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HIGH POWER RF WINDOW AND WAVEGUIDE COMPONENT DEVELOPMENT AND TESTING ABOVE 100 MW AT X-BAND

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Introduction

SLAC is committed to developing an X-band source capable of producing 100-MW, 1-μs pulses to power the next linear collider [3]. The first experience encountered at SLAC in the X-band regime above a few megawatts was in the relativistic klystron program in cooperation with LLNL and LBL [2]. About 280 MW had been transmitted through a variety of waveguide components but at very short pulse widths (~40 ns) and very low pulse-repetition rates. The likelihood of high peak-power rf breakdown in most X-band components and especially rf windows increases as the rf pulse length becomes longer. Testing components at peak power levels above that at which they are expected to reliably perform is essential in a development program.

Traveling Wave Resonator

A traveling wave resonator (TWR) is well suited to high-power test the critical components where a very high power source has not yet been developed but a moderately high power source is available. The SLAC X-Band TWR [1] was first run at high power in June 1991. The parameters are shown in Table 1. The rf power source for the TWR is one of the early XC series klystrons that were part of the 100 MW klystron development program.

There were problems in pushing the peak power-handling capability of the TWR to the 300 MW level that are described below. This TWR was designed with no specific upper peak power-handling capability in mind, but it had to be well above 100 MW. Its upper limit was expected to be determined by rf breakdown in one of the components in the resonant loop rather than by the rf source. The 300 MW level was achieved with a dummy section of waveguide in the component test piece position (see Fig. 2). Each component in the resonant loop was designed for ultra-high vacuum. An emphasis was placed on minimizing the likelihood of rf electric field breakdown and on bandwidth. Bandwidth is important in all loop components so that operation is not confined to too narrow a frequency range.

Initially, intermittent rf electric field breakdown was experienced, but not exactly where it was expected to occur. It had been incorrectly assumed that the peak power-handling capability of the TWR would be limited by breakdown in one of the tunable components—probably the variable phase shifter. As it turned out, the first breakdown was observed in the high-vacuum crush-seal rf waveguide flanges that had previously worked well in the relativistic klystron program at nearly 300 MW but for rf pulses that were only about 40 nanoseconds in length. In the original flange version, the vacuum seal is made early in the bolt tightening process. The "rf seal" was not good, resulting in a gap along the perimeter of the inner waveguide surface. The gap interrupted longitudinal rf current and exposed the gasket and flange corners to high-rf electric fields, resulting in breakdown above about 60 MW, sometimes lower.

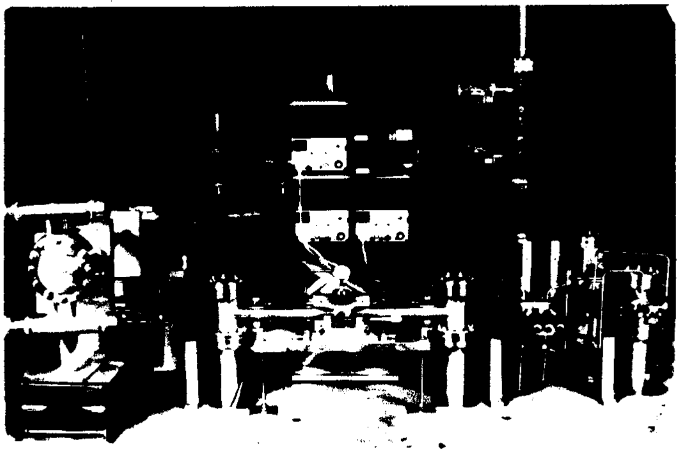

Figure 1. X-band Traveling Wave Resonator

Table 1. TWR Parameters

Highest TWR Power to Date	300 MW, 800 ns, 60 pps
Available Source Power	30 MW
Resonant Loop Length	340 cm
Number of Wavelengths	106 at 11.424 GHz
Input Coupler Ratio	10.1 dB
Separation Between Resonances	71.5 MHz
High Power Gain	10.6 dB
One-way Loss in Loop	0.354 dB
Variable Phase Shifter Range	±30° (±6 MHz)
6 Element Tuner Range	$\Gamma \leq 0.10$ @ any f
Loaded Q	5500
RF Voltage Time Constant	153 ns
Coupling Coefficient, β	1.23

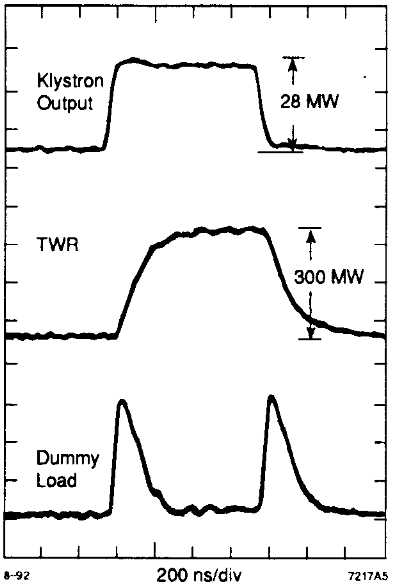

Figure 2. TWR Waveforms

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The solution to this rf-flange breakdown problem was to change the copper gasket cross section to one with a 0.25 to 0.40 mm ridge along the perimeter of the rf sealing edge. The ridge is only needed on the side of the copper gasket facing the female flange. The rf seal, with this fix, is made earlier in the bolt-tightening process than is the vacuum seal. Slots are machined at the midpoint of the ridge along each narrow wall to serve as a pumpout for the trapped space on the vacuum side of the copper/stainless steel seal. A redesign of the stainless steel flange sealing surface might have been preferable if not for the hundreds of flanges on components already in use and the subsequent mating problem.

