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# 50-MW X-band Klystron Sources for the Next Generation of Linear Colliders\*

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## Abstract

The first in a new series of high-power pulsed klystrons has been tested with the following results: Frequency = 11.4 GHz, beam voltage = 415 kV, power output = 51 MW, pulse length = 1.5  $\mu$ s, and efficiency = 37%. Several tubes of this type will be used in the Next Linear Collider Test Accelerator (NLCTA) at SLAC. The rf performance of the klystron, which employs a standing-wave extended-interaction output circuit, is closely approximated by simulations performed with the SLAC CONDOR code. The same code predicts considerably higher efficiency, using a traveling-wave output circuit. A klystron with such a circuit will be constructed in the future. Another klystron is also planned in which beam confinement is accomplished by a periodic permanent magnet (PPM) stack, for which simulations also predict good performance.

## 1. INTRODUCTION

The SLAC design for a 500 GeV  $e^+e^-$  "Next Linear Collider" (NLC) calls for an operating frequency in the main linacs of 11.4 GHz, with approximately 8000 1.8 m sections, each powered by 400 MW, 250 ns rf pulses. These pulses are formed by pulse compressors fed by 100 MW klystrons (or pairs of 50 MW klystrons) with a pulse length of 1.5  $\mu$ s. A 540 MeV test accelerator (NLCTA) will be built at SLAC to validate the NLC design and will use four 50 MW, 1.5  $\mu$ s klystrons. This paper deals with the design of these klystrons.

## 2. BACKGROUND

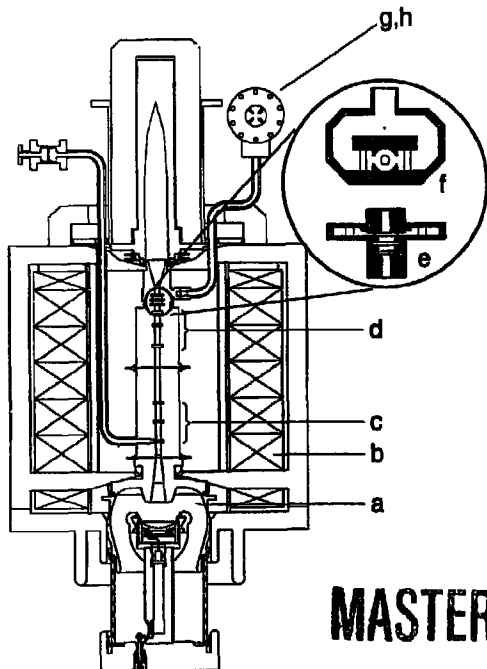
Klystron tubes have been the preferred microwave sources for scientific accelerators, and have established an excellent reliability record at SLAC, CERN, DESY, and elsewhere. The Stanford Linear Collider (SLC) employs the largest complement of high-power pulsed klystrons, with 245 65 MW, 3.5  $\mu$ s tubes, capable of operating at a PRF of 180 Hz. The SLAC klystrons, developed a decade ago, represent the current state-of-the-art for such devices. After an initial spate of failures during the first year of operation in the SLC, these tubes (SLAC 5045s) have performed with a mean time between failures of 45,000 hours.

The NLC specifications require the development of a microwave tube with at least an order of magnitude higher power density in the electron beam than in a 5045 klystron. This makes precision in electron optics and beam confinement critical, because the least amount of beam interception in a drift tube or a cavity will vaporize copper and potentially result in tube failure. Furthermore, with 2000 or more

klystrons operating in the NLC, the use of ordinary electromagnets for beam confinement (each consuming about 20 kw) is out of the question, and alternatives must be found in either superconducting solenoids or permanent magnets. The 500 GeV NLC is only the first step toward a 1.5 TeV goal for this future collider. With the number of klystrons increasing by as much as a factor of 9 from the initial machine, there is clearly a need for either a much higher power microwave source (of which fewer would be bought) or for klystron designs that are amenable to mass production, at costs that are a fraction of the current costs of the SLAC 5045 klystrons. The latter is one of the objectives of the SLAC development program. Research toward higher power is being carried out at several other institutions, with both conventional and fast wave interaction devices under study.

