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Development of X-Band Klystron Technology at SLAC*

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DEVELOPMENT OF X-BAND KLYSTRON TECHNOLOGY AT SLAC

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*Abstract**

The SLAC design for a 1-TeV collider (NLC) requires klystrons with a performance which is well beyond the state-of-the-art for microwave tubes in the United States or abroad.

The electrical specifications for the NLC klystrons are not fully established, but they are approximately as follows:

Frequency:	11.4 GHz
Peak Power:	75 MW
Pulse Length:	1.5 μs
Repetition Rate:	180 Hz
Gain:	50 dB
Efficiency: (including beam focusing)	50%

SLAC is in the seventh year of a program to develop these klystrons. The choice of X-band as the operating frequency, along with the sheer size of the NLC, have resulted in some new, most demanding standards for the klystrons which may power this future machine. These are related to the overall efficiency required, to the high rf gradients that must be supported at the output circuit without vacuum breakdown, and to the manufacturing cost of the 5,000-10,000 klystrons needed for the collider.

1. THE EARLY PROGRAM

It is generally accepted that the manufacturing cost of two identical klystrons is higher than that of a single klystron at twice the power, provided that production yield is not compromised by the increased power. We have opted for the highest power output consistent with a reasonable life cycle cost for the tube. In the beginning of the development program this was 100 MW per klystron.

Several experimental klystrons were designed, constructed and tested in the early 90's to meet that objective. The results were disappointing, for two reasons: In order to use existing modulators, which were limited to about 450 kV, a relatively high beam current was chosen (Perveance of 1.8×10^{-6})[1]. This resulted in poor beam optics and some beam interception; the high perveance also limited klystron efficiency.

The very first klystron in the XC series, (XC1), which was built with a conventional single-gap output cavity, produced 70 MW. However, this was only for pulses below 50 ns. At longer pulses, rf breakdown drastically limited peak power, with the result that, at the required 1.5 μs pulse length, this tube could produce only 20 MW. In further tests, it was found that the output cavity resonance was higher than the design frequency, because the cavity gap had been eroded by repeated discharges. After that, all subsequent XC klystrons were built with extended interaction cavities of one type or another, but the design eventually converged to a multi-gap, disc-loaded output cavity, operating in either a standing or a traveling-wave mode. These were the output circuits used for the 50-MW XL series klystrons.

2. THE XL SERIES OF 50-MW KLYSTRONS

It was decided to target the next series of tubes to 50 MW and to lower the perveance to 1.2×10^{-6}. The reduced perveance resulted in stable and more efficient XL-series klystrons. Five such tubes were built and tested. All produced the desired 50 MW at 1.5 μs, within the 440 kV beam voltage.

XL-1 and XL-2, employed standing-wave output circuits. XL-3 was a 4-gap traveling-wave output klystron and exhibited improved efficiency over the previous two tubes, although its output was conditionally stable, i.e. it was necessary to adjust the beam-confining magnetic field to eliminate parasitic oscillations. The next klystron, XL-4, built with the same output circuit, but with added loss, was stable and operated faultlessly up to 75 MW, where its efficiency was close to 50%. The design for these solenoid-focused tubes was frozen at that point. The next klystron, XL4-2, is identical to XL-4 and has been tested with identical results.

The cavity arrangement used and the test results at the 75 MW level are shown in Figs 1 and 2.

