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RF POWER GENERATION FOR FUTURE LINEAR COLLIDERS*

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1. Introduction

The next linear collider will require 200 MW of RF power per meter of linac structure at relatively high frequency to produce an accelerating gradient of about 100 MV/m. The higher frequencies result in a higher breakdown threshold in the accelerating structure hence permit higher accelerating gradients per meter of linac. The lower frequencies have the advantage that high peak power RF sources can be realized. 11.42 GHz (four times the present SLAC operating frequency) appears to be a good compromise and the effort at the Stanford Linear Accelerator Center (SLAC) is being concentrated on RF sources operating at this frequency. The filling time of the accelerating structure for each RF feed is expected to be about 80 ns.

A relativistic klystron collaboration between SLAC, LBL and LLNL was successful in studying the problems of generating hundreds of megawatts of RF power at 11.4 GHz and driving a pair of high-gradient accelerator structures. The electron beam for the klystron was produced by a 1.2 MeV induction linac at LLNL. This klystron produced 330 MW of peak power with a pulse duration of 40 ns. An electron beam was accelerated with a gradient of 80 MeV per meter. This work is described in detail elsewhere.[1,2] While much was learned from the relativistic klystron project, the induction linac for generating a megavolt, kiloampere electron beam for each RF power source is very expensive, making this scheme a less promising candidate for a 1 TeV collider.

Under serious consideration at SLAC is a conventional klystron followed by a multistage RF pulse compression system, and the Crossed-Field Amplifier (CFA).

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2. Conventional Klystron with RF Pulse Compression

The present objective is to develop a conventional klystron that will produce at least 100 MW of RF power with a relatively long RF pulse duration; when used with a suitable RF pulse compression scheme it will produce several hundred megawatts with a pulse duration of about 100 ns.

An experimental klystron designed to operate at 11.42 GHz and deliver 100 MW with a RF pulse width of 800 ns has been built and tested. The cathode of this klystron is pulsed at 440 KV and has a microperveance of 1.74. The klystron has a single gap output cavity with two waveguide output ports (fig. 1).

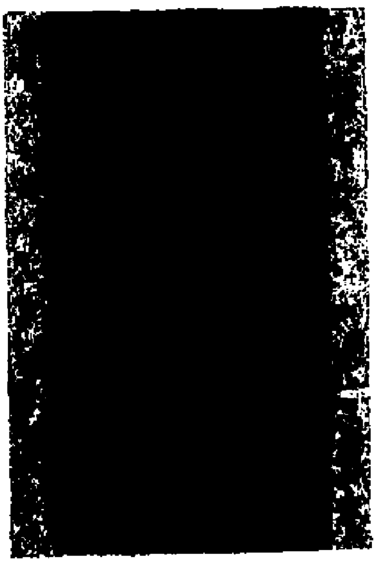


Figure 1: High-power X-Band klystron.

In a design such as this, many of the conventional tube technologies are being pushed to their limits. For example, the power density in the electron beam is in excess of 316 MW/cm^2 at a 1 μs pulse width and the peak RF voltage gradient in the output cavity exceeds 1 MV/cm. The beam compression ratio is 200 : 1. About one-half of the beam compression is obtained electrostatically in the gun and the remainder is accomplished with 6 kG converging focusing field. The focusing of the beam requires great care, or damage can easily be done to the tube. The RF output ceramic windows are highly stressed.

The initial period of testing resulted in a measured peak output power of 66 MW combined from both ports, with a pulse width of 30 ns (fig. 2). Attempts to lengthen that pulse width resulted in a lowering of the RF breakdown threshold in the output gap and an increased risk of damage due to beam interception especially in the region between the penultimate cavity and the entrance to the collector. The RF breakdown threshold was raised significantly with a few hundred hours of RF processing (fig. 2).

