CALABAZAS CREEK RESEARCH, INC.

Final Report for Phase I Program DE-FG02-07ER84911

Fundamental Power Coupler for ILC

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Project Summary:

The current designs of fundamental power couplers for the International Linear Collider (ILC) are expensive and require excessively long conditioning times. The goal of this program was development of a new technology for power couplers. This technology is based on the cylindrical TE01 mode and other over-moded technologies developed for the X-band rf distribution system of the NCLTA. During the Phase I program, a TE10 to TE01 mode transducer suitable for use as a part of a power coupler in the ILC was designed and tested at low power.

I. Introduction

The present design of fundamental power couplers for the superconducting cavities of the International Linear Collider (ILC) requires an elaborate two-window solution for optimum protection of the cavity. Damage can occur to the cavity during mounting in the cryomodule and from window fracture during linac operation. The coaxial couplers consist of a “cold section,” which is mounted on the cavity in the clean room and closed by a ceramic window, and a “warm section,” which contains the transition from the coaxial line to the waveguide. This section is evacuated and sealed against the air filled waveguide (WR650) by a second ceramic window. A diagram of the coupler is shown in Figure 1.

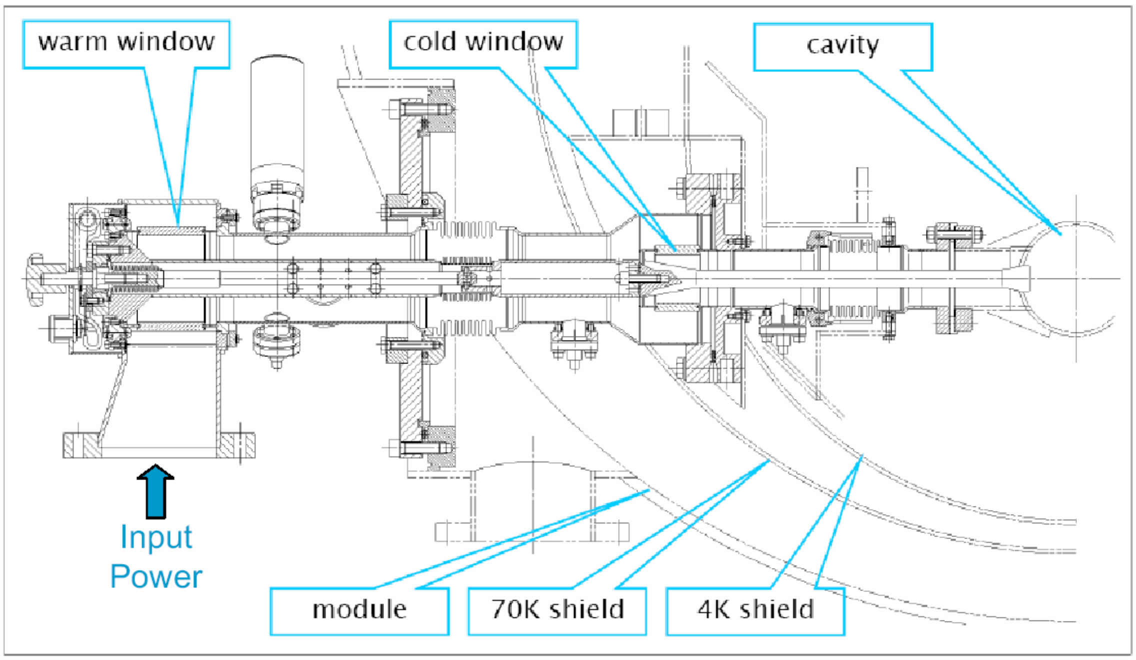

Figure 1 Schematic of the TTF-3 power coupler proposed for use in the ILC. The input power is supplied in a TE10 rectangular mode. This mode is converted to a coax TEM mode for coupling to the high Q superconducting cavity. Matching to the cavity is provided by length adjustment of the coax line.