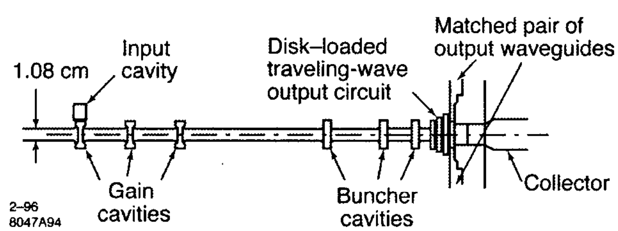

Figure 1

* Supported by Department of Energy contract DE-AC03-765SF00515

[1] Beam perveance is defined as Current/(Voltage)$^{3/2}$

A total of six conventional cavities are employed. The first three "gain cavities" are of the reentrant type in order to enhance R/Q and are stagger-tuned to obtain the bandwidth necessary for the pulse compressors used in the NLC, which require rapid 180° phase switching in the klystrons. The next three cavities are "pill-boxes" and are tuned well above the operating frequency to bunch the beam, while dividing the voltage among them to avoid rf breakdown. The output circuit is a 4-section, disk-loaded structure coupled symmetrically to two output waveguides, which are subsequently re-combined in a single guide leading to a mode transducer.

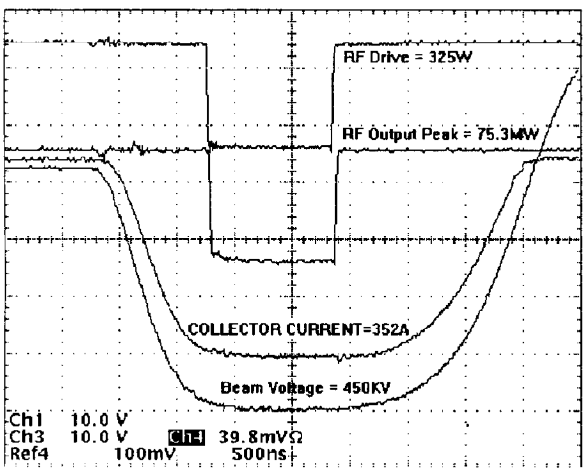

Figure 2

The output circuit deserves particular mention. As indicated above, the XL1 and XL2 output circuits were designed as standing-wave cavities. (Fig 3) They were 3-section, disc-loaded circuits operating in the π mode. The objective was to develop an rf voltage comparable to beam voltage across the three gaps, in phase with the beam. Thus the beam voltage and the cavity dimensions chosen for the π mode to be at 11.4 GHz determined the spacing of the disks. The field strengths across the three gaps were made more or less equal, with adjustments made for end effects and for the two coupling irises. In the π-mode, the overall R/Q of this extended cavity was about 15 and the coupling coefficient about 0.8, these being conventional klystron definitions. The Q_{ext} was 60 and was chosen to produce a total voltage across the entire cavity approximately equal to the beam voltage. The goal was a lower maximum surface gradient in the cavity, compared to the gradient of a single-gap cavity at the same total decelerating voltage. The method succeeded, by a factor of approximately 2. A larger number of sections would have further reduced the surface gradient, but would have introduced the possibility of a monotron oscillation at the 0-mode. This actually occurred in the case of one of the XC klystrons, where a four-section output was employed.

The foregoing is a description of ordinary klystron design. Although it resulted in two successful tubes, this method treats the output circuit as a single cavity. It does not take into account the fact that the beam slows down as it interacts with each gap; nor that the rf current flowing into each section increases at each step, since it is made up of current flow from previous sections and current coupled from the beam. Thus, two available degrees of freedom in the design are not utilized, if the klystron approach is taken. A design method based on traveling-wave tube theory can be more effective, and leads to both velocity and impedance tapering along the disk-loaded circuit. This is the method used in the XL3 and XL4 klystrons, where the output circuit operates near the $\pi/2$ mode and has a total of four sections. Oscillations in the 0-mode are avoided because the coupling to the output waveguide is much tighter in the traveling-wave circuit, thanks to impedance tapering. Nevertheless, XL3 exhibited some higher frequency instabilities, which were traced to the last two drift tunnels. In XL4 these were made of stainless, rather than copper, and the tube was unconditionally stable.