After this initial phase of testing, the klystron was used in two other tests that were critical parts of the collider RF source program. The first of these was

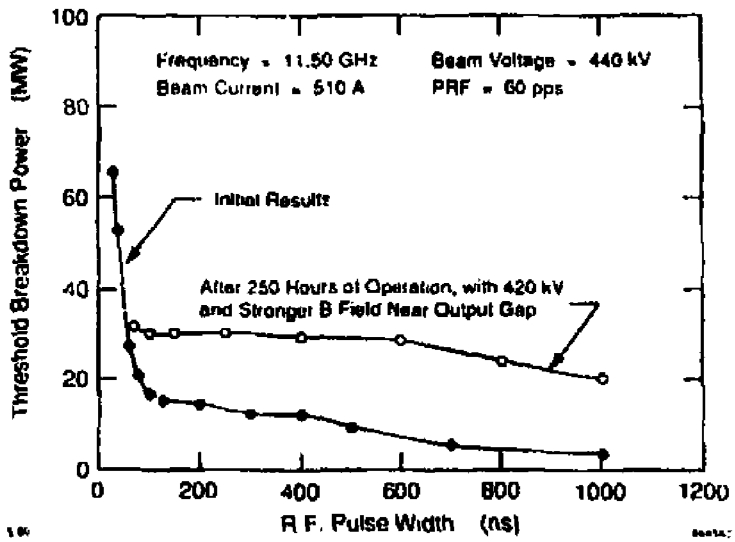


Figure 2: Effect of pulse width and processing on RF breakdown threshold.

a high-power test of the three-stage RF binary pulse compression system, and the second was a test of the first experimental CFA. In the latter test, a fraction of the klystron RF output was used as a 1 MW driver for the CFA.

At the full RF pulse width of 800 ns, 25 MW was available to use in testing a three-stage binary pulse compression system described later.[3] Testing of this system was temporarily suspended due to failure (puncture) of one of the klystron RF output windows. This necessitated replacement of the windows and cathode, which was at operating temperature at the time of failure.

During this repair, inspection with a boroscope revealed severe melting of both the drift tube near the output cavity and the nose tips in the output cavity. Cold testing revealed that the resonant frequency of the output cavity had also increased several hundred MHz due to the melting of the nose tips. Currently, the klystron is running at reduced power as an RF drive source for the CFA tests and later will be used for more RF pulse compression system testing. The damaged klystron successfully made about 10 MW of useful RF power available for these other test programs but it has not been operated at full beam voltage since being repaired.

The second version of this klystron is expected to ready for test in August. The major change will be a double gap output cavity that is expected to reduce the RF voltage gradients by about 40%.

It appears that the objective of 100 MW from a conventional klystron operating at this frequency remains feasible. Other changes that are being considered for future versions of this klystron are the following: (1) A higher current density cathode to reduce the amount of beam compression that is to be accomplished by the magnetic field, thus reducing the length of the tube and the size and cost of the focusing magnet; (2) a traveling-wave output circuit to further reduce the RF voltage gradient; and (3) dividing the RF output into parallel combinations of ceramic output windows.

3. Crossed-Field Amplifier

Magnetron oscillators have generated single-shot power of the order of gigawatts at nanosecond pulse widths, but phase coherent CFAs with multimegawatt outputs at X-Band are not common. CFAs have inherent characteristics of low beam impedance, compactness, high efficiency, and relatively low cost of manufacture; and as such, are good potential candidates for linear collider applications where large quantities of tubes are required. SLAC has therefore undertaken the development of a CFA to operate at 11.42 GHz. The first experimental tube was designed to operate at the backward wave space harmonic with a phase shift of 225°/section and with a cold platinum cathode. The design voltage and current are 140 kV and 1700 A, respectively. The objective is to produce an RF output power of 100 MW with a pulse width of 100 ns. RF pulse compression will not be used.

Preliminary results show that a peak power of 10 MW was generated at 95 KV, 415 A at 11.50 GHz, with a pulse width of about 50 ns. A photograph of the first experimental tube is shown in fig. 3.

