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MULTIMEGAWATT RF POWER SOURCES FOR LINEAR COLLIDERS*

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Abstract

Conceptual designs for a future linear collider operating at 11.4 GHz call for peak rf power as high as 240 MW per meter, with an accelerator length of 14 km. This is an extremely high total power, which results in requirements for microwave sources that cannot be met with existing microwave tubes. While some new tube concepts are being considered, work is proceeding at several laboratories in the US and abroad on conventional 100 MW klystrons for this application. The electron beam necessary for this power to be generated, unless carefully controlled, can easily cause intrapulse melting at the klystron output circuit. This, coupled to the need for good efficiency, high production yield, and long life, poses some difficult problems to the klystron designer. Experimental klystrons at SLAC and other laboratories are approaching the goal of 100 MW in 800 nsec pulses, but much work remains to be done before a design is available which is suitable for manufacturing thousands of these tubes.

I. Power Source Options

Proposals for future linear colliders call for center-of mass-energies in the 0.5–1.0 TeV range. From studies conducted at SLAC, an attractive approach for what is referred to as the Next Linear Collider (NLC), is a 14 km machine, operating at 11.4 GHz. In Phase I of this project, a gradient of 50 MV per meter is required to reach 0.5 TeV. For Phase II, the collider would be expanded to a full TeV by doubling the gradient, i.e., quadrupling the RF power. This power calculates to 60 MW per meter for 0.5 TeV and 240 MW for the full TeV.

Despite a short pulse length (100 ns), this is a substantial concentration of power at a frequency where no conventional high power microwave tubes are available, or have ever been developed. No ground-based or ship radars using X-Band sources above one megawatt are in existence and there is no previous experience with X-Band accelerators at this power level.

The absence of an established technology for a power source has stimulated some novel approaches. The high peak powers required suggest high current, lower voltage tubes, such as a multiplicity of magnetrons or crossed field amplifiers. The numbers are impressive. If, for instance, state-of-the-art 5-megawatt crossed-field amplifiers were considered as sources, a total of almost 70,000 tubes would be required. Unit cost in these quantities could probably be lowered below the $1000 level by employing advanced automated manufacturing methods, similar to those used in the production of cooker magnetrons. Furthermore, one could aspire to triggering the CFA's with RF, eliminating the need for modulators. The combination of these possibilities is intriguing and perhaps worth pursuing. A CFA development program was, in fact, initiated at SLAC, but for tubes in the 100–200 MW level. The effort was discontinued for budgetary reasons. SLAC physicists, in collaboration with LLNL, also took a hard look at the relativistic klystron as a potential NLC source. Although a power output of 270 MW was reached (with short pulses), a decision was made against further development because of the complexity and cost of the device.

Other approaches include some tube schemes which were initially proposed several decades ago, at a time when there was DOD interest in microwave "superpower" tubes. Modern versions of these are the "cluster klystron" and the "sheet beam klystron." Such devices require a great deal of R&D work in order that some inherent problems in spurious mode control and in beam optics can be solved; but they hold promise as NLC sources if these problems could be brought under control. They are being pursued at a low level at SLAC.

Finally, there is the gyro-klystron, a "fast wave" amplifier which, in oscillator form, has been very successful as a generator of very high peak and average powers at millimetric frequencies. Significant progress has been made recently at obtaining stable gain from an X-Band gyroklystron at the University of Maryland.

Clearly then, there are several alternatives to the NLC source requirement, some of which deserve R&D efforts. However, a test accelerator is being planned now, and construction may begin within the next 2–3 years. The resulting urgent need for sources is not consistent with longer-term R&D. Consequently, the decision was made at SLAC to design and build a 100 MW klystron. The plan is to use this tube in conjunction with an RF pulse compressor which will increase peak power by a factor of about 5, while reducing the pulse length from 800 to 100 ns.

The remainder of this paper addresses the issues associated with the design of the klystron, the approaches taken at SLAC and elsewhere, the available results, and the outlook for the future.

II. The Klystron Design Problem

Output power capability in linear-beam microwave tubes scales approximately as the inverse of the square of the frequency, on the basis that maximum power is limited by the area available to dissipate beam or RF losses. Thus, the klystrons which power the SLC, producing 60 MW at 2.856 GHz with 210 Joule pulses, would scale to 3.75 MW and 13 Joules at 11.4 GHz. Of course, the power of these standard SLAC klystrons is not the limit of what can be attained at S-band. Experimental SLAC tubes have been built and operated at 150 MW. Even so, the increase in Joules per unit area, is quite considerable.