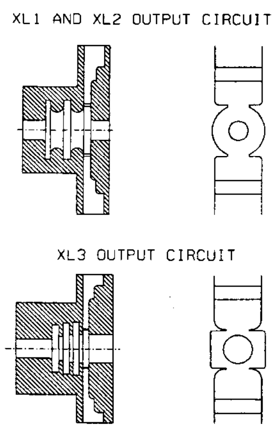

Figure 3

The original XL4 has accumulated 500 or more hours of operation at rated pulse energy and at a repetition rate of 60 Hz. As indicated above it has been operated at 75 MW and it is believed to be capable of even higher peak power. XL4-2 was tested up to 90 MW, at 100 ns pulse length. Two design changes since the XC series contributed significantly to the reliability of the tube. The first was the use of a TE_{01} window, rather than the traditional TE_{11} design, in which rf current crosses the interface between the window and its copper casing. This required the use of a "flower-petal" mode converter within the klystron vacuum. The second change was to attach an ion pump directly to the electron gun, although this required floating it at beam voltage. The improved pumping speed shortened tube processing considerably. Window and gun ceramic failures at test were very frequent in the XC program. There were none in the five XL klystrons tested.

Although the XL4 is not expected to be the rf source for the NLC, four more XL4's are currently being produced at SLAC for use in the NLC Test Accelerator and for experiments at KEK. A power-voltage plot of the first two XL4's is shown in Fig 4. Working drawings are available to potential industrial manufacturers of NLC klystrons, to prepare them for an eventual procurement of final prototypes.

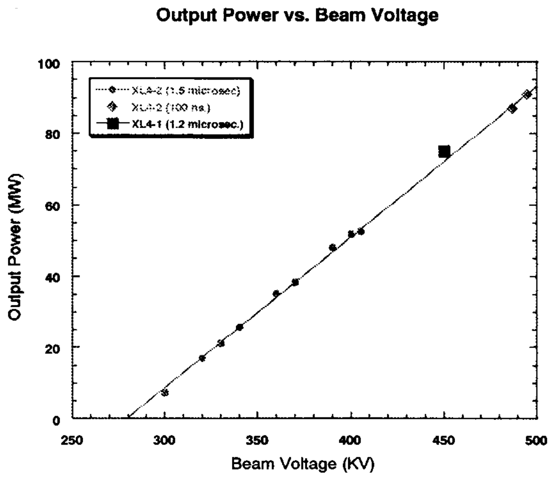

Figure 4

3. PPM KLYSTRONS

The NLC source cannot be a solenoid-focused klystron. The solenoid power is of the order of 20 kW, which is higher than the average power of the klystron and hence results in an unacceptable overall efficiency. Superconducting solenoids have always been a fallback option, but they present a considerable complication to the design of a machine with several thousand such devices. Periodic permanent magnet focusing (PPM) was more attractive, but although very common with traveling-wave tubes, relatively untried with klystrons. It was decided to further drop the klystron perveance for the PPM version. A new gun was designed with a microperveance of 0.6. It was felt that, although this would require a higher beam voltage, and a new modulator, it would probably also result in improved efficiency, and hence not quite as high a voltage. This indeed turned out to be the case.

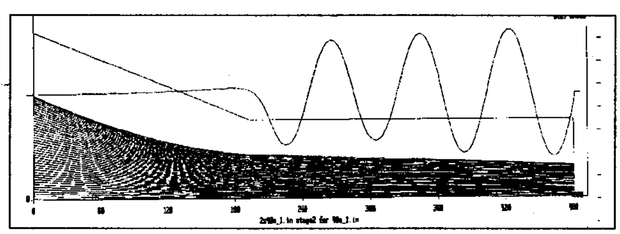

Figure 5

The parameters of these X-band klystrons are very favorable to PPM focusing. The high voltage and low perveance resulted in a long space charge wavelength, and the small cavities allow short magnetic periods. The key to PPM focusing is a high ratio of beam plasma wavelength to magnetic period. There is a stop band in beam transmission at low voltages and the edge of the stop band is a function of this ratio. In helix TWT's a typical λ_p/L ratio is 2.5. In the NLC klystron it was possible to attain twice that ratio.