Tuning Capability. Most traveling-wave resonators use as a tuning device, a variable phase shifter consisting of a pair of moveable multistage choke shorts with a 3 dB hybrid coupler. This type of phase shifter at X-band could be vulnerable to rf breakdown at peak power levels above a few MW. It was decided that a full 360° tuning range was not absolutely necessary; a precision-variable "squeeze-type" phase shifter with limited tuning range would have a better chance of withstanding rf breakdown. This variable phase shifter is used as a trimmer to keep the loop tuned to resonance and has a tuning range of ±30°. The components tested thus far have had sufficient bandwidth so that the operating frequency that is selected for high-power testing coincides with one of the natural resonant frequencies of the TWR (with the variable phase shifter set near mid-range). These natural resonant frequencies are about 71.5 MHz apart. The TWR can be kept on resonance by varying the drive frequency to the klystron but this scheme does not work well when there is a significant line length effect between any mismatches and the correction tuners described below.

A well-known property of high Q TWRs is the extreme sensitivity to relatively small reflections in the resonant loop portion of the circuit. For example, a discrete voltage reflection coefficient $\Gamma=0.05$ results in a reduction of power gain of 40% and a VSWR mismatch to the klystron driving the TWR of 3:1. The resonance curve becomes double peaked when the effective mismatch exceeds a critical value depending on the loss and the coupling [4]. A small mismatch also results in the growth of an undesirable backward wave, much larger than Γ, that also double peaks above a different critical value of Γ and at a different pair of frequencies. The critical values of $|\Gamma|$ for this TWR are 0.043 and 0.088 for the forward and backward waves, respectively. It is desirable to precisely tune out any residual mismatches, whether they be attributable to a permanent part of the TWR loop or to the device under test.

The tuner used is a six-element section that can easily match out any combination of reflections where the aggregate reflection is 0.10 or less at any phase angle. Three corrugated, copper-plated, stainless steel diaphragms, separated 3/8 λ_g from each other, are located on each broadwall. The opposite two rows of diaphragms on the broadwalls are displaced 1/8 λ_g from one another. The tuning range may actually be greater but it would place some additional risk to the 0.05-mm-thick diaphragms to stretch them further. It was experimentally verified that any admittance in the complex plane could be produced by the six-element tuner in front of a dummy load where the VSWR ≤ 1.22. This tuner replaced an earlier design using five smaller-diameter tuners in the narrow walls that did not have adequate tuning range to cover all mismatch possibilities.

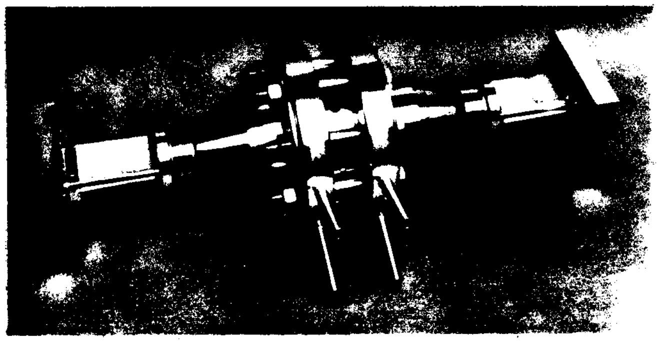

Figure 3. 47 mm diameter overmoded window.

RF Windows

The thin 27-mm-diameter pillbox window reported in Ref. [1] is no longer used for high power. A low-power version is still used on the secondary arms of directional couplers. The thick 27-mm-diameter window continues to be used as the output window on klystrons. The 47-mm-diameter thick (3.7 mm) window [1] had problems with mode conversion and was redesigned with a more gradual taper. Its excessive length has reduced its attractiveness for use on the klystron output. Inconsistent results have been obtained thus far on high-power tests on the TWR. Mode conversion may still be a problem and further optimization of the taper may be required. The overmoded window is shown in Fig. 3.

The quality of the braze fillet at the edge of the window is especially critical at higher frequencies since braze imperfections do not tend to scale with window size. Circular windows operating in the TE_{01} mode are attractive candidates for this reason. A half-wave TE_{01} circular window sandwiched between two compact TE_{01}/TE_{10} mode converters is going to be tested on the TWR. The success of this window depends largely on the mode-conversion efficiency and peak power-handling capability of the mode converters which must be TWR tested first. Also being tested are TE_{11} windows that have rf corona rings to hide the braze fillets.