With a 100-megawatt klystron source augmented by a pulse compressor, the NLC would require about 1700 tubes for the 500 GeV Stage 1 machine. That is a prodigious number of very advanced microwave tubes, which will have to be produced with very good yield and reliability, if the economics of the machine are to be sensible. A klystron design is needed which provides an adequate margin of safety

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Table 1. 100 Megawatt Klystron Projects

	Design Voltage (kV)	Micro-Perveance	Maximum Power (MW)	RF Pulse Length (ns)	Comments
Novosibirsk [a]	1000	0.3	55	700	Gridded gun, permanent magnet focusing. Parasitic oscillations limiting power
KEK [b]	450	0.6	11	70	Failure due to output window fracture
Haimson	500	1.4	100	50	50 ns beam pulse
SLAC	440	1.8	72	100	Pulse breakup limiting output power, 1 μs beam pulse

[a] Operating frequency: 14 GHz. [b] Phase I Klystron designed for 30 MW.

electrically and thermally, and make possible production in large quantities by relatively unskilled workers.

Klystron design usually proceeds by choosing the beam voltage and current, or by selecting the "perveance" of the electron gun, defined as current/(voltage)$^{3/2}$ Simplicity, along with modulator cost and efficiency, argue for as low a beam voltage as possible, but for a linear-beam microwave tube at this frequency, conversion efficiency is known to deteriorate as the microperveance increases from, say, 1 to 2. The choice of the higher perveance and current also forces a beam of higher convergence, if the klystron cathode is to be operated at a current density and temperature consistent with long life. In turn, a higher convergence inevitably requires more precision in beam optics, with the attendant impact on reliability and cost. To provide some perspective, the SLC klystrons, which have a fine record of reliability and long life and operate at 44% efficiency, use a microperveance of 2 and an area beam convergence of 18, resulting in an average current density at the cathode of 6 amp/cm. An NLC klystron at the same perveance, efficiency and cathode loading requires a convergence of 200.

An additional argument for lower perveance is that the necessary beam confinement magnetic field can be correspondingly lower. The average output power of the NLC klystron, as postulated above, is less than 20 kW. Yet, the power consumed by the electromagnet can range from 15 to 50 kW, depending on the length of the tube and the inner diameter of the magnet. Thus a klystron electronic conversion efficiency of 40% can be degraded to an overall efficiency of 20% or less. A superconductive magnet can eliminate this need for additional power, but with considerable additional system complexity and initial cost. An alternative is permanent magnet focusing, which requires very low perveance.

There are two failure mechanisms which, together or in combination, set a limit on the power obtainable from the klystron. The first is RF breakdown in the output circuit. The second is intrapulse heating due to beam interception. The two are interrelated, with pulse heating probably the root cause of failures. In view of the above, beam control becomes a critical issue and this, more than any other consideration, is the strongest argument for lower perveances. These mechanisms need to be examined in more detail since they are at the core of the NLC klystron design problem.

In a conventional klystron RF power is extracted from the bunched beam while it traverses a resonant cavity shaped to present a short gap to the beam. The RF voltage across that gap must be equal or slightly higher than the DC beam voltage in order for the interaction between beam and circuit to be efficient. Consequently, as the beam voltage is increased, the RF gradient across the output gap may cause breakdown above a certain limit. The value of this limit is very difficult to determine because it is a function of vacuum and surface conditions in the immediate vicinity of the output gap.

Experiments at SLAC have produced some empirical values for RF breakdown in accelerator cavities with no beam present. At 2.856 GHz the gradient above which breakdown will occur was found to be approximately 3 MV/cm. It has been suggested that this threshold increases as the square root of the frequency so that at 11.4 GHz it would be almost 6 MV/cm. In fact, klystron output cavities in experimental tubes have been found to break down at a tenth or less of this value. It is clear that beam interception at the output gap or its vicinity creates the local conditions that cause RF breakdown to occur.

These local conditions arise from intrapulse heating as a result of beam interception. It can be shown that at 440 KV, where the SLAC tubes are designed to operate, 3 amperes of beam current intercepted on one square millimeter of copper surface will melt the metal within the one-microsecond beam pulse. This current is less than one percent of the klystron beam current at that voltage and consequently rather difficult to detect. If the melting occurs in the output circuit during the RF pulse it can be expected to cause some form of local plasma in which the RF field must be developed. Hence the RF breakdown.

