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THE X-BAND KLYSTRON PROGRAM AT SLAC*

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The X-band rf source development at SLAC can be considered a qualified success. A total of twelve klystrons were built. Six of them are still in use. The latest tube, XL4, produced 75 MW at an efficiency of 47.5 percent.

However, victory cannot be declared as yet, since an NLC prototype has not been fully designed and the decision between permanent magnet focusing and a super-conducting solenoid has not been formally made. Daryl Sprehn's paper will present the status of the PPM klystron development. We believe that a PPM X-band source will work, at 50 as well as at 75 megawatts. But we are prepared to adapt the XL4 design to a super-conducting solenoid, should the PPM klystron develop unexpected problems.

The SLAC program is now in its seventh year. It may well be the longest and most expensive microwave tube development on record, in a government laboratory or in industry. Direct and related costs for the total effort are probably of the order of \$10 million. In these circumstances it is perhaps not surprising that it has been possible to produce a klystron with the performance of XL4. At the same time, it must be said that the necessary leap in technology from the SLAC 60-megawatt S-band production klystrons to a klystron of comparable performance at four times the frequency could not be realized without some very careful experimentation and, most importantly, without the infrastructure for tube fabrication and testing available at SLAC.

The design of an 11.4 GHz 50-100 MW klystron, with microsecond pulses and a pulse repetition frequency of 180 Hz presents a number of technical challenges which will be listed below, not necessarily in order of importance, since each one is a potential show-stopper.

- **Beam optics:** The energy density in the klystron beam is of the order of 200 joules per cm². Any measurable beam interception in a drift tube is likely to result in intra-pulse melting of the drift tube wall. Near-perfect electron gun optics are necessary. This is particularly difficult because of the high beam convergence made necessary by cathode emission limitations.
- **Output windows:** The rf power density at 11.4 GHz results in serious stresses at the surface of the window ceramic. All windows must be coated to guard against multipactor, as well as surface charge accumulation. The ceramic-to-metal seal at the window periphery is

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- **Output circuit design:** The output circuit rf gradient is the ultimate and most serious limitation to the power capability of the klystron. The voltage developed at the output circuit slows down the beam and extracts energy from it. To avoid a high gradient that voltage must be distributed over a long gap, longer than is possible with a single cavity, without producing negative beam loading and hence regeneration. Special, extended interaction circuits must be developed.
- **Vacuum:** A very hard vacuum is an absolute must. A poor vacuum can affect cathode activity and electron optics. It will also trigger breakdown at the gun, the window and the output circuit. Furthermore the tube must not only be properly baked and pumped before pinch-off; it must also incorporate adequate electronic pumping with good conductance paths to protect against potential sources of gas as a result of operation, particularly at the gun.