One of the problems encountered was that the cathode current was considerably lower than expected. Multimode computer simulations of crossed-field interaction reveal that this may have been due to interference by the underlying fast wave forward-wave component which has a relatively strong electric field at the cathode. As the RF wave builds up along the circuit, this component of electric field can cause the energy of the back bombarding electrons to be so high that the secondary emmission coefficient of the platinum cathode falls below unity, thus limiting the current available. This has led us to look at another design which synchronizes with the backward-wave fundamental component instead of the backward-wave space harmonic and will have a phase shift of 150°/section. This new design will also have an RF circuit with a tapered impedance along it, so as to have a constant power generated per unit length. Such a waveguide-coupled circuit is shown in fig. 4.

Figure 3: Crossed-field amplifier.

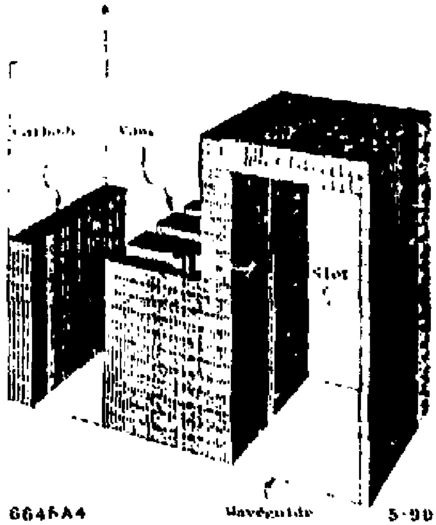


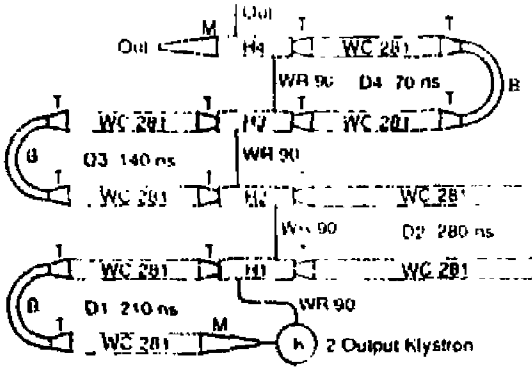
Figure 4: Simulation of waveguide coupled anode circuit.

It has the potential of producing hundreds of megawatts of peak power per tube by periodic coupling between the anode circuit and the waveguide. This can have the advantage that the RF voltage along the circuit can be held below a certain level and back-bombardment energy can be made relatively constant. Also, multiple output ports and output windows can be accommodated.

The existing experimental CFA is being modified to improve the high-voltage standoff capability and the vanes are being trimmed to better match the operating frequency with that of the klystron

4. Binary RF Pulse Compression

A three-stage, high-power binary RF pulse compressor has been tested at SLAC. In each stage of an ideal system, the RF pulse length is compressed by half and the peak power is doubled. This is accomplished in each stage by delaying the first half of the input RF pulse using low-loss TE_{01} delay lines. With appropriate phase keying, the first half of the pulse is added to the second half in a 3 dB hybrid. A schematic of the three-stage compression experiment with an output combining stage is shown in fig. 5. This technique is described in more detail elsewhere.[3,4] In practice, the peak power multiplication is approximately 1.8 per stage due to the losses in the various components. The overall peak power gain and efficiency of the



H	3 dB Hybrid Directional Coupler H1 is Stage 1 etc
T	Taper Between Two Diameters of Circular Waveguides
D	Delay Line Using WC281 Waveguide
WC281	Length of 2.81 in. I.D. Circular TE^{01} Low loss Circular Waveguide
B	180° Bend
WR90	Short Length of Rectangular Waveguide
M	Mode Coupler from Rectangular to Circular Waveguide

Figure 5: Three-stage, single klystron RF pulse compression schematic.

binary pulse compression system at SLAC are 5.5 and 68%, respectively. The final compressed RF pulse is about 70 ns in duration, making this technique applicable to feeding high-gradient accelerator sections with short filling times.