## 3. XL-1 KLYSTRON DESIGN AND PERFORMANCE

Figure 1 is a drawing of the XL-1 klystron tube. The klystron elements are: an electron gun (a) with an electrostatic



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Figure 1. The XL-1 klystron.

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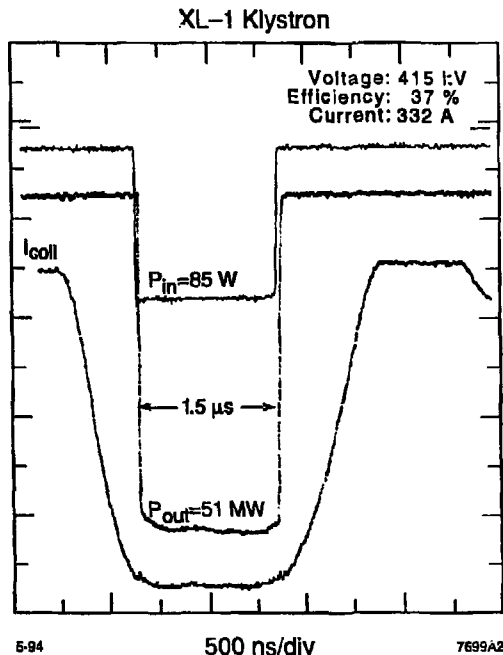


Figure 2. XL-1 test.

convergence of 120:1, matched to the fringing magnetic field of the electromagnet (b). Three gain cavities (c) of conventional, reentrant design, tuned at or near the operating frequency. Three pill box bunching cavities (d) tuned at higher frequencies. A 3-cell, disc-loaded waveguide cavity (e), operating in the  $\pi$ -mode. The last cell in the output cavity is coupled through balanced irises to two waveguides, which are combined again to form a single output in the  $TE_{10}$  waveguide (f). There is, finally, a transition (g) from the rectangular guide to a 2 1/2-inch circular  $TE_{01}$  waveguide, which leads to an output window (h) operating in the same mode.

The XL-1 klystron was designed for operation under the following specifications:

Frequency	11.42 GHz	Gain	50 db
Voltage	440 kV	Pulse width	1.5 $\mu$ s
Current	350 A	PRF	180 pps
Peak power	50 MW		

A klystron at this power and frequency must be designed to withstand high-voltage gradients at the gun and rf gradients at the output cavity and window, which can lead to destructive discharges unless carefully controlled. In the XL-1, the highest gradient in the electron gun is 250 kV/cm, which appears to be safe for a well-processed tube. The rf gradient in the output cavity is calculated to be approximately 500 kV/cm. This is about a factor of 2 less than the gradient in a single-gap reentrant cavity, which is the reason for the extended-interaction design. Although much higher rf gradients can be

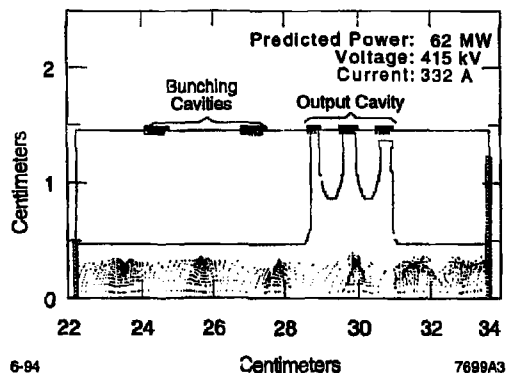


Figure 3. CONDOR simulation for the XL-1 klystron.

tolerated in accelerator structures, the presence of a high-current electron beam traversing the cavity drastically lowers the level at which an rf discharge can take place. In the case of the output window, it is important to keep rf gradients low at the surface of the ceramic by choosing a sufficiently large diameter, but it is even more important to minimize the gradient between the ceramic window and its copper sleeve. Hence, the output window is designed to operate in the  $TE_{01}$  mode, in which no current crosses the metallized and brazed metal-ceramic joint. Thus, the klystron output is conveniently in the  $TE_{01}$  mode, which is also used to transport power to the pulse compressor, operating in the same mode to minimize losses.