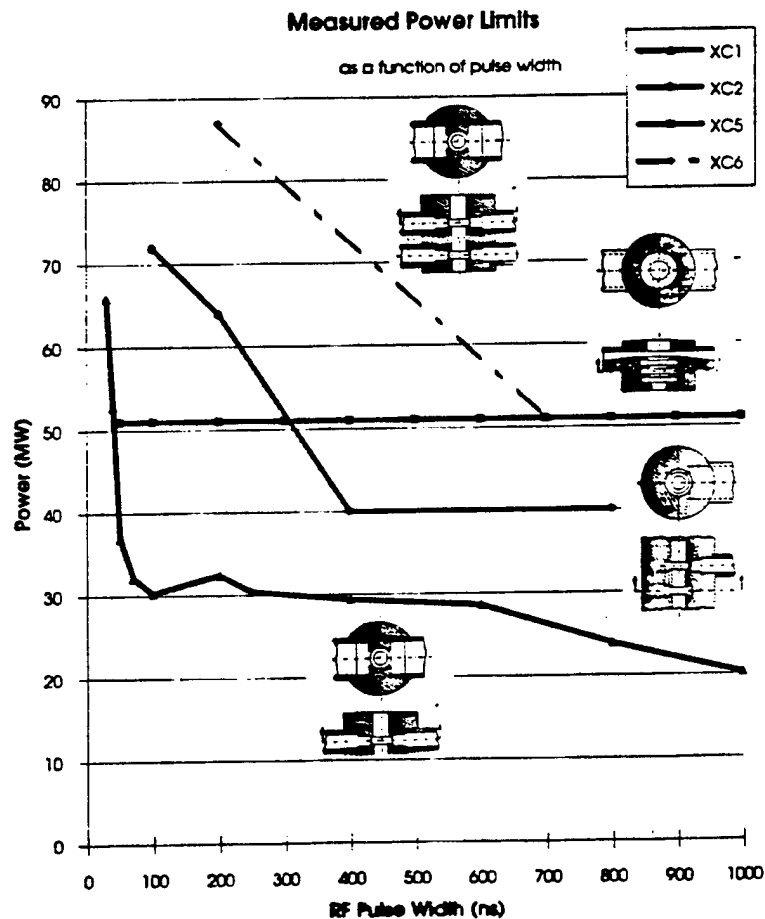


Figure 1

The 11.4 GHz program at SLAC began with the XC family of klystrons, which were designed for 100 megawatts. They were intended to be powered by the modulators used in S-band (5045) klystron production. The X-band klystron perveance was selected to be the same as

that of the 5045 (1.8×10^{-6}) in order to reach the desired power within the 440 kV rating of the modulator.

The very first tube in this series, XC1, produced 65 MW, 6 years before XL4. Unfortunately, it did so only as long as the pulse length was below 50 ns. At 200 ns, only 30 MW could be sustained without the single-gap output cavity breaking down. At 1 μ s, only 20 MW could be extracted. This can be seen in Fig. 1 where the performance of four of the eight XC klystrons is shown, in terms of the power attained at different pulsewidths. XC2 and XC3 employed coupled cavity output circuits, operating in the 2π -mode. Both have survived, after numerous rebuilds, to repair window failures. XC2 now provides power for the SLAC resonant ring and is operated below 30 MW. It can be run as high as 70 MW for short pulses.

Because of the lack of circular symmetry in their output circuits, the XC2 and XC3 klystrons could not be simulated by the CONDOR 2 1/2 D program. Design was largely empirical. These tubes would fail in test with broken windows, partly because of the poor vacuum resulting from breakdown in the output circuit and because of the inherent weaknesses in the early TE_{11} windows. To test the capability of the output circuit itself, and to detect the source of rf breakdown, the XC4 klystron was built without windows, but with a built-in waterload instead. This klystron was pushed to about 60 MW and failed because the output circuit destroyed itself. The gradient in the coupling iris was obviously excessive, but this was not known in detail from simulation.

At this point, during 1992, several lessons had been learned about the design of multi-megawatt klystrons at X-band. First, a window solution was needed. It was clear that even multiple windows with thin alumina disks were not practical. Secondly, beam optics were not satisfactory and were suspected of contributing to gassing problems at the output. The electron beam used in the early XC klystrons employed a combination of electrostatic followed by magnetic compression in order to achieve the convergence necessary. A new gun with a higher electrostatic convergence was needed, although the cathode current density would remain relatively high. Third, the XC2-XC4 output circuits were not symmetrical and, in addition to the simulation difficulty, there were concerns that dipole modes in the output cavities might be steering the beam. Reentrant cavities were not attractive, although one more klystron, XC6 was constructed with two, uncoupled, reentrant cavities in tandem, each with two output waveguides and windows. XC6 produced almost 90 MW at 200 ns, but developed gun arcing problems at longer pulses and was set aside. Gun arcing was the fourth concern. Entirely too much time was necessary to age the guns of these tubes. If that process was rushed, irretrievable damage occurred.

