at the customer facility, see Figure 4.

Figure 4: VKL-7966A Klystron (Photo courtesy of TJNAF)

The entire rf circuit is made from copper with rectangular cavities. All cavities have a diaphragm tuner mechanism to optimize the cavity settings at test. The output window is a pillbox design with an alumina ceramic.

Unlike the super-power klystrons, the collector on the VKS-7966A is isolated from the body to allow the monitoring of body current. It is made with thick-walled OFE copper with drilled-holes for the coolant to pass.

4.4 Test Results

All three klystrons met the specification requirements and have been delivered to TJNAF. Even with the high gain of over 55 dB, the klystrons showed no hint of instability. Typical measured data at saturated rf output power is presented in Table 2.

A key concern was the Incremental Gain of the klystron when operating at 80 and 40 kW of output power at reduced drive power because the RF phase and gradient in the FEL cryogenic cavities must be regulated to a very high degree of accuracy. A broadband, very high gain feedback system is employed in the accelerator system to control the RF drive level of the klystron.

When the klystron is operating at either the 80kW or 40kW output power level and the RF drive is changed by 1 dB, there must be a corresponding output power change of 0.5 dB or greater. See Figure 5.

Parameter	JLab Specification	Measured
Beam Voltage, kV		33.5
Beam Current, Amps		6.5
Frequency, GHz	1.497	1.497
Output Power, kW	100	110
-1 dB Bandpass, MHz	5	14
Efficiency	> 50%	51%
Gain	48 dB	55.5 dB
RF Drive Power, Watts	1.6 max	0.31
Incremental Gain, dB/dB	> 0.5	0.53
Body Current, mA		13
DC Body Current, mA		3
Magnet Current, Amps		22
Magnet Voltage, Volts		86

Table 2: Typical VKL-7966A Operating Data

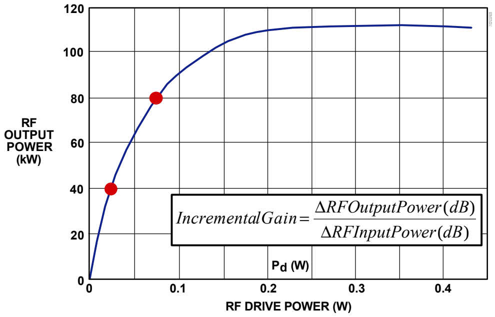

Figure 5: VKL-7966A Transfer Curve

5 CONCLUSION

CPI has reinvented its methodology for the electrical and mechanical design of high-power and super-power klystrons for scientific applications. The measured results, especially the high degree of stability under various operating and mismatch conditions, instill high confidence in our computer simulations. A mode of producing the large klystrons is in place.

6 ACKNOWLEDGEMENTS

The authors would like to thank their co-workers at CPI for their contributions throughout the development of these products and the CPI management team for their support and patience. Finally, many thanks go to the technical leaders and their colleagues at the sponsoring laboratories, in particular: Dan Rees, Paul Tallerico–LANL, Michael Ebert–DESY, Roger Kaplan–Cornell University, Richard Walker–TJNAF

7 REFERENCES

[1] W. R. Fowkes, et al., “1.2 MW Klystron for the Asymmetric Storage Ring B Factory”, SLAC-PUB-6778