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Design of a 50 MW Klystron at X-Band*

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ABSTRACT

This paper describes the design and performance of the XL-1 klystron; a 50 MW klystron operating at a frequency of 11.424 GHz for use on the SLAC Next Linear Collider Test Accelerator (NLCTA). Problems associated with the development of high-power rf sources for NLC, and the solutions implemented on XL-1 are discussed.

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Background

Eight Next Linear Collider (NLC) prototype klystrons, known as the XC-series klystrons, have been evaluated at SLAC with a goal of 100-MW rf output power at X-band. It was found during the development of the 100 MW tubes that conventional single-gap output circuits and pillbox rf windows could not operate at the required power levels. A number of extended interaction output circuits of different varieties, and TE_{11} pillbox rf windows, were evaluated to determine their energy handling capabilities [1]. The best performance results were 87 MW at 300 ns rf pulse width for the XC-6 klystron [2] and 50 MW at 1.0 μs rf pulse width for the XC-5 klystron, both limited by klystron saturation. The highest power transmitted through TE_{11} pillbox windows was 25 MW, at 1 μs rf pulse width through the two windows of the XC-5 klystron. Higher levels were obtained with windows tested in our X-band Traveling-Wave Resonator (TWR) [8].

About half way through the project, the confined-flow focusing system was changed. Klystrons XC-1 through 3 had an electron gun with an electrostatic Beam Area Compression (BAC) of 36:1, and subsequent adiabatic compression to a final BAC of 200:1. Klystrons XC-4 through 8 had a fully electrostatic electron gun [3] with a BAC of 110:1. Several of these later tubes experienced gun arcs in areas of high electrode gradients, causing irrecoverable damage to the electrodes.

The rf power requirement for the NLCTA klystron is initially 50 MW, with an eventual upgrade to 100-MW tubes. Because of this, effort has shifted to the development of a reliable 50 MW klystron for the NLCTA. This paper describes the successful test of the first tube in this series, the XL-1 klystron.

TABLE 1. XL-1 klystron specification

Beam voltage	440 kV
Beam current	350 A
Microperveance	1.2 $A/V^{3/2}$
Frequency	11.424 GHz
Peak output power	50 MW
Average power	13.5 kW
Gain	>50 dB
rf pulse width	1.5 μs
PRF	180 pps
Tunnel diameter	9.525 mm
Beam diameter	6.35 mm
Cathode diameter	71.4 mm
Beam area compression	125:1
Cathode loading (max)	12.8 A/cm^2
Magnetic field	0.47 T

The XL-Series Klystron

Design parameters for the XL-series klystron can be seen in Table 1. The beam voltage of 440 kV is unchanged from its XC-series predecessor, while the beam current has been reduced to 350 A. These parameters require a minimum rf efficiency of 32.5% to meet the 50 MW goal, a value thought readily achievable based on past experience. The reduced microperveance of the gun allows lower surface gradients on the gun electrodes, diminishing the likelihood of fatally damaging arcs.

The first klystron of this series, XL-1, can be seen in Figure 1. This klystron is confined-flow focused with a magnetic field of 0.47 T. The XL-1 is a seven-cavity klystron, with a waveguide-coupled input cavity, two gain cavities, three inductively tuned nose-cone removed pillbox cavities [5], and a three-cell standing-wave disk-loaded output circuit. The output power is symmetrically extracted from the third cell of the output curcuit, and combined in the vacuum envelope using a tee, with a single waveguide exiting the magnet. An ultra-compact TE_{10}-to-TE_{01} mode transducer [6,7] is used to convert the output to circular waveguide. The ceramic rf window is a half-wave disk of 99.5% purity alumina.

Three design improvements are responsible for the successful operation of the XL-1 klystron. These improvements were to the electron gun, the klystron buncher and output circuit, and the TE_{10}-to-TE_{01} mode transducer and window assembly.

FIGURE 1. XL-1 Klystron after bake.

TABLE 2. X-band klystron gun electrode gradients.