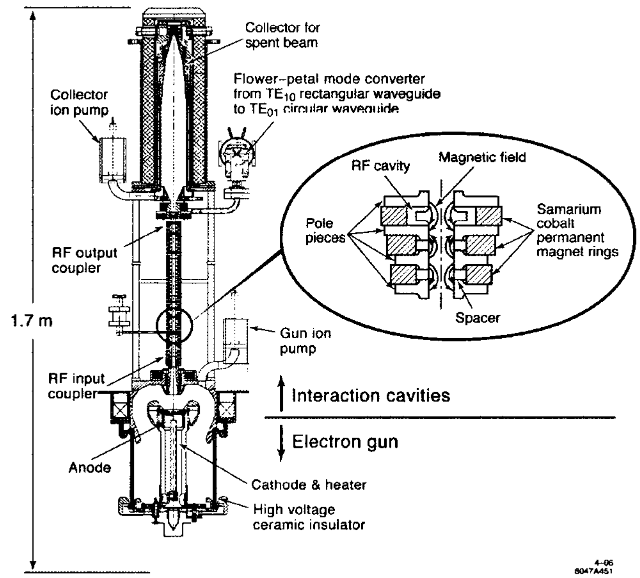

Figure 6

The result was that the stop band was pushed down to a very low voltage. Fig 5 shows that that there is not even a slight ripple in the beam as a result of the periodic focusing. A low beam interception during the rise and fall of the beam pulse (as well as during the pulse) is essential to these klystrons, which carry an extremely high power density in the beam.

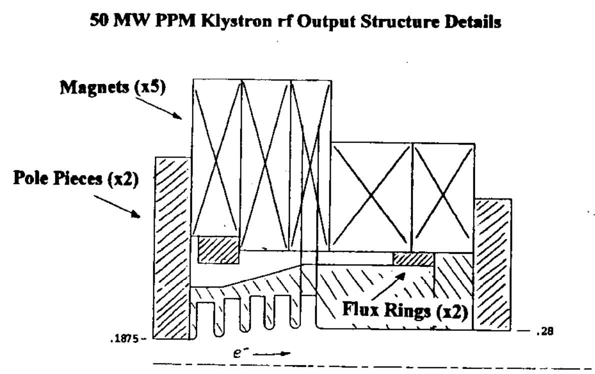

Figure 7

A beam tester was first built to confirm simulations on gun optics and PPM focusing. The magnet material used was Samarium Cobalt with a peak field about 3000 Gauss. There were 20 magnetic periods, approximately the number the klystron would require, and the device was operated up to 550 kV. Beam transmission was found to be excellent (of the order of 99.9%). Furthermore, it was better than 99% down to 100 kV, which was what was hoped for.

An experimental klystron followed. It employed the same type and number of cavities as the XL4 but, because of the higher voltage and lower current, the output was a 5-section traveling-wave circuit. The gain and bunching cavities were nested between pole pieces (Fig 6) and larger magnets were used to provide a straight field at the output circuit. (Fig 7) Output power was taken in two waveguides and two TE_{01} windows. A number of small, low-power solenoids were used in the vicinity of the gun to control beam entrance conditions, but turned out to be unnecessary. Beam transmission was again excellent.

Stanford Linear Accelerator Center

50-MW X-Band PPM Klystron Simulation and Test Results

Item	Experiment	Simulation	Unit
Peak RF Power Output	56	59	MW
Peak Beam Power	93	91	MW
RF Efficiency	60	65	%
Gun Perveance	0.66	0.60	μK
Beam Voltage	459	465	kV
Beam Current	205	190	A
Intercepted Beam Power @Rated RF Output	1	0.0	%

Figure 8

Test results compared to simulations are shown in Fig 8. Power output up to 60 MW was measured, at an efficiency of 60 per cent. Beam transmission at full power was lower (96%) but, apparently, the interception was of slow electrons, because there was no appreciable temperature increase at the output circuit at full saturation. The CONDOR simulation is shown in Fig 9 and a picture of the tube is Fig 10.