CONDOR predictions and the actual experiments suggested that efficiency for the XC series of klystrons, at their perveance of 1.8×10^{-6} , was going to fall well short of the NLC requirements. Furthermore, the cathode loading of these tubes (over 20 A/cm² at the cathode edge) raised questions about tube life in service. It was decided to lower the perveance to 1.2×10^{-6} and to initially design for a 50-MW output at 440 kV. A 600 kV modulator would be constructed for second-generation 100-MW klystrons. It was also decided to use disc-loaded structures as output circuits, in either a standing-wave or a traveling-wave mode. While a new lower perveance gun was being designed and fabricated, three more XC klystrons would be built with traveling and standing-wave output circuits.

The standing-wave, "extended-interaction", output circuit had been extensively studied in industry for klystron applications requiring either very high output circuit efficiency (very high CW power), or a wide bandwidth. In this case neither requirement is present. The principal objective is to gradually slow down the klystron beam, while keeping rf gradients to a minimum. It was decided to operate in the π mode. The design method is to construct a cavity consisting of two or more sections and resonating at 11.4 GHz at its π -mode. The R/Q is measured and an appropriate Q_{ex} is selected by requiring the product to approximately equal the beam impedance. Simulation through CONDOR is made possible by approximating waveguide coupling by a radial transmission line.

In the case of the traveling wave output circuit, the design method devised is more complex, requiring a tapering of the structure in both phase velocity and impedance and a final match to the waveguide output involving interactive simulation and cold test. The traveling-wave circuits require more sections and employ thinner irises than the standing-wave types. Unlike coupled-cavity circuits, they are too short to have significant gain and do not require loss, or a reverse termination, for stability. In some respects they are designed as more heavily loaded standing-wave circuits, but are better matched to the beam velocity and current. They operate in the $\pi/2$ -mode.

The two traveling-wave klystrons, XC5 and XC7, were the first tubes to produce 50 MW at a full microsecond. Their efficiency, however, was only of the order of 30%. Both tubes were lost with broken windows and both also suffered from gun arcs. The klystron with the standing-wave output circuit, XC8, was unstable. Its output circuit was a four-cell, π -mode structure which, in its 0-mode had a negative beam loading impedance. This fact was ascertained at test and through subsequent calculations. Subsequent standing-wave output circuit klystrons, (as well as XL4) incorporated a stainless steel resonant cavity in series with the output waveguide, located in such a way as to load the 0-mode at the output circuit.

The XC series was terminated with XC8, but the lessons learned and much of the disloaded waveguide output circuit designs were directly applicable to the XL klystrons, which operate at the same voltage (440 kV) and employ the same size drift tube (approximately 1 cm).

The XL series consists of four klystrons, the first two with 3-section standing-wave outputs and the rest with four-section traveling-wave circuits. We lost almost all of the XC klystrons, at least once, because of broken windows, and there was an urgent need for a new approach. In the NLC, TE_{01} circular waveguides are necessary for both power transmission and pulse compression, and a compact (flower-petal) transition was developed for use between the circular and rectangular waveguides. It was decided to use that transition as part of the klystron vacuum envelope and provide the tube with a circular waveguide output, with a circular TE_{01} window built into it, in a "pillbox" configuration. All XL klystrons were equipped with windows of this type. There have been no window failures in klystrons since that change was made, even though a single window was used in all four tubes.

There was one gun ceramic failure in XL1. An autopsy of the tube showed that there had been a deposit on the ceramic of what appeared to be cathode or heater material. We concluded that, with the vacion pumps attached to the collector end of the tube, and relying on either the input waveguide or the drift tubes to access the window enclosure, there was not adequate pumping speed at the gun to clear gasses from the heater or from the minor discharges that are

part of gun processing. When XL1 was repaired, a vacuum pump was attached directly on the gun tubulation at the high voltage end of the gun ceramic. It requires a small floating supply, but this is a minor complication, considering that gun processing is speeded up considerably in this manner. All XL klystrons have this feature and there have been no more gun failures.

