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DEVELOPMENT OF MULTIMEGAWATT KLYSTRONS FOR LINEAR COLLIDERS

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Abstract

A number of experimental klystrons have been constructed and evaluated at SLAC, KEK and INP, aiming toward output power objectives of 100 and 120 MW at 11.4 GHz (SLAC and KEK respectively) or 150 MW at 14 GHz (INP), with pulse lengths on the order of 1 μs. Since rf breakdown is considered to be the principal mechanism limiting power for such tubes, most of the effort has been concentrated on the design of output circuits that reduce rf gradients by distributing fields over a longer region of interaction. Another klystron component receiving emphasis has been the output window, where the approach for future tubes may be to use a circular TE01-mode, half-wave window.

Best results to date in this continuing international effort are: 50 MW with 1 μs pulses, using a traveling-wave output circuit (SLAC and INP), and 85 MW with 200 ns. pulses (SLAC), using two conventional reentrant, but uncoupled, output cavities. At KEK a klystron with a single, but not reentrant, cavity has produced 80 MW in 50 ns pulses. Finally, Haimson has demonstrated 100 MW at 50 ns with a traveling-wave output. This paper addresses primarily the work performed at SLAC during the last two years.

I. THE PROBLEM

A future electron-positron collider, if it operates at X-Band, will require approximately 2000 klystrons at the 100 MW level, for a center-of-mass energy of 0.5 TeV. For 1 or 1.5 TeV, which are top energies that physicists would like to build into the design of such a machine, the number of tubes becomes so large that economics would force consideration of sources with powers of more than 100 MW per unit. Such sources may have to be different from conventional klystrons. Research on other devices is in progress at various institutions.

The conventional klystron (with some form of extended interaction output) appears to offer the most direct, and probably the most economical approach to the 100 MW level for several reasons: The peak power has already been demonstrated, the necessary manufacturing processes are standard, and the klystron is a high gain, stable, sturdy tube, capable of high average powers. There are two remaining problems: Producing 100 MW at the required pulse length, which in current SLAC collider designs is 1.5 μs; and finding an alternative focusing system for an electromagnet, since its DC power consumption is prohibitively expensive, given the number of tubes in the machine.

The magnetic focusing issue is not serious. Superconductivity provides a solution, and beyond that, there is reason to hope that periodic permanent magnet focusing (PPM) can be made to work for these tubes.

The principal problem is the pulse length in combination with high peak power. In a well-designed klystron with good beam optics and little beam interception, the vulnerable areas will be the windows and the output circuit. Windows have in fact accounted for most of the experimental klystron failures at SLAC. The weakness is in the metallized and brazed joint between the ceramic window and its copper sleeve. There is a solution, however, described later. The major remaining hurdle is in the output circuit which must develop high gradients in order to extract energy from the bunched beam and may cause breakdown in vacuum.

To avoid very high gradients, interaction between circuit and beam must take place over an extended space, rather than the usual short gap in a reentrant klystron cavity. Such extended interaction circuits, however, whether of the standing or traveling wave variety, are large compared to wavelength and capable of supporting unwanted modes or resonances. Some of these may be trapped if they do not couple well to the output waveguide. When excited they can develop very high fields and cause oscillations or, if they are of the dipole variety, steer the beam into the drift tube. These effects may not manifest themselves unless the beam pulse is long enough, due to high Q's and long filling times, in some cases appearing 200 ns or more after the onset of the pulse.

The work at SLAC has been focused on the study of various output circuit alternatives, the objective being to minimize rf gradients while maintaining good interaction efficiency. In parallel with this effort, various types of output windows have been evaluated in a resonant ring.

II. EXPERIMENTAL KLYSTRONS

Results on the first three experimental klystrons built at SLAC were reported at this conference two years ago. Subsequently, the basic klystron was redesigned, with new optics and provisions for re-using a tube, by switching output circuits. Five tubes were built with this configuration. The gun for these tubes has a microperveance of 1.8 and an an area convergence of 100. It is not intended for extended service and has both high cathode current loading and high gradients. Beam parameters for the XC series of tubes are listed in Table I.