In initial tests of the XL-1 klystron at a pulse width of 250 ns, a power of 58 MW was measured using calibrated crystals, since the average power was too low for reliable calorimetry. When a wider pulse was used to drive the tube, an oscillation was observed. Its frequency was 17 GHz, and it was subsequently determined to be related to the three pill box buncher cavities, which, although of different diameters for different frequencies in their fundamental  $TM_{01}$  mode, all resonated at 17 GHz in the  $TE_{11}$  mode because of identical gap lengths. The oscillation was easily suppressed by an increase in the confining magnetic field (shrinking the beam diameter), but this also resulted in reduced output power. The klystron was eventually processed to the full 1.5  $\mu$ s pulse length, and operated there for many hours. The target of 50 MW output power was reached at approximately 415 kV (Figure 2). A simulation using CONDOR, a "2 1/2 D" particle-in-cell code, produced the picture in Figure 3, and a power-output prediction of 62.5 MW (to be compared with the 58 MW measurement, with no beam compression).

#### 4. PLANS FOR FUTURE WORK

A total of seven klystrons are planned for the XL phase of NLC source development. The XL-2 will have an output circuit identical to XL-1, but with modified buncher cavities to avoid oscillation, and a modified  $TE_{01}$  window, with considerably reduced rf gradients. Because of this improvement, it is expected that this tube will be operated to the full

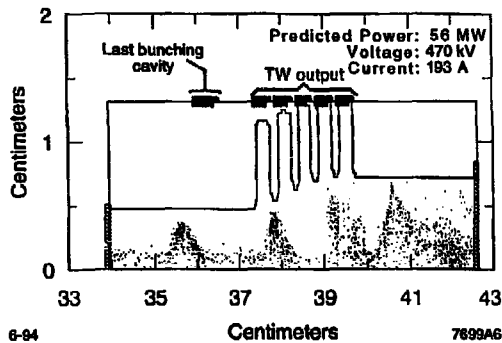


Figure 4. CONDOR simulation for a PPM TW-output klystron.

available voltage of 440 kV, where a power output of about 65 MW is predicted. The XL-3 will have a traveling-wave output circuit, for which the CONDOR power output prediction is 85 MW. Although there is demonstrated success in these simulations, there is a question of higher rf gradients in the travelling-wave circuit that can only be resolved by experiment. The remaining four klystrons, built for the NLCTA, will use either one of the two output circuits, depending on the XL-3 results.

In addition to these electromagnet-focused klystrons, a 50 MW tube is being designed, where beam confinement is accomplished with an alternating axial magnetic field (Periodic Permanent Magnet focusing, or PPM), a method commonly employed in traveling-wave tubes, but at much lower power levels. CONDOR simulations, taking into account both the periodic magnetic fields and the rf fields, show both good beam confinement and high efficiency. The CONDOR predictions are shown in Figure 4 for the case of a traveling-wave output and reduced beam perveance. A sketch of a 50 MW PPM klystron is shown in Figure 5, drawn approximately to the same scale as the XL-1 klystron shown in Figure 1.

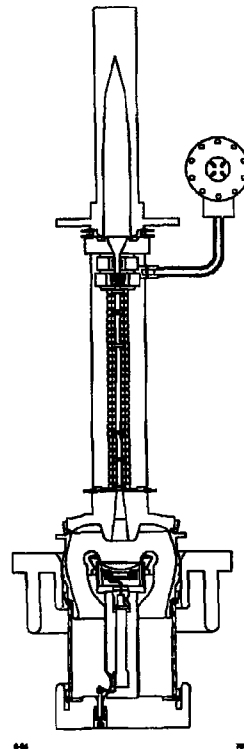


Figure 5. A 50 MW PPM klystron

This would be a considerably simpler device, and much of the manufacturing techniques used in industrial TWTs could be applied to reduce production costs. It is expected that a prototype will be tested next year.