The high-power test of this binary pulse compression system was temporarily halted due to the klystron window failure described earlier. Prior to this event, approximately 10 MW from each of the two output waveguides of the klystron was used to feed the two input ports of the first pulse compression stage. There were some problems that limited the success of these first high-power tests. These were: unbalanced and mismatched input lines, incomplete signal monitoring and a missing mode transducer and high power termination on the output stage combiner. The highest-measured compressed output pulse with these limitations was 37 MW. With all of the high-power components now in place and with complete diagnostics for tuning, we expect 10 MW, 800 ns pulses at each input to produce 55 MW compressed pulses at each Stage 3 output, and 98 MW with these two outputs combined.

Tests were resumed using a 1 KW traveling wave tube amplifier as a driver as a substitute for the klystron being repaired. The final missing components were installed and the signal monitoring system was completed. The test results now compare very closely with those predicted from the individual component losses which were measured on a network analyzer before the system was assembled.

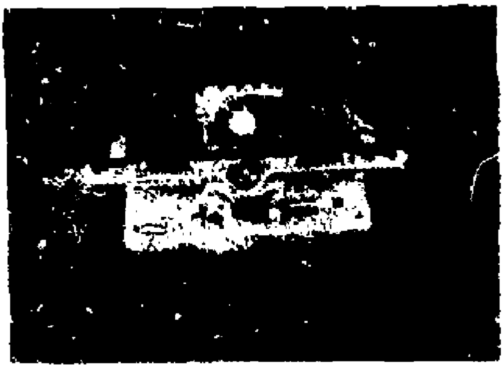


Figure 6: High-power phase shifter.

Figure 7: High-power X-Band window.

When two X-Band klystrons become available, the binary pulse compressor will be reconfigured to utilize both of these high-power sources. If each klystron produces 100 MW with a pulse duration of 800 ns, we expect 550 MW, 100 ns compressed pulses at each Stage 3 output, and 980 MW after combining to a single output. These goals are, of course, limited by peak power handling capability of the pulse compression system. The high-power testing of the binary RF pulse compression system will resume after the initial testing of the second 100 MW klystron in August 1990.

5. High-Power X-Band Component Development

High peak power X-Band waveguide components with clean, high-vacuum properties are not generally available commercially. Several high-power components have been designed and built at SLAC that have been used sucessfully in the RF source development program. Among them are broadband sidewall directional couplers, magic tees, RF ceramic windows, phase shifters, tuners and loads. These components are made with the same vacuum standards that are used in high-power microwave tube fabrication. Some of these components are shown in figs. 6 and 7. The objective for all of these devices is to handle peak RF power in the hundreds of megawatts. The most critical of these devices is the RF ceramic window. There is very little operating experience with X-Band windows above a few megawatts.

A traveling wave resonant ring has been designed and is nearing completion: it will be used to test RF windows, waveguide components and two-port output structures at significantly higher peak RF power levels than they will be expected to operate. This test vehicle will have a peak power gain of 12 dB and will use one of the X-Band klystrons as a source. Residual mismatches in the high power ring and in the device under test will be tuned out using a five element tuner that has movable diaphrams in the narrow wall of the tuner waveguide. The ring will be precisely tuned to the desired resonant frequency using a high-power squeeze type phase shifter designed and built for this purpose. The waveguide components are made of copper and stainless steel and are designed to operate with a vacuum in the 10^{-9} Torr range. The components in the high-power portion of the resonator are water-cooled.

6. Conclusions

The TeV collider RF source development effort at SLAC is being concentrated on both the high-power conventional klystron followed by some form of RF pulse compression (not necessarily three-stage binary described here) and the CFA. The relativistic klystron provided an excellent experimental source for initial high-gradient accelerator experiments. The induction linac required to make high current relativistic beams for these klystrons appears at present to be too expensive for use in a high pulse rate mode. The 100 MW conventional klystron is promising but requires stable operation at 800 ns with pulse compression to 100 ns. This has yet to be demonstrated. Problems with RF voltage breakdown in cavity gaps, ceramic windows and pulse compression waveguide components must be solved. The CFA development is not as far along as the klystron and will be a serious collider RF source candidate only if stable operation can be achieved above 200 MW. If one of these two approaches emerges as the more feasible, the focus of further effort will be toward producing that source at low cost.

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