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Table I: Beam parameters for XC series of SLAC klystron

Voltage (kV)	440
Microperveance	1.8
Tunnel Diameter (cm)	0.953
Filling Factor (nominal)	0.65
Solenoid Field (kG)	5.7

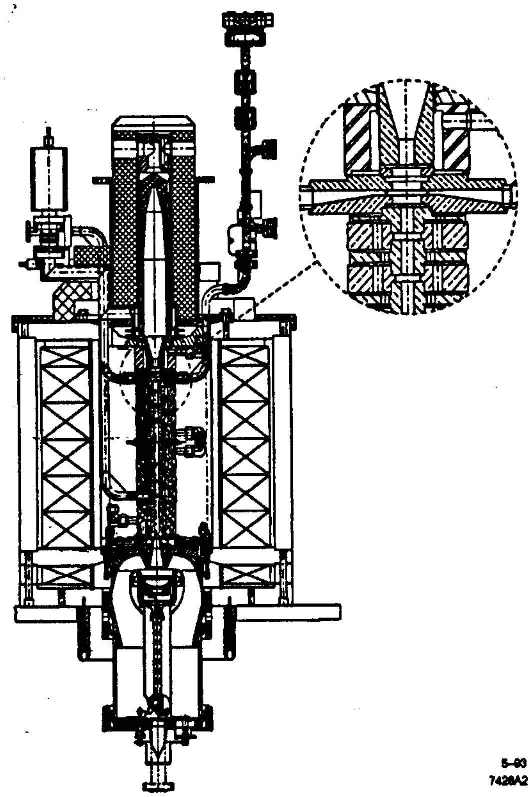

Figure 1. Assembly drawing of XC8 in focusing coil.

The klystrons built in this program to date have been designated XC1 through XC8. A complete tube in its magnet is shown in Fig. 1. This is a drawing of XC8, which employed a 4-cell π-mode standing-wave output. This particular klystron was assembled with built-in, bakeable waterloads, rather than windows, in order to evaluate what appeared to be a promising output circuit, without danger of breaking a window in test. All tubes in the XC series were equipped with two output waveguides and two output windows, except for the XC6 klystron which used four waveguides and windows.

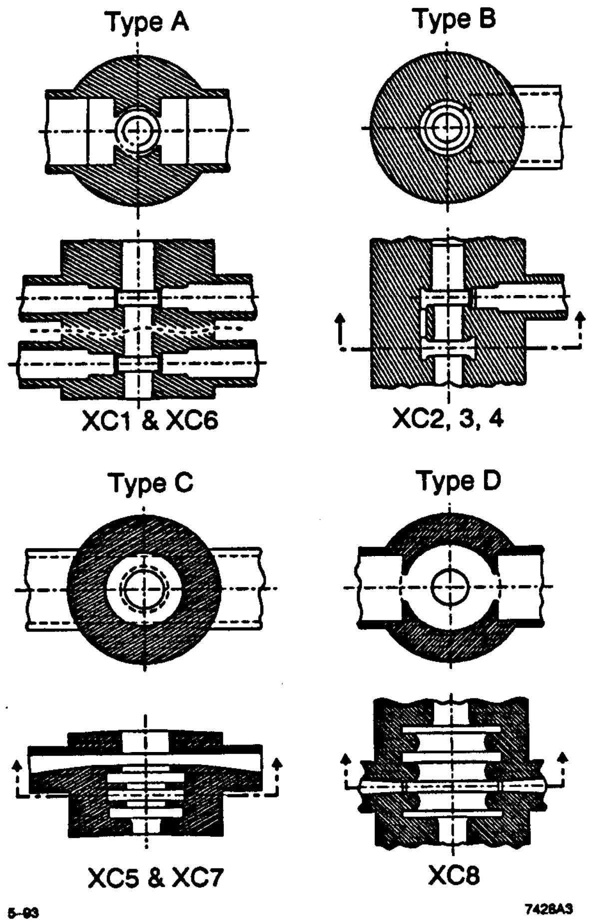

Figure 2. Five types of output circuits tested by SLAC in XC series.