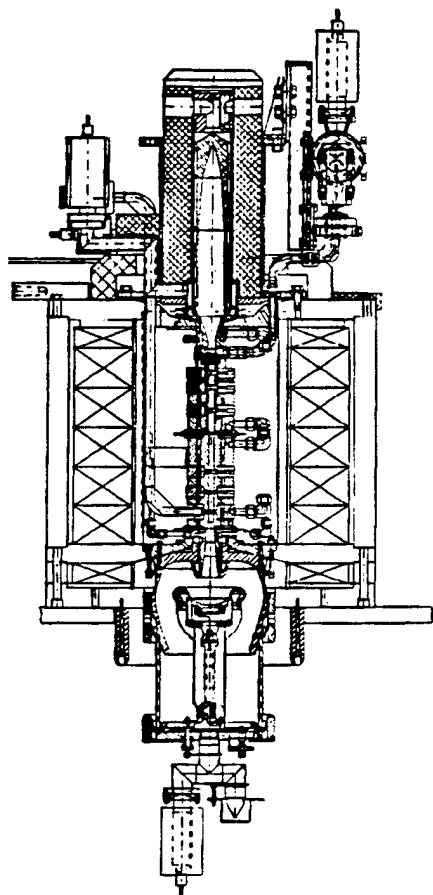


Figure 2

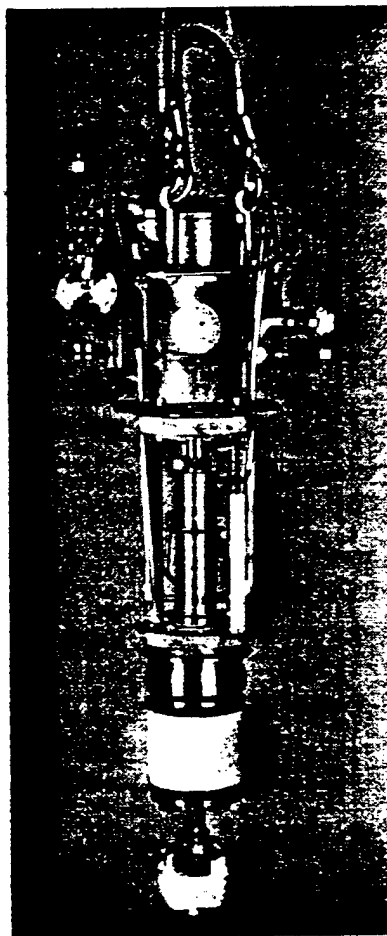


Figure 3

The new gun optics at a microperveance of 1.2 required a electrostatic beam area convergence of 125:1 for a current density at the edge of the cathode of 13 A/cm^2 . This is still high, but consistent with tube service of several thousand hours in a test accelerator. The magnetic field used is 4700 gauss, which requires 25 kW for the solenoid, a prohibitively high figure for the NLC. The beam optics have been extremely good, with no measurable interception on a dc basis and only a slight depression in the collector pulse at saturation in the case of some of the tubes. This indicated a body interception of the order of 1%.

A drawing of the klystron (XL4) is shown in Fig. 2. All XL tubes have three gain and three bunching cavities (in order to distribute the higher rf voltages necessary for optimum bunching). Fig. 3 is a photograph of the same klystron.

