

Component Development for X-Band Above 100 MW*

W. R. Fowkes, R. S. Callin, and M. Studzinski

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 USA

I. Introduction

The requirement for some of the components described in this paper began with the Relativistic Klystron program done in collaboration with LLNL and LBL. This effort culminated in a klystron operating at 11.4 GHz delivering 330 MW into a pair of high-gradient accelerating structures [1]. The electron beam for this klystron was formed in a 1 MeV induction linac at a very low duty cycle. The subsequent RF source development work at SLAC for the Next Linear Collider utilized some of these components, and required further and new development of others, to work reliably at higher average power [2].

2. RF Windows

Perhaps the most critical component is the high-power RF window. The first window used at high power was a standard "pillbox" design that is broad-band and requires no additional matching elements, other than that provided by the symmetrically located steps from rectangular to circular waveguide at each end of the circular pillbox. The 27-mm diameter alumina ceramic in the X-band version of this window is very thin physically (about 0.8 mm), and is therefore fragile and difficult to braze. This thin window had several drawbacks. The braze of the metallized edge to the copper sleeve was not always successful. Those that survived the initial brazing operations would sometime fail later during the crush-seal flange tightening process, or in bake. The performance of the thin-window high-peak power was usually satisfactory for very short RF pulses, but puncturing and fractures occurred above 25 MW at pulse widths in the 100 to 800 nsec range.

A thicker ceramic design, and perhaps one with a larger diameter as well, appeared to be necessary. Half-wave windows are narrow-band by themselves, but can be broad-banded using various techniques [3]. Trapped ghost-mode resonances are always of concern with a thick ceramic. Special care must be taken—by choosing a suitable combination of diameter, thickness, and dielectric constant—so that these trapped resonant frequencies are not located near the operating frequency.

An alumina window with an electrical thickness of $0.43 \lambda'_g$ and the same diameter, but lower RF electric field for a given power, as in the thin window described above, was chosen and is shown in Fig. 1. This design uses two symmetrically located inductive elements, in addition to the pillbox transitions, to accomplish the broad-band response where the VSWR ≤ 1.50 over 10% and ≤ 1.10 over 5% bandwidth. The dimensions were chosen primarily to avoid ghost-mode resonances, but the electrical thickness was also chosen based on earlier experience of others in broad-banding thick windows that were not exactly $\lambda'_g/2$. The design optimization was done using a model based on cascading equivalent circuit elements and transmission line sections. The ghost-mode problem is not taken into account in the model, and is determined in a separate calculation.

At this writing we have had no failures of this 3.7-mm thick, 27-mm diameter window; but it is felt that as we push higher in peak power, the surface electric fields stresses at some point will be too great and breakdown will occur. A larger, 47-mm diameter window has been designed that has a frequency response similar to that of the

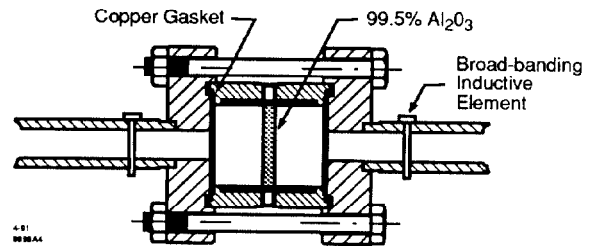


Figure 1. Thick (3.7 mm) pillbox window with broad-banding elements.

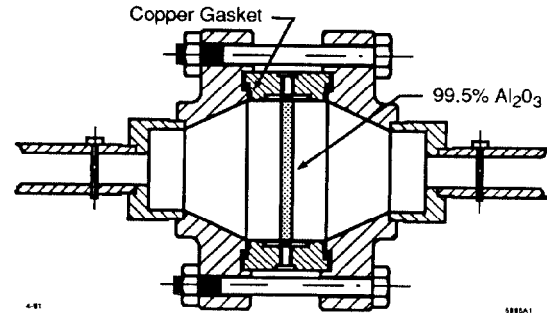


Figure 2. Large diameter ($2a = 47$ mm) window.

27-mm diameter window. It employs similar broad-banding techniques and uses circular 26° tapered sections to the larger diameter. However, the 47-mm diameter portion of the waveguide can support a total of five modes outside the dielectric, which may cause problems. This latest design, shown in Fig. 2, has not yet been tested.