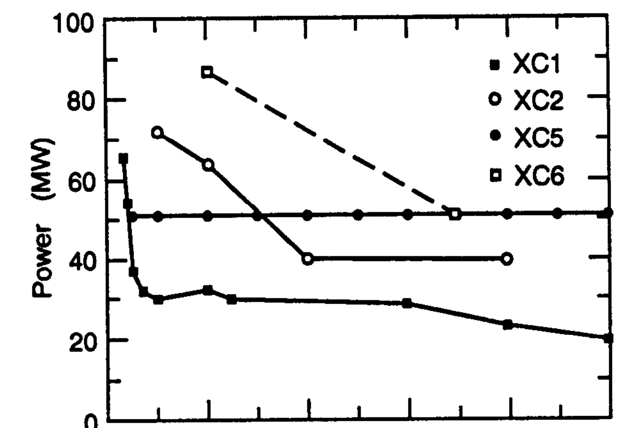

Figure 3. Effect of pulse width on achievable peak power.

III. OUTPUT CIRCUITS

Five types of output circuits have been tested and are shown in Fig. 2.Representative results for each type of circuit are shown in Fig.3.

The basic strategy in the development of output circuits is to reduce rf gradients immediately next to the beam, while preserving a high degree of overall coupling between beam and circuit. The approach has been to apply standard klystron or traveling-wave tube design formulae, and analyze candidate circuits for R/Q, coupling coefficient and surface gradients using SUPERFISH and MAFIA. Subsequently, large-signal interaction beween beam and circuit is investigated with either

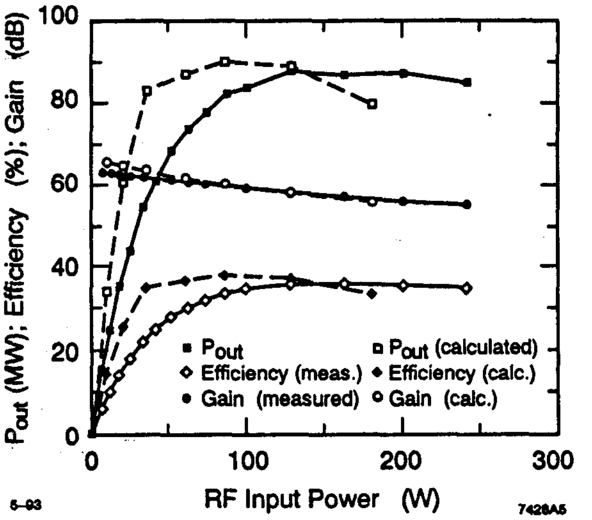

Figure 4. Comparison of computed and measured performance of XC6—two uncoupled output cavities (200 ns pulses, 60 pps).

one-dimensional disk models or two-dimensional particle-in-cell codes. In the early stages of the program, the latter were not available except for the simpler varieties of standing-wave circuits, but now it is possible to simulate both standing and traveling-wave circuits with either CONDOR or MAGIC.

A single reentrant cavity (Fig.2, Type A) in XC1 produced less than 20 MW without pulse breakup at a full microsecond. The tube failed because of a broken window, but a post-mortem showed severe erosion of the output cavity drift tube tips. The cavity interaction gap was 0.5 cm long and 0.95 cm in diameter. The calculated gradient at the gap (for 100 MW output) was 1 MV/cm. Clearly, that was excessive.

More recently in the program the XC6 klystron used two uncoupled Type A cavities with much better results. The spacing and tuning of the cavities was adjusted by CONDOR simulation to divide the output power equally between the two cavities. Actual tests showed good agreement with theory in both power distribution and predicted efficiency as seen in Fig. 4. This klystron failed because of gun arcing before testing was completed. It also produced 50 MW at a pulse length of 700 ns and could conceivably have been processed to the same or longer pulse length at 86 MW. Power from the four waveguides was measured independently. A complete test of the tube would have included combining the power from the two cavities in two Magic-Ts, but the gun failure prevented futher tests. XC6 will be rebuilt.