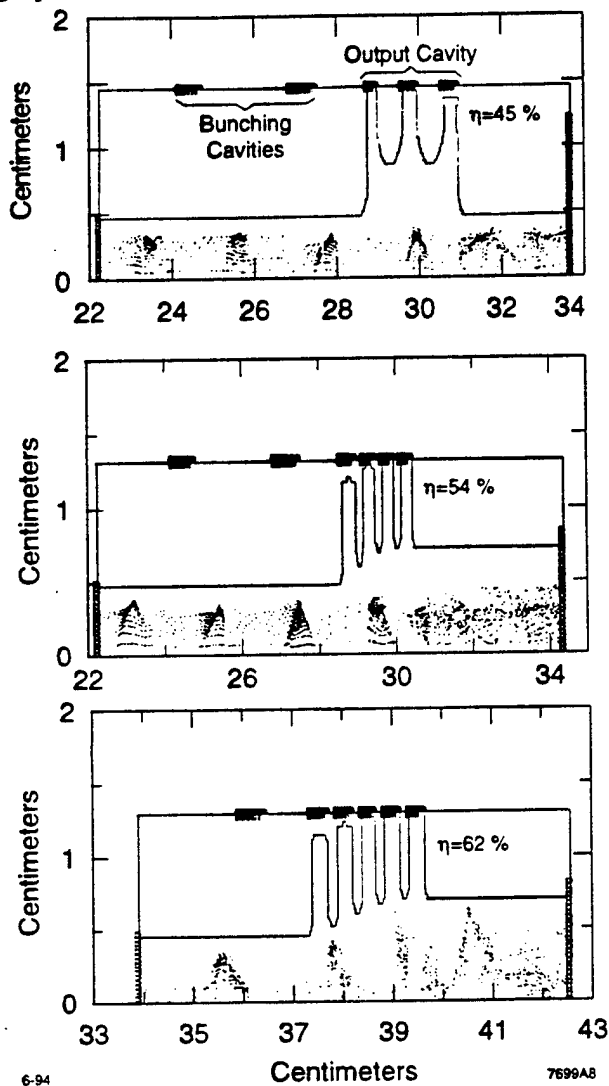


Figure 4
(Top to Bottom XL1, XL4 & X5011)

CONDOR simulations of XL1 and XL3 are shown in Fig. 4. The y-axis is exaggerated to provide more detail, but it is clear that the traveling-wave structure has thinner irises which taper into a larger entrance to the collector, a useful, if fortuitous feature, which allows more room for the beam to expand as it exits the interaction space. All XL klystrons, except XL4, suffered from instabilities at higher frequencies. These had several sources, but originated in the bunching cavity section of the tubes. To avoid them, the klystron beam had to be compressed, or the pulse width had to be narrowed, or the drive power had to be reduced. As a result, stable operation of the tube did not always coincide with the best efficiency. XL1, XL2 and XL3 all

produced the specified 50 MW at 1.5 μ s. XL1 attained a power of 58 MW, and XL3 67 MW, both for short pulses of the order of 200 ns. Fig. 4 also shows the simulation for the PPM klystron which will be tested at SLAC next month. There is a marked difference in the shape of the bunches which, in the case of the solenoid-focused tubes remain more or less the same in diameter. For the PPM case they expand and stay fairly close to the circuit. This may contribute to higher efficiency, but it may also lead to interception. Fortunately, the circuit expands also, as its impedance is tapered.

A number of design changes were introduced with the last of the XL klystrons:

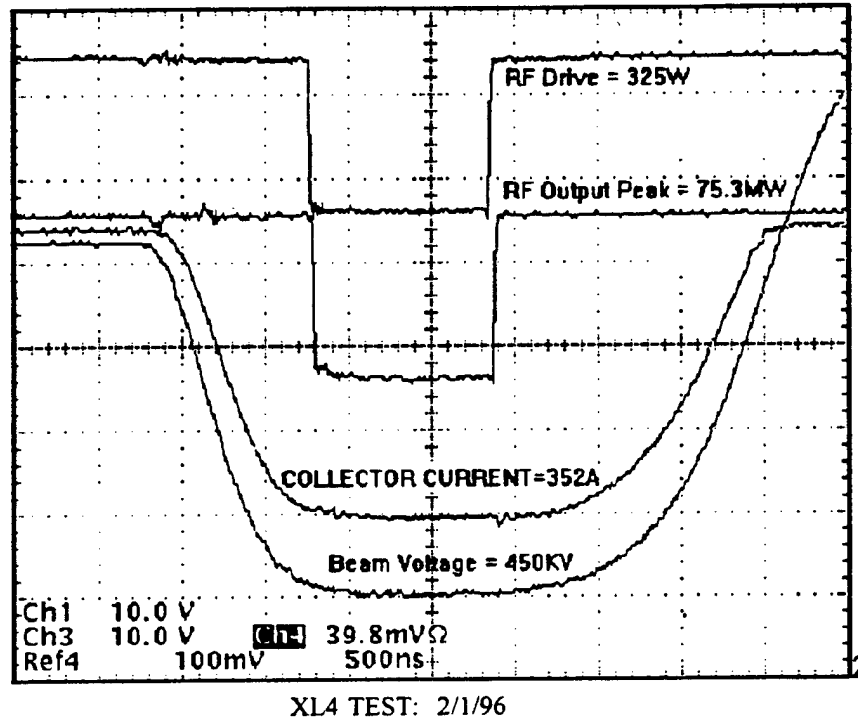
- The spacing and tuning of the bunching cavities was adjusted, by CONDOR simulation for increased rf current at the output.
- The output circuit was scaled to a slightly lower frequency. XL3 was not properly centered.
- The last three drift tubes, ahead of the output circuit, were fabricated from stainless steel to dampen oscillations which were determined to be located there.
- The output circuit was coated with the same titanium nitride compound used at SLAC to coat windows. The objective was to discourage rf breakdown. Pulse breakup was present in the first three XL klystrons. This required considerable processing time, before a tube could be operated at rated peak power and pulse length.