Klystron	Anode gradient (kV/cm)	Focus gradient (kV/cm)
XC-1 through 3	255	308
XC-4 through 8	420	300
XL-series	250	230

The Electron Gun

The electron gun optics were designed using EGUN [4]. The gun has an electro-static BAC of 125:1. A magnetic field was designed with the aid of POISSON [9] to match the electron trajectories in the gun region. The lower microperveance of the XL-series klystrons allowed for greater electrode spacing and hence lower surface fields on the electrodes. The electrode gradients of the X-band tubes built to date are compared in Table 2. The electrode gradients for the XL-series klystron are the lowest for X-band development tubes, with a substantial reduction in the focus electrode gradient.

During the development of the XC-series of klystrons, none of the first three klystrons were returned to the tube shop for repair because of gun voltage breakdown damage. However, two of the subsequent five klystrons with fully electrostatic electron guns were damaged. This damage was due to the high anode gradient.

Klystron Buncher and Output Circuit

The first three cavities are of the standard re-entrant pillbox variety, which provide the bulk of the klystron gain. Unlike the 5045 and other S-band klystrons that have a single inductively tuned penultimate cavity, the XL-series uses three such cavities. On some of the previous XC-series klystrons, erosion of the penultimate cavity due to rf breakdown was observed. Using three cavities allows equal distribution of the gradient, while maintaining a high rf current. All six of these cavities are one-time tunable.

The output circuit is a three-cell, standing-wave, disk-loaded waveguide. The third cell in the output circuit is symmetrically coupled to two reduced-height waveguides. A quarter-wave step transformer is used to match the two reduced-height waveguide outputs to a full height WR90 waveguide. Two mitered bends per output are used in conjunction with a waveguide tee to combine the power in the vacuum envelope. This allows a single waveguide to exit the magnet. Circuits tested in the XC-series klystrons that were asymmetrically coupled showed signs of asymmetric beam erosion in the drift tunnel downstream of the cavity. This phenomenon has not been observed in tubes with symmetric coupling.

TABLE 3. Best simulation results for XL-1.

Beam voltage (kV)	Beam current (A)	Saturated output power (MW)
440	350	70
415	332	62.5

The number of resonant modes in any given passband is equal to the number of cavities in the structure in disk-loaded output circuits. The likelihood increases of monotron oscillation caused by negative beam loading in one or more of the unwanted modes as these circuits become longer. The XL-1 klystron has negative beam loading in both the 0 and $\pi/2$ mode. Minimum beam-loaded Q's (Qb) are –1500 at approximately 80 kV and –850 at approximately 170 kV. Either of these modes can oscillate if the external Q (Qe) for that particular mode is larger than the minimum Qb. The XC-8 klystron (which had a four-cell, standing-wave, disk-loaded waveguide) oscillated in the 0 mode because the Qe for that mode was larger than Qb [1]. The XL-1 klystron has Qe's sufficiently low in both modes to prevent oscillation.

Klystron interaction was simulated and optimized using the 2.5 D particle-in-cell code CONDOR [10]. Results of the simulation can be seen in Table 3. The saturated gain for both of these cases is approximately 61 dB. Figures 2 and 3 show the klystron output power and cavity surface field gradients, respectively, as a function of drive power.

TE10 to TE01 Mode Transducer and Window Assembly

The use of the compact-mode transducer serves two purposes. First, it allows us to use a TE_{01} window, to be described in a paper not yet published. The NLCTA will use an over-moded TE_{01} circular waveguide for transport of rf to the accelerator. The use of the compact-mode transducer on the klystron transforms the rf power into this mode as soon as possible, minimizing wall losses.

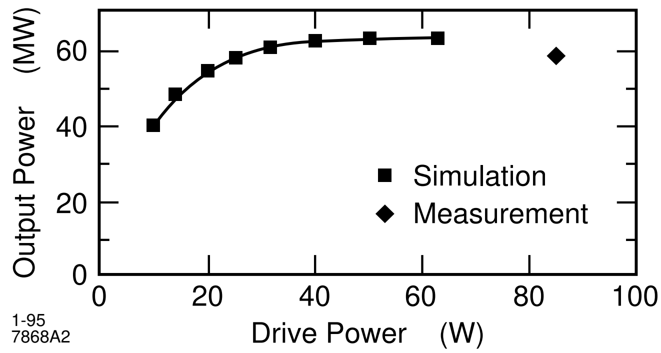

FIGURE 2. XL-1 CONDOR simulation at cathode voltage 415 kV, cathode current 332 A.