The solution to the problem must be two-fold. First, beam optics must be excellent, particularly in the vicinity of the output circuit. Second, output circuits must be designed in which field gradients are minimized, most likely by arranging that the interaction with the beam takes place over several gaps, rather than just one, as in the case of an ordinary klystron. This can be done with coupled resonant cavities, i.e., a standing-wave circuit, or with travelling-wave output. In both cases ordinary klystron cavities would precede the output circuit, providing RF gain and a bunched beam to drive the output.

With this background we can now review the work performed to date in this country and abroad. Four groups are addressing the problem independently: at the Novosibirsk Institute in the USSR, the VLEPP collider and its power sources are being designed to operate at 14 GHz. The other groups, at KEK, SLAC, and Haimson Research Corporation, are designing 11.4 GHz klystrons. Table 1 summarizes the approaches taken by each of the four groups.

The Soviet design is extremely ambitious, and attempts to address, in one vacuum envelope, several fundamental issues of the NLC power source. The tube consists of a klystron input section and a travelling-wave output. A probable reason for the extremely low perveance is that the tube is designed for periodic magnetic focusing. For this scheme to be effective, a long plasma wavelength in relation to the magnetic period is required. Finally, the tube is equipped with a gridded gun and an arrangement of electrodes that serve to provide the correct potential profile for beam formation and focusing. These electrodes, which serve to distribute cathode-anode gradients more uniformly, together with the grid, offer the possibility of pulsing the klystron using a quasi-DC high voltage supply and a low voltage modulator in series with the grid.

Experimental results on the VLEPP klystron are not known with great precision. The tube has apparently produced as much as 50 MW with 700 ns pulses, but with a repetition rate of only about 1 Hz. Peak power was apparently limited by parasitic oscillations in the travelling-wave section, and not by beam interception, which is reported to be as high as 40% with full RF output.

In Japan, KEK has approached the design of a 100 MW klystron in two stages. The first tube, a microperveance 0.6 conventional klystron, was designed to produce 30 MW and was tested to 11 MW, with 70 ns RF pulses. A window failure terminated testing at that point. A full power klystron is expected to go to test later this year. It is designed to operate at 550 KV, at a microperveance of 1.2. The ouput cavity is not extended, but employs a longer interaction gap than is conventional in order to reduce surface gradients. KEK calculates a 700 KV/cm gradient for this output cavity and an efficiency of 45% for the tube.

The Haimson Research klystron employs a travelling-wave output as do the Soviets, but with a more conventional beam and focusing system. It is designed to operate at 500 KV, at a microperveance of 1.4, and is focused by an electromagnet. This tube is the only one in this survey to have produced over 100 MW. It may owe this distinction to the fact that it was operated with both high voltage and RF pulses of the order of 50 ns. The Haimson tube is also reported to have good efficiency and stability, which suggests a mature design for the output circuit.

III. Experimental Results at SLAC

At SLAC three klystrons have been built and tested, though the third and last tube was damaged early in test and did not produce significant results. All of these tubes employed higher perveance guns than those used by the other groups, and were designed to operate at 440 KV. A conventional single-gap output cavity was used at the first of these klystrons, designated XC1 . It was calculated to have a maximum surface gradient of 1300 KV/cm at full power output. The second and third klystrons made use of a double-gap "extended interaction" cavity, operating in the 2π mode. The maximum surface field for this cavity was calculated at 750 KV/cm. A photograph of the XC2 is shown in Fig. 1 and a drawing in Fig. 2. The second SLAC klystron tested produced the best results. Four conventional cavities are used to drive the extended interaction output. The beam is formed by an electron gun with an electrostatic area convergence of 35:1. The beam is further compressed by the confining magnetic field to a total area convergence of 200:1. Two RF windows are used, which in the case of the XC-2 were of the pillbox type, with a thickness of only 30 mils. These windows failed repeatedly and the tube was repaired twice, the second time with much thicker windows.