CONDOR Simulation at 465 kV and 57.8 MW

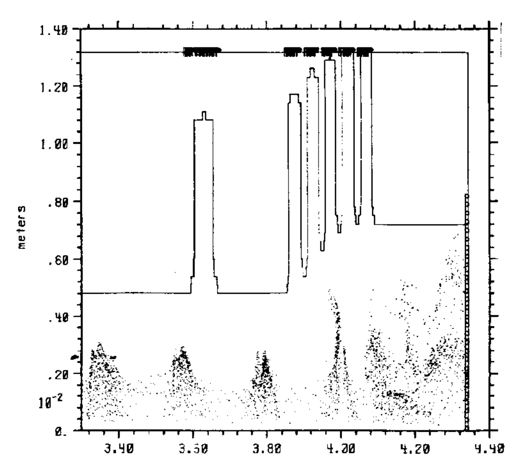

Figure 9

Current plans for the NLC call for 75-MW sources, with 1.1 μs pulses. A new PPM klystron has been designed, this time at a microperveance of 0.75. It is expected to reach test in September. It will be very similar to the experimental PPM klystron, but it will employ larger, stainless, drift tunnels. It is expected that this will be the prototypical electrical design for the NLC.

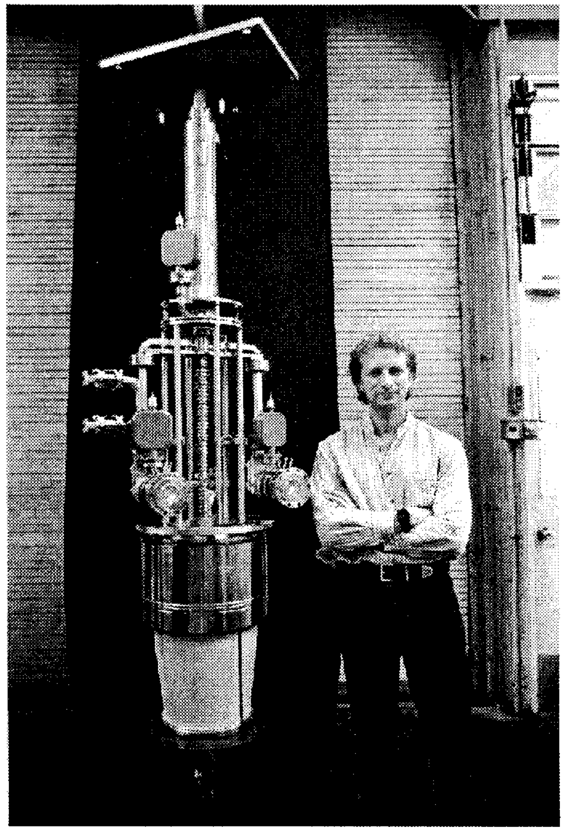

Figure 10

4. COST ISSUES

Obviously, life cycle cost is a major consideration in designing these klystrons. It is a function of the acquisition cost, tube efficiency, and useful life of the klystrons. Acquisition cost has particular importance because of the number of klystrons in the collider and their impact on the total cost of the machine. There has never been comparable klystron procurement in the history of the microwave tube industry. Not only are the quantities very large, but the specifications will be much more difficult than those for any klystron now commercially available. For this reason, SLAC has initiated a separate program to design for manufacture the PPM 75-MW klystron now under development. The plan is to run the two programs in parallel, eventually producing several prototypes, which can be demonstrated to meet the final specifications for NLC klystrons. The cost in quantity of these prototypes will be estimated by using outside parts quotes and by amortizing the cost of the necessary production equipment and tooling over the quantity of tubes produced. The cost target for the 75-MW PPM klystrons is of the order of $30,000 each, in quantity 5000 and in 1997 dollars. The current scenario, if the NLC is funded, calls for supplying industry with working drawings of the prototype klystron and inviting competitive bids. It is likely that at least two contract awards will be made to produce the initial complement of tubes, which will be near 5000 pieces.