Ghost mode resonances are an ever-present threat when thick windows are used. Table 2 shows the calculated trapped resonances for the 27-mm-diameter by 3.7-mm-thick pillbox window that is presently used. For narrow-band operation, dimensions are chosen so that the closest ghost-mode resonance is at least 2% away from the operating frequency.

Table 2.

Mode Name		Calculated Frequency	Measured Frequency
TE_{02}	even	10.56 GHz	10.66 GHz
TM_{11}	even	10.85	10.77
TE_{61}	even	11.11	not observed
TE_{32}	even	11.68	not observed
TE_{13}	even	12.27	not observed
TE_{71}	even	12.31	not observed
TM_{21}	even	12.36	not observed

Window Coating. Alumina ceramic high-power rf windows must be coated with a thin film of anti-multipactor coating to supress excessive secondary electron emission. Titanium coatings have been used since 1965 to decrease multipactor on alumina ceramic and various metal surfaces. Since 1980, titanium nitride has been used by SLAC as the preferred coating. Titanium nitride window coatings for X-band applications are reactively sputtered in an ultra-high vacuum DC sputtering system. Coating thickness is estimated by Rutherford backscattering measurements of the titanium surface coverage. A window coated too lightly exhibits excessive multipactor heating and arcing, while a window coated too heavily has excessive losses in the thin film. Both cases lead to window failure.

Window Testing. A series of 11.4 GHz klystron windows have been tested in the X-band TWR to optimize TiN coating thickness. Window testing is accomplished by installing them in the 32-cm test section of the TWR and slowly increasing rf power while maintaining 10^{-9} Torr scale vacuum. Windows under test have been viewed through sapphire viewports on both input and output window faces. A television camera has also been used to record light produced by multipactor and by arcing. Coating thicknesses of ~18–20 Å (13.5 min sputtering time) have been found to produce the best results so far. Patience in processing up is essential. Tests are continuing as operating time allows. Result are shown in Table 3.

Table 3.

Type	Coating Time	Max. P	Notes
27 mm	9.0 min.	35 MW	
27	10.5	25	
27	12.0	40	
27	13.5	89	arcing @ 80MW
27	15.0	40	
47	13.5	100	failed lower @ 20MW
27	15.0	44	
27	13.5	57	stopped prior to failure
27	13.0	67	stopped prior to failure

Two windowtrons have also been tested (Fig. 4). The windowtron is two windows in series where the waveguide volume between windows can be baked to 550 °C and subsequently sealed off at 10^{-10} Torr vacuum levels. In this manner, each window is similar to a sealed-off klystron window, where one side is not re-exposed to air prior to operation. An uncooled version ran to 55 MW with no damage and a cooled version ran to 85 MW where the input-side window failed. Initial results of TWR window and windowtron tests are encouraging, where continued operation above 50 MW was possible in many cases.

Other Components

The so-called "grapefruit" rf load in Fig. 5 is now used in most high-power applications. It is compact, has good bandwidth, and has been high-power tested to about 32 MW peak power and 3.8 KW average power. The design reported earlier [1] has been upgraded to allow baking with a klystron to 550°C. Its ultimate power-handling capability is not known but it is expected to be able to handle at least 50 MW peak with a pulse width of 1 μs at 120 pps.

The basic design of the directional couplers has not been changed from that reported previously [1], except for a change made on the secondary arms of the 56 dB sidewall directional couplers. A short, squeezable matching section has been added to each secondary-arm, low-power window. This allows the windows to be fine-tuned for a perfect match at the center frequency before the final braze onto the directional coupler. The match of the secondary arm windows has been the limiting factor in the overall coupler directivity in the past.

Magic tees continue to be used as power splitters and combiners. When the four-port tees are used as splitters the fourth port (E arm) is usually shorted rather than terminated because of space limitations and the limited number of available high power loads.

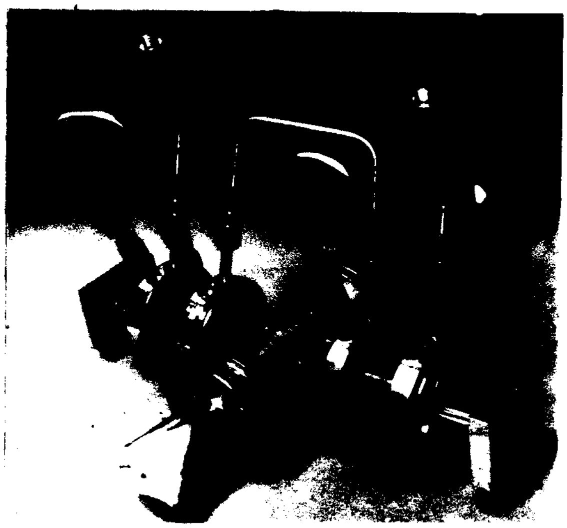

Figure 4. Water-cooled windowtron

Figure 5. 50 MW Grapefruit load bakeable to 550°C

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