3. Couplers, Magic Tees, and High-Power Loads

It was felt that cross guide, directional couplers of the Moreno type would be more susceptible to electric field breakdown than some of the sidewall designs. For measuring high-peak power, a broad-band sidewall coupler was designed, using an array of five circular holes, with RF voltage coupling factors based on binomial coefficients. The nominal coupling ratio of this design is 56 dB, and the directivity is typically 35 to 40 dB. The match of the RF windows used on the secondary arms determine the overall directivity. For special applications where a high directivity, broad-band coupler with much tighter coupling is required it was necessary to go to a much longer sidewall design. A 10 dB design uses an array of 31 holes with RF voltage coupling factors, based on Tchebycheff coefficients [4]. This design was used as the input bridge coupler for the Travelling Wave Resonator (TWR) described later.

A conventional magic tee was designed to be used either as a power splitter or power combiner. A single-ended inductive post (2.54-mm diameter, with a spherical end) placed in the throat of the junction provides broad-band matching for the H-arm. An inductive post also provides the matching for the E-arm, but over a much narrower bandwidth. When used as a power splitter, the unused E-arm is usually shorted. The corners in the junction that are exposed to high-RF electric fields have a ~ 1 mm radius. No RF breakdown has been experienced in these devices.

The first high-power load to be put into operation was a $0.75 \lambda'_g$ alumina ceramic disk 85 mm in diameter separating a water chamber from the waveguide vacuum. Extra care (unnecessary as it turned out) was taken to avoid overmoding by tapering from 27 to 85 mm in diameter over an electrical distance of about 16 wavelengths. This load worked very well over a very narrow band but had to be retuned to operate at frequencies only 1 or 2% away from the center frequency.

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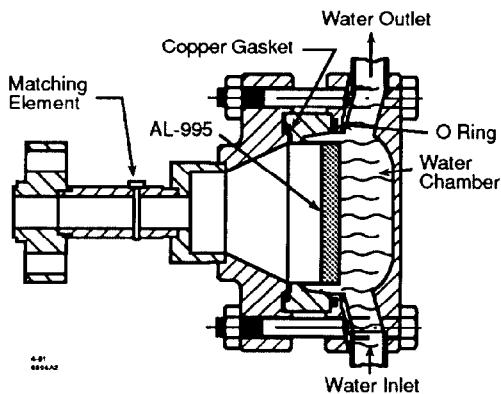


Figure 3. A 50 MW X-band ceramic/water load.

The narrow bandwidth was due to the line length effect between the ceramic/water mismatch ($VSWR \sim 3$) and corrective matching located some 16 wavelengths away in the WR 90 rectangular waveguide portion to avoid the possibility of mode conversion.

The solution to the narrow bandwidth problem appeared at first to be a long, tapered, lossy metal, water cooled load that required no matching elements. Such a load was designed and built using type 430 stainless steel. The cross-sectional a and b dimensions were tapered through cutoff over approximately 2 meters so that the power lost per unit length and the maximum RF electric field were approximately constant throughout its length. The match over a broad-band of this tapered load was good but it had several drawbacks. The pumping speed of the small cross-section required that several ion pumps be distributed along the length of the load. The original design construction had the four tapered sides welded rather than brazed together. There were likely some unwanted gaps at the corners, possibly trapping contaminants at high current joints, resulting in excessive gassing and some RF breakdown.

Tapering through cutoff has some disadvantages. The RF electric field, constant along most of the load by design, rises at the region near cutoff as the impedance becomes infinite and then imaginary moving through cutoff. If we were to improve on this design we would have the cross-sectional dimensions stop short of cutoff at the tip and still maintain approximately constant dP/dz and maximum electric field along its length. All joints conducting RF current would be brazed rather than welded.

The most promising high-power RF load design appears to be a much more compact version of the quarter wave ceramic/water load. This load is sufficiently broad-band ($VSWR \leq 1.50$ over 7% and ≤ 1.10 over 2.6%) and is shown in Fig. 3. A $0.75 \lambda_g$ thick alumina disk, 47 mm in diameter separates water from vacuum in the same manner as the longer, larger, narrow band version described earlier. The ultimate energy/pulse capability is about one third that of the larger, narrow-band version but the very broad-band feature makes it more attractive overall. Two of these loads connected to a power splitter will be used for future 100 MW klystron experiments. A single unit will be used as the dummy load for the Travelling Wave Resonator described later.

4. RF Crush-Seal Flanges and Waveguide Pumpouts

Crush-seal flanges, both rectangular and circular, have been developed to operate at peak power levels in excess of 100 MW. The inner surfaces have been copper plated where RF losses are of great concern, such as in the TWR resonant Loop. These flanges must be mass-spectrometer leak-tight to a helium sensitivity of 2×10^{-10} standard atm cc/sec helium, and must be bakeable to 550°C for time periods exceeding one week. Annealed OFE copper gaskets are used for the sealing media. A unique solution has been applied to avoid diffusion bonding of the copper gaskets to stainless surfaces during bake cycles.