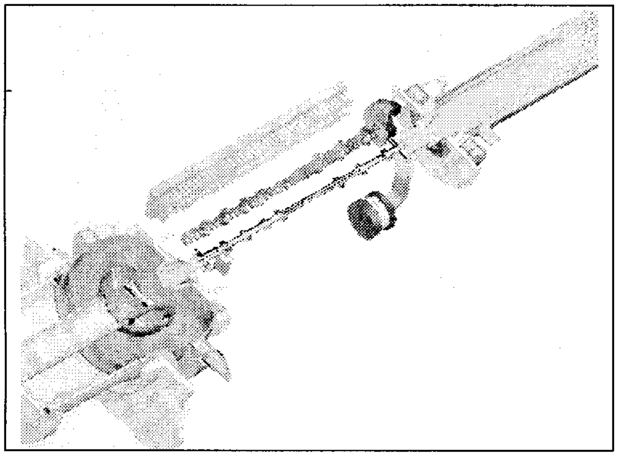

Figure 11

A preliminary sketch of the proposed design for manufacturing is shown in Fig 11. It features a drastic reduction in the number of vacuum joints, by leaving the magnetic pole pieces and their spacers outside the vacuum. The output circuit will probably be assembled by diffusion bonding the diamond tool-machined copper parts, following the method now used in the fabrication of the NLCTA accelerator sections. Other tube subassemblies will be aggressively simplified. A great deal of emphasis is being placed in cost-reducing the gun, and the cathode in particular. In a separate program, partially funded by the Air Force Office of Scientific Research, we are investigating producing oxide cathodes by plasma deposition.

In calculating the cost of the equipment necessary to produce the NLC klystrons, an important issue is the time necessary to pump and test a klystron, since that will determine the number of pump and test stations that must be purchased by the manufacturer. It will be assumed that potential manufacturers do not currently possess manifolded exhaust equipment, capable of processing 4-5 klystrons at a time, nor arrays of 500 kV automated modulators. This processing time is intimately associated with the gases, primarily hydrogen, that are evolved in bakeout or in tube test. SLAC is conducting experiments to establish processes, which either avoid hydrogen brazing of parts, or outgas them, without tying up expensive equipment.

Another issue, and one that affects all rf components of the collider, is vacuum breakdown in the presence of high rf gradients in the klystron, or in waveguides, pulse compressors and the accelerator sections themselves. Rf processing time, for klystrons or rf components, can be a critical cost factor. The problem is being aggressively investigated at SLAC, along two fronts: Dark current emission from test surfaces is being studied in a resonant ring, with an embedded X-band cavity; X-ray imaging techniques will be used to determine emission sites, which can be subsequently studied with an Atomic Force Microscope. An electron microscope is also used to examine surfaces subjected to the treatment necessary for making rf parts in order to determine how these treatments must be modified to reduce or eliminate emission sites.

The X-band klystron program at SLAC is now in its eighth year and is probably the most comprehensive project ever undertaken to develop a microwave tube. It is not completed as yet, but when it is, it should serve not only as the foundation for the industrial production of the NLC klystrons, but also as a valuable milestone in the state-of-the-art of all high-power microwave tubes.

ACKNOWLEDGMENT

This program is obviously a team effort. Credit must go to the Tube Development Group under Robert Phillips, with Daryl Sprehn responsible for the PPM klystron design; the Klystron Manufacturing Group under Chris Pearson (who built a dozen or more experimental tubes with 100% yield); the RF Component Group, under Arnold Vlieks; The Electronic Engineering Department, under Ron Koontz; and the supporting personnel of the SLAC Klystron/Microwave Department.