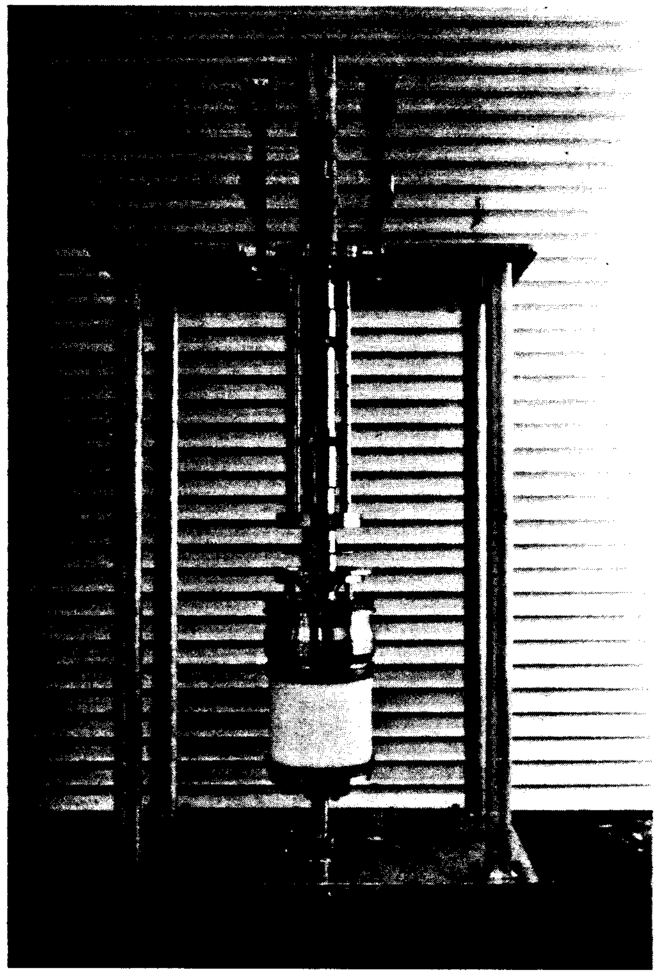

Figure 1.

The XC2 klystron was equipped with an isolated collector so that beam interception could be measured and the tube tested more safely. This did not turn out to be as useful as it was hoped. During test, transmission ap-

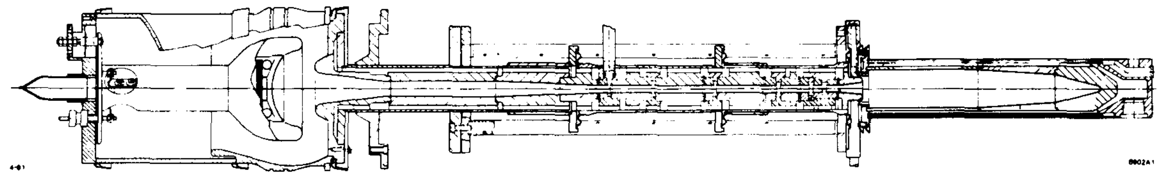

Figure 2.

peared to be perfect at all times, even with the tube operated into saturation. However, when the klystron was opened to replace a broken window and the beam tunnel was borescoped, a slight melting at the entrance of the beam tunnel and in the drift tube tips of the output cavity was observed. This was presumably due to pulse heating resulting from beam interception too small to detect by observing the difference between the cathode and collector currents.

Power output vs. beam voltage for the XC-2 is shown in Fig. 3. Note that during these tests the beam pulse width was fixed at 1 μs, while the RF drive pulse ranged from 800 ns at low levels to 100 ns at the maximum power of 72 MW. The benefits of the lower gap fields in the XC2 klystron are illustrated in Fig. 4, which compares the observed thresholds of RF breakdown as a function of pulse length for the XC1 and XC2.

The power of 72 MW, at the design voltage of 440 KV is to be compared with a value of more than 100 MW predicted by simulation. The code used allows radial motion in the beam but may not be providing sufficient detail in the simulation of electron motion due to the actual cavity fields. For the code to predict the low efficiency observed, a much smaller beam diameter must be postulated than is likely to be the case, given the damage observed at the cavity drift tube noses.

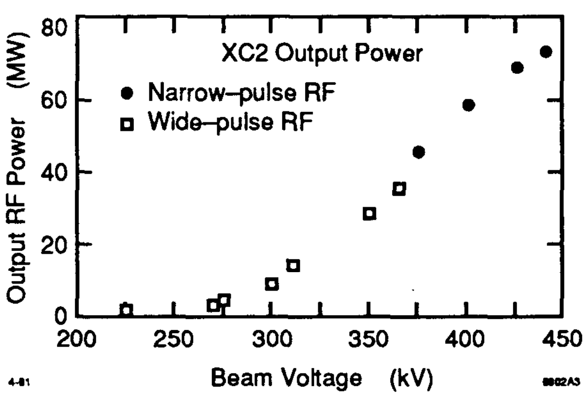

Figure 3.