The copper gaskets are coated with a $\sim 50 \text{ \AA}$ layer of titanium nitride (TiN) by reactive sputtering. This hard TiN coating does not bond to the stainless surfaces under bakeout, which makes for easy disassembly of the flange after bakeout. These flange designs are similar to earlier seal designs developed at SLAC in the early 1960's by Merdianian. They are relatively insensitive to small imperfections in the copper gasket surfaces, and to edge rollover due to annealing of stainless steel by grazing. The copper gaskets are easily punched from sheet, and are always annealed before use.

A serious problem with X-Band waveguide is its poor vacuum conductance. A meter of waveguide has a conductance of less than 0.7 l/sec. It was necessary to place small ion pumps (8 l/sec) relatively close together—approximately one every 3 meters of waveguide—to maintain pressures low enough to avoid RF breakdown in the waveguide when operating at high-peak power. In order to maximize the pumping speed in this size waveguide, a pumpout was constructed using a 1.5-in OD tubulation, slotted on two sides, so as to envelope a 15-cm section of waveguide containing a total of 264 pumpout holes, each 1.3 mm in diameter. The size of these pumping holes was a tradeoff between adequate RF rejection at 11.4 GHz and pumping speed. The effective net conductance of the entire pumpout structure is about 7 l/sec, and the measured RF loss is equivalent to about 30 cm of WR 90 copper waveguide.

5. High Power Traveling Wave Resonant Ring Utilizing Variable Tuners and Phase Shifter

The RF electric field breakdown limit on conventional X-band components is not usually known. Our experience with high-vacuum waveguide RF seals, RF windows, directional couplers, and ceramic/water loads has been in the relativistic klystron program, where the RF pulse width was only 50 nanoseconds and the pulse repetition rate was 1 or 2 pps. The breakdown limit on most of the components developed thus far had not been reached under those conditions. Traveling Wave Resonators (TWR's) have been used primarily to test RF windows, but also to test other low loss components at power levels higher than RF sources are capable of producing. An S-band TWR has been in operation at SLAC since 1962 to test RF windows power levels as high as 200 MW.

A TWR designed to operate at 11.424 GHz has been built to test windows and other components at peak RF power levels in the 100 to 300 MW range. At this writing this TWR is under vacuum and awaiting one of the 100 MW klystrons which will be used as the driving source [5]. The TWR has been thoroughly tested at cold-test power levels, and is shown in Fig. 4. The specifications for this TWR are shown in Table 1.

Operation at a precise frequency may be desired at times. The high-power waveguide resonant loop incorporates a squeeze-type phase shifter that is used to make minor corrections in the TWR resonant frequency because of temperature changes. Gross changes in resonant frequency must be made by replacing a pair of short waveguide spool pieces with another set of a slightly different length, based on calculation. Test pieces of a different electrical length will require a similar change. The squeeze-type phase shifter has 46-cm long slots centered in the broadwalls of the copper WR 90 waveguide, with vacuum pumping on both sides of each slot. The slot vacuum chambers are designed with dimensions so that they are anti-resonant to unwanted RF coupled through the slots. There is a micrometer control of the cutoff wavelength and resulting phase shift over a range of $\pm 30^\circ$, which corresponds to a TWR resonant frequency change of $\pm 6 \text{ MHz}$. All of the waveguide parts in the high-power loop portion of the TWR are water cooled, to dissipate heat and for temperature stability. There are no plans at this stage to use a feedback control system for temperature stabilization.

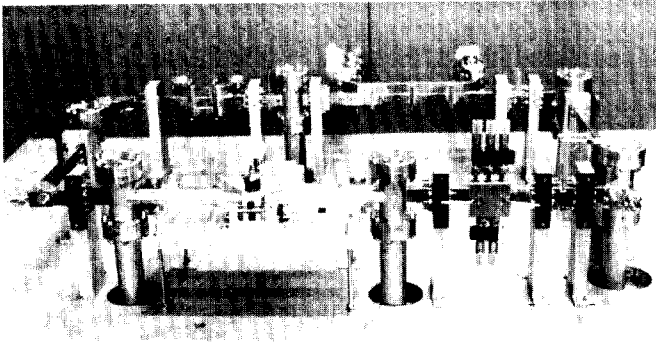


Figure 4. Tunable traveling-wave resonator.