Second, it is desirable to have the rf window oriented vertically, which offers some protection against foreign matter accumulating on window surfaces and contributing to breakdown. The mode transducer and window assembly accomplishes this.

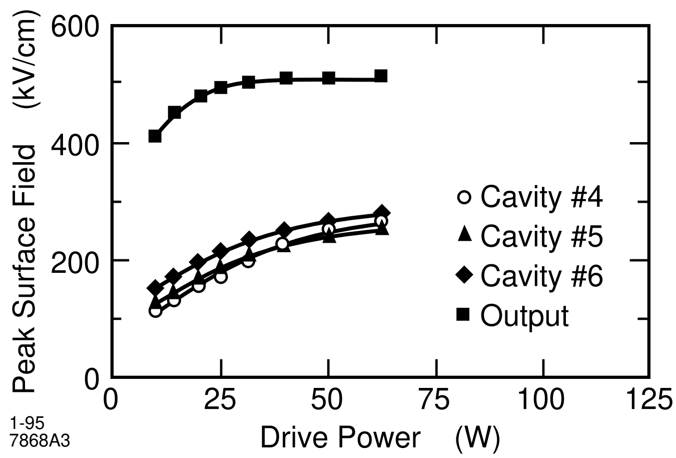

FIGURE 3. XL-1 Cavity field gradients as a function of drive for cathode voltage 415 kV, cathode current 332 A.

Because of the unreliability of conventional TE_{11} circular pillbox windows for this application, a different approach was necessary. The primary factor limiting the power-handling capability of this window is that, for the TE_{11} circular mode, the electric field lines terminate at the window braze joint. Most of the activity associated with window breakdown originates at the location along the metalization where the electric field is maximum. This problem can be overcome by the use of circular modes with no normal component of electric field at the conductor, and hence the use of the TE_{01} mode.

Test Results

The XL-1 was initially tested in October 1993. The klystron was processed to a cathode voltage of 415 kV with a narrow cathode pulse and a beam current of 332 A. It produced 58 MW at 250 ns rf pulse width, at frequency 11.455 GHz, with the nominal beam diameter. The modulator was then tuned for wide cathode pulse operation, and the klystron was reprocessed to a cathode voltage of 415 kV. At the longer cathode pulse width, an monotron oscillation at a frequency of 17.3 GHz was observed. It was later determined that this oscillation was caused by a synchronously-tuned TE_{11} mode trapped in the inductively-tuned cavities. The XL-2 klystron has been modified to stagger-tune this mode and remove the oscillation. This oscillation is sensitive to beam diameter. Reducing the beam diameter suppressed the intensity of the oscillation to manageable levels. However, the smaller beam diameter did lower the efficiency; the maximum output power was measured at 51 MW for a 1.5 μs rf pulse width, at frequency 11.455 GHz.

The single TE_{01} circular half-wave window handled this power level at 60 pulse-per-second duty without incident. The window temperature was 50°C, which was the maximum temperature measured during tests in the TWR. We decided not to run the tube at higher pulse rates for fear of breaking the window at elevated temperatures.

The klystron was moved to a different test stand for use as an rf source for the accelerator structure test area (ASTA), where it suffered an unrecoverable gun arc. The klystron was returned to the tube shop for autopsy and rebuild. Autopsy revealed severe arcing between the anode corona shield and the high-voltage ceramic, which punctured the ceramic. The arcing was localized in four places spaced 90 degrees apart. There was also noticeable surface discoloration of these areas. These four locations correspond to access holes in the base of the cathode. It appears that cathode exhaust gas coated the ceramic, which lowered the ceramic voltage hold-off capability in those four regions. Both the focus electrode and anode showed no signs of severe arcing.