The results of these changes were impressive. The klystron produced with the specified 50 megawatts at only 400 kV, with 1.5 μ s pulses at 120 pps. It was then operated at 75 MW and 1.1 μ s, which is the current klystron specification for the 1 TeV NLC. This required 450 kV. Oscilloscope traces are shown in Fig. 5.

In addition to the improved efficiency and the absence of oscillations, XL4 is essentially free from the pulse-shortening or missing pulse phenomena in all previous XC and XL klystrons. The tube was not run beyond 450 kV partly because of modulator limitations, but principally because the waterloads employed were beginning to exhibit what appeared to be cavitation boiling behind the ceramic window. Other load arrangements involving a 3-db water-cooled attenuator produced gas at higher peak or average power. We cannot stress enough the need for an excellent vacuum at these pulse energy levels, both in the klystron as well as in the waveguides and transitions leading to the load. These klystrons are pinched-off the pumps in the 10^{-10} Torr scale. We try to operate them at the 10^{-8} scale or better while they are being processed, on both sides of the output window.

XL4 is the last experimental tube in the solenoid-focused XL series. We plan to produce five more identical klystrons for use in SLAC and KEK experiments. X5011 will be the PPM klystron described in the next talk. However, research at SLAC will continue on two important general topics.

The first topic is a better understanding of rf breakdown and a search for practical methods of suppressing it. This work has been in progress for a year or more and is a continuation of earlier work at SLAC by Wang and Loew¹.



Frequency: 11.424 GHz
 Cathode current: 354 A
 Repetition rate: 60 Hz
 Pulse width: 1.1 ms

Perveance: 1.17×10^{-6}
 Gain: 54 db
 Efficiency: 47.5% (CONDOR: 52.6%)
 Power measured calorimetrically
 Klystron at saturation

Figure 5

An X-band resonant ring is used, with a nested demountable reentrant cavity. Gradients in excess of 500 MV/m can be developed across a short gap and the surfaces involved can be treated in a variety of ways to study the effect on dark current. Rf breakdown is the ultimate limit to the power that can be produced by these X-band klystrons. Powers well in excess of 75 MW would be possible if means could be found to limit the dark currents produced at the output circuit, which ultimately lead to breakdown. It will be sponsored in part by the Air Force Office of Scientific Research.

Finally, as a part of a parallel effort to engineer the NLC klystron for quantity production, we plan to develop an alternative to the dispenser cathode, which is both very expensive and limited in current density. It is possible that new methods of producing and

¹ J. W. Wang and G. A. Loew, "Progress report on high gradient RF studies in copper accelerator structures," presented at the 14th International Symposium on Discharge and Electrical Insulation in Vacuum, Santa Fe, NM, September 16-20, 1990.

processing oxide cathodes will make possible several times the current densities currently available in electron guns, at much lower temperature and hence with good life and low cost.

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