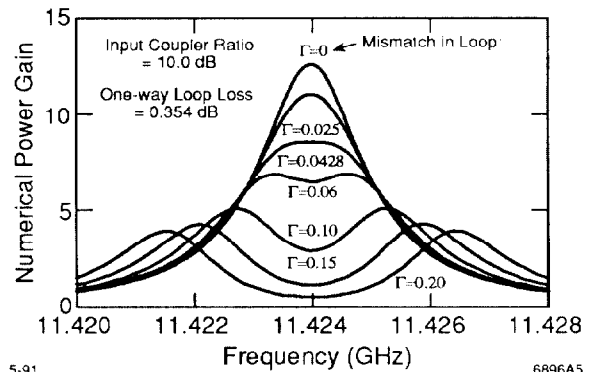
Table 1. TWR Parameters

Expected TWR power	100 to 300 MW
Source power	10 to 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
Measured cold gain	11.0 dB
One-way loss in loop	0.354 dB
Variable phase-shifter range	$\pm 30^\circ$ (± 6 MHz)
Six-element tuner range	$\Gamma \leq 0.05$ any phase
Loaded Q	5500
Voltage time constant	$0.153 \mu\text{sec}$
Resonance coupling coefficient β	1.23

The extremely critical residual mismatch problem afflicting TWR's is handled by a variable tuner section, with six movable diaphragms in the broadwall. This device will be used to tune out residual mismatches up to an aggregate $|\Gamma|$ of about 0.05 in the resonant loop. Even a small mismatch can cause a serious deterioration in the overall gain of a TWR, as well as cause the buildup of a backward wave, resulting in a much larger mismatch at the input to the TWR as seen by the klystron driver. For example, in this TWR a net voltage reflection coefficient of 0.05 in the ring results in a reduction in power gain of about 40%, and an input reflection coefficient seen by of the klystron of nearly 0.50 (VSWR of 3:1). The resonance curve of the forward wave for the loss and coupling parameters of this TWR becomes double-peaked, for an aggregate residual reflection greater than $|\Gamma| = 0.0428$. Figures 5 and 6 show the theoretical effect that residual mismatches have on the power gain and the input reflection coefficient, as functions of frequency. It is interesting to note that the backward wave resonance does not become double peaked until the loop mismatch exceeds $|\Gamma| = 0.088$, where both it and the input reflection become double-peaked [6].

The maximum-peak power of the TWR will probably be limited by the device under test, which will usually be an RF window. The other critical component in the TWR will be the phase shifter. Should it happen that the breakdown threshold of the phase shifter is lower than that of the device under test, the phase shifter will be replaced by a straight section of waveguide, and the ring kept on resonance by adjusting the frequency of the source driving the klystron.

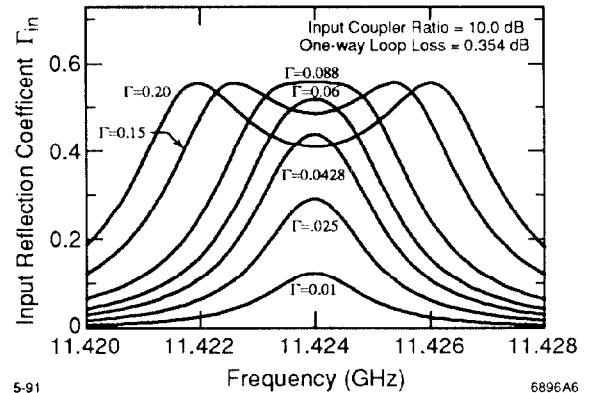
There are viewports on each bend that are used to observe activity on the window under test, and to help determine if there is any RF breakdown occurring in the phase shifter, tuners, or couplers. The entire ring is made of copper, with stainless steel crush-seal RF flanges that have copper plated RF conducting surfaces. Six ion pumps are distributed around the resonant loop, and another six ion pumps are used on the lower-power waveguide feed lines.



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Figure 5. Effect of loop mismatch on TWR gain.



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Figure 6. Effect of loop mismatch on input mismatch seen by klystron.

6. Conclusions

At this writing the variable phase shifter and tuners for the TWR and the compact version of the 0.75 wavelength ceramic water load have not been high-power tested. The cold-test measurements on all these devices agree with theory, but their peak-power handling capability remains to be demonstrated. The theoretical design of the 47-mm diameter, thick RF-output window has not yet been satisfactorily confirmed. The 27-mm diameter thick window has performed well, but has not yet been pushed to the high-peak and average power levels, where it is expected to perform reliably. The TWR is expected to be a useful tool to determine the RF breakdown threshold of these—and perhaps other—transmission devices that have low loss and short filling times.

References

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