The XL-1 has been rebuilt, and is presently in the ASTA test stand. Modifications were made to the gun, eliminating the access holes, and a corona shield was added to the cathode baseplate, along with a vacion pump. A TE_{01} traveling-wave window, operating with reduced electric field, was installed on the klystron. The field reduction and pure traveling wave within the dielectric are both accomplished using a pair of symmetrically located irises. The klystron has been tested to a beam voltage of 435 kV and a beam current of 345 A, and has produced 52 MW at a frequency of 11.424 GHz with a 1.05 μs rf pulse width, and 60 MW at a frequency of 11.444 GHz with a 250 ns rf pulse width. A summary of these results can be seen in Table 4, and a plot of the oscilloscope waveforms in Figure 4.

TABLE 4. XL-1 and XL-1B rebuild maximum saturated output power.				
Klystron	rf pulse width (ns)	Voltage (kV)	Output power (MW)	Frequency (GHz)
XL-1	250	415	58	11.455
XL-1	1500	415	51	11.455
XL-1B	250	435	60	11.444
XL-1B	1050	435	52	11.424

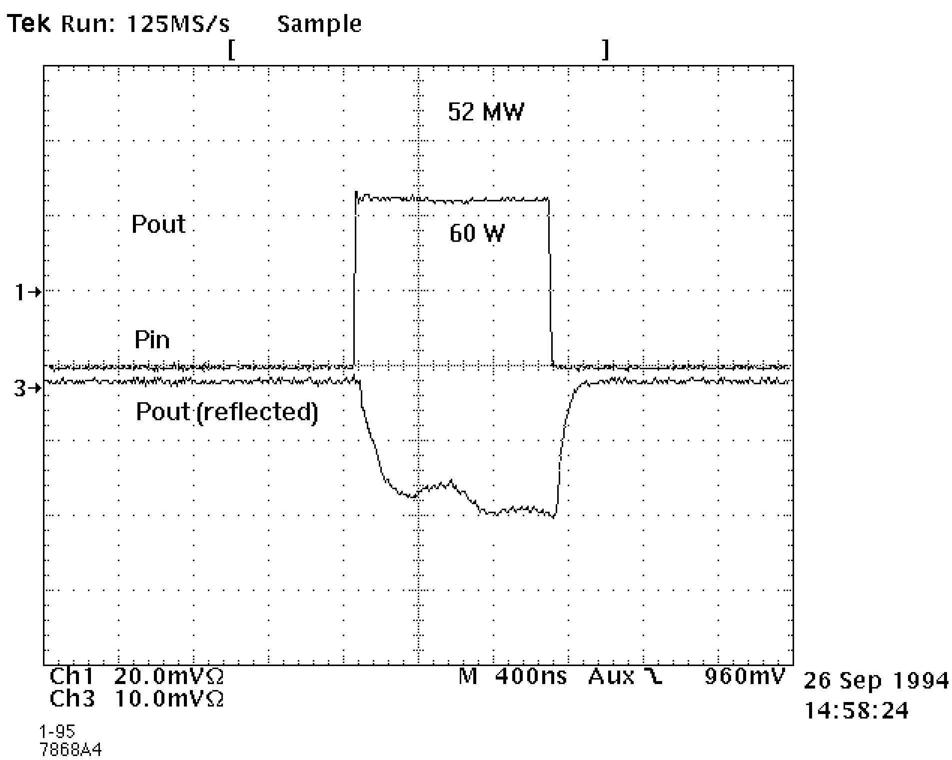

FIGURE 4. The XL-1 rebuild, tested at beam voltage 435 kV, beam current 345 A, and frequency 11.424 Ghz.

Future Next Linear Collider Test Accelerator Klystrons

Three more confined-flow focused klystrons are planned for use on the NLCTA. The XL-2 klystron will be identical to the XL-1, except for several minor modifications. Cavities four, five, six, and the output circuit have been diamond machined at KEK. Also, the transit angles of cavities four, five, and six have been staggered in order to tune the previously mentioned TE_{11} mode. The XL-2 is presently on bake, and will be tested in late October of this year.

The XL-3 klystron is the same as the XL-2 klystron, except that it has a different output circuit. The circuit is a four-cell, traveling-wave output operating in the $\pi/2$ mode. The CONDOR simulation of the XL-3 klystron predicts output power at saturation greater that 80 MW. This klystron will be tested in early 1995. A periodic permanent magnet (PPM) focused beam diode is being designed, and will be tested sometime in the middle of 1995. A PPM focused klystron will be tested shortly thereafter.

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