Output circuits of the B type (2π transit angle beteen two inductively coupled cavities) were used in three klystrons. Two of these are still in use as power sources. A third, XC4, was built with no windows and integral loads in order to test the power limits of the circuit without window failures. The circuit failed at approximately the 40 MW, 1 μs level and was found to be badly damaged in the iris coupling the two cavities.

The XC5 klystron employed a Type C traveling-wave output. This disc-loaded circular waveguide circuit operated in the $2/3\pi$ mode, but at the time of its design only one-dimensional simulations were possible. These predicted good efficiency but provided no detail on either matching conditions or surface gradients. This klystron produced 52 MW at 1 μs (29% efficiency) with excellent stability and no pulse breakup. It was lost because of an open cathode heater. The tube was rebuilt with a modified output, using four, rather than three cells prior to the waveguide coupler. This circuit was not as successful; although its efficiency was comparable, it could not be operated at the longer pulse lengths, conceivably because of a trapped mode.

The most recent klystron, XC8, uses a standing-wave disk-loaded waveguide circuit, operating in the π-mode with thick disks and large iris openings (Type D). The result is a very low R/Q (about 15) and low surface fields in the vicinity of the beam. Because of the low R/Q, the optimum loaded Q is relatively high (about 100) and, together with the large separation between the 0 and π modes due to the large irises, produces little mode mixing. Calculated surface fields at 100 MW are 350 KV/cm at the entrance and exit of the circuit and 850 KV/cm at the middle iris tip. One-dimensional simulations predict an output of 100 MW for this circuit. Unfortunately, it has a rather fatal flaw: At the 0-mode, beam loading is negative, leaving open the possibility that the tube will monotron oscillate. The XC8 klystron does just that, at approximately 8.5 GHz. The solution is to shorten the circuit, which can be done with little sacrifice in gradient or coupling coefficient, and which should produce an unconditionally stable circuit at the 0-mode frequency.

IV. WINDOW DEVELOPMENT

In the early stages of the program the windows used were thin circular ceramic wafers, approximately 0.8 mm thick, coated with titanium nitride. These windows had the virtue that they were very wide-band and largely free of ghost modes, thus reducing the risk of trapping modes in the output circuit, or the window itself. They were found to be very fragile, both in resonant ring tests and in the tubes themselves. They were replaced with 0.43 wavelength windows (TE11 mode, 3.7 mm thick). All klystrons tested in the latter stages of the program employed these windows. They are not reliable with longer pulses and have failed in resonant ring tests as well. In one such test the onset of failure was recorded with a TV camera, making it obvious that the eventual discharge which fractured the window originated at a hot spot on the periphery, at the maximum field point.

The SLAC design for the RF feeds in the linear collider calls for 7.5-cm TE01 waveguides connecting klystrons to pulse compressors and to the accelerator. A very compact and very efficient WR-90-to-circular waveguide transition has been developed for this purpose. It is planned for use in future klystrons, together with a half-wave TE01 window. The waveguide arrangement is shown in Fig. 5, and the frequency-response of transition and window (terminated in a matched load) appears on Fig. 6.We expect a single window of this type to operate well at full peak power and pulse length.