The XC-2 klystron was used in a recent experiment to perform high power tests on a "binary" pulse compressor consisting of three stages, each of which combined the delayed leading half of an input RF pulse with the trailing half of the pulse. Delays were implemented by using overmoded low loss circular waveguides. The klystron was operated with an output of approximately 30 MW and 800 ns pulses, producing an input to the pulse compressor

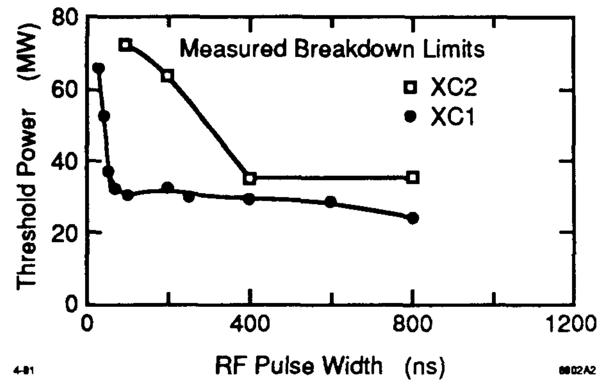

Figure 4.

of 25 MW. The result was compressed pulses of 120 MW with pulse lengths of 70 ns. The experiment is the subject of a separate paper in this conference.

IV. Future Directions at SLAC

It should be clear from the above that the design of 100 MW NLC klystron, especially one that can be produced in quantity, is a non-trivial problem. At SLAC the program for continued tube development is planned to address several issues.

The initial choice of a microperveance 1.8 beam was based on the successful SLAC S-Band work and the availability of ceramic seals and modulators for voltages below 450 KV. It now appears that for an adequate safety margin in a tube that must be produced in quantity, it would be prudent to use a lower perveance. A new test bed is being prepared which will permit operation up to 600 KV. In the meantime we plan to continue our work at 440 KV using new beam optics, without magnetic beam compression and with a total area convergence of 120, accomplished electrostatically. The purpose is to improve beam quality and to reach higher power levels without pulse breakup. During this phase of the program, klystrons will be constructed in which output circuits can be easily interchanged and a study of alternatives conducted efficiently. It is expected that standing-wave as well as traveling-wave extended interaction output circuits will be evaluated in this fashion. When the design of a new microperveance 1.2 gun and the higher voltage test bed are complete, the tube development program will continue at the lower perveance, using the same techniques of output circuit interchangability for evaluation.

In parallel with the main program of refining beam optics and selecting an optimum output circuit other klystron sub-components require development and production. Principal among those is the output window. The windows currently used in the XC series of klystrons are 1.1 inches in diameter and 0.15 in. thick. They are not expected to be adequate for full power tubes, but will be evaluated in an X-Band resonant ring now nearing completion. Meanwhile, larger windows are being designed. Consideration is also being given to TE_{01} windows, with a transition to this mode within the tube envelope.

The core of the problem is at the output. Before a successful 1 μs, 100 MW klystron is built, it will be essential to understand, in some detail, the interaction between the beam and the fields at the output circuit. A general description of this process is provided by simulation codes which, in the "large signal" regime, predict interaction efficiency with accuracies that are of the order of perhaps 10 percentage points, as indicated above. A byproduct of this calculation is also a beam interception calculation. For the NLC klystron it is critical to evaluate the tradeoffs between efficiency and beam interception with better accuracy. A moderate uncertainty in efficiency can be tolerated, but a few percentage points of interception will destroy the circuit.

Furthermore, means must be found to detect beam interception with considerably more sensitivity than is currently available through the isolated collector. If some melting of the output circuit can occur during a single pulse, there must be provision in the modulator to remove beam voltage on a pulse-to-pulse basis. This is essential both in the development phase of the klystron, in order to reduce tube losses, as well as in the operations phase of the collider.

Finally, it will be necessary to use "beam shavers" at several locations in the tube in order to control beam scalloping. These are slight constrictions in the drift tube diameter built of a refractory metal, such as molybdenum. Molybdenum may also serve to protect drift tube noses in the output circuit.

It is expected that the combination of lower perveance, improved output circuits and the other features described above should produce successful klystron prototypes during the next year. They will be used in a Test Accelerator at SLAC whose construction should begin in the 1993–94 period.

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