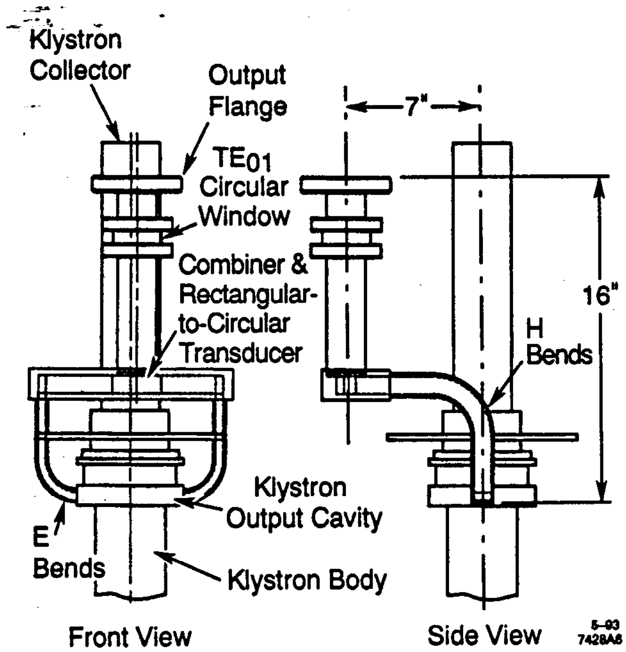

Figure 5. Arrangement of waveguides used to obtain TE_{01} circular waveguide output.

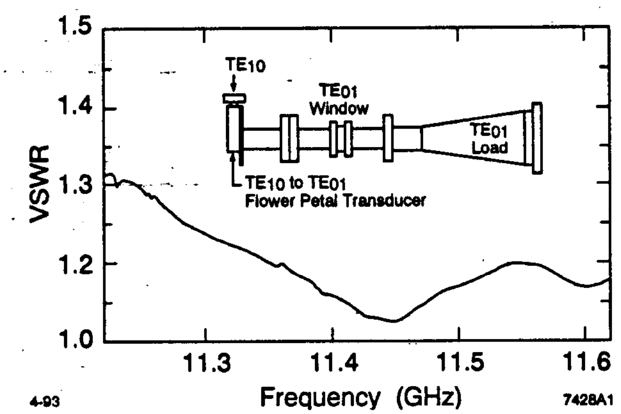

Figure 6. Measured rf match and schematic of combined TE10 to TE01 transducer and TE01 disk window with matched termination.

V. KLYSTRON DEVELOPMENT IN JAPAN AND RUSSIA

The klystron development program at KEK (and Toshiba) parallels the work at SLAC. The approach differs in that the microperveance used is 1.2 instead of 1.8, but future work at SLAC will also be performed at lower perveance. The output circuit used is a single TM01 cavity, with no reentrancy, but with a longer transit angle than the reentrant cavities in SLAC klystrons. The calculated gradient for this cavity at the 120 MW output level is 720 KV/cm. This klystron is reported to have produced 80 MW with 50 ns pulses, at an efficiency of 30%. Tube design parameters are shown in Table II.

Table II: KEK klystron design operating parameters

Frequency (GHz)	11.424
Power Output (MW)	120
Beam Voltage (kV)	550
Beam Current (A)	490
Beam Microperveance	1.2
Cathode Diameter (cm)	7.2
Cathode Area Convergence	110
Magnetic Field (kG)	6.5
Pulse Length (ns)	500
Number of Cavities	5

There are no recent results reported from the Russian klystron effort at Novosibirsk and Protvino. The Russian frequency is 14 GHz, and the previously published performance of their very advanced klystron (grid-modulated, PPM focused, traveling-wave output) was 55 MW at 700 ns.

VI. FUTURE PROGRAM AT SLAC

The XC8 klystron is the last of the experimental klystrons at SLAC aiming at the 100 MW level with a microperveance 1.8 beam. It may be rebuilt with a shorter cavity or with the double cavity output of XC6, but no new tubes will be started. The next klystrons will be 50 MW, 1.5 μs sources for the NLCTA (Next Linear Collider Test Accelerator), which requires four klystrons. They will operate at the same voltage (440 KV) as the XC series, but at a microperveance of 1.2, so the transition to the new design will not involve too many new parts. The first tube in the series will use a 3-cell π-mode standing wave circuit (Type D) and a TE01 window. An improved, CONDOR validated, traveling-wave backup design exists. The first tube, XL1, should be tested in August. Shortly after that it is expected that a PPM version of the XL1 will be built and tested.

A new modulator is being constructed at SLAC for the purpose of eventually continuing the 100 MW program at a microperveance of 1.2 and 550 KV. This phase should begin when the tubes required by the NLCTA are delivered.