Power couplers have been limiting elements of superconducting cavities in the past. The first series of TESLA high power input couplers have limited the power capability for the one module assembled for the TESLA test facility (TTF) linac. After a few months at lower power levels (corresponding to 15 MV/m) in the machine, the power could not be raised without new conditioning of the couplers. The major change in newer couplers recently tested was to implement a bias voltage between inner and outer conductor to suppress multipacting. The current couplers are a 3rd generation design, and several dozen were built by Saclay. Extensive testing of the latest generation coupler (TTF-3) was performed at 20-25 MV/m but there has been limited testing at 35 MV/m. The performance was rated acceptable, but RF processing is considered to be too slow (approximately 100 hr, limited by outgassing; also requires approximately 20-50 hours of in-situ processing) and costs too high. At the present processing time and cost, the 21,000 couplers required for the ILC would require many years for delivery and cost in excess of $630 million. The goals of the ILC program are to reduce the processing time to less than 20 hours with a 60% reduction in current costs. Achieving these goals with the current coupler design approach may prove to be unobtainable. Alternate design approaches are being studied.

The TTF-3 coupler is a complex, adjustable coupler with a large number of individual assemblies. Production will likely reduce the cost but not to the level desired for the ILC. The couplers are tuned by changing the coax waveguide length, requiring bellows that are a potential source of multipactoring. The windows are also another source of multipactoring.A less expensive alternative would be a fixed coupler with an external 3-stub tuner that can handle higher power levels. This would improve reliability and reduce complexity and cost.

The over-moded technology developed for the X-band RF distribution system for the Next Linear Collider Test Accelerator (NLCTA) could reduce surface fields and multipactoring of the coupler. Specifically, the TE_{01} mode in circular waveguide solves many problems related to high power transmission in waveguides. It is an ideal mode for reducing loss and peak RF fields. The TE_{01} mode is used for high Q storage for pulse compression and high power windows, fast switches, and phase shifters. The absence of surface electric fields eliminates multipactor, allowing fast RF processing. TE_{01} mode windows have no field at the braze joint, which also reduces the possibility of RF breakdown. Another useful property of the TE_{01} mode is the absence of longitudinal currents. This property allows very low RF loss from gaps at waveguide sections at different temperatures, thereby reducing heat loss and mechanical stress.

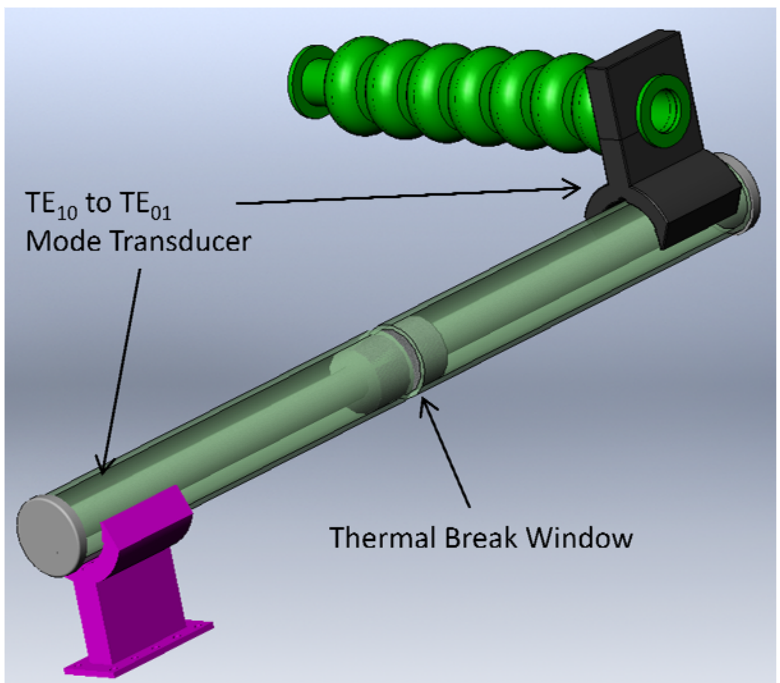

Figure 2 Conceptual drawing of power coupler using overmoded TE01 waveguide technology.

Calabazas Creek Research, Inc. (CCR), in partnership with the Accelerator Research Department A (ARD-A) at Stanford Linear Accelerator Center (SLAC), has completed a feasibility study of applying overmoded technology to the ILC power coupler. A conceptual drawing of the proposed coupler is shown in Figure 2. There are three main components to this coupler, a rectangular TE_{10} to circular TE_{01} mode transducer, a thermal break window and a circular TE_{01} to cavity mode coupler. The analysis of these components is presented in the following sections. Following the component description we present a summary of our findings.

II. Design and test of the TE_{10} to TE_{01} Mode Transducer

The TE_{01} circular waveguide mode used in many components of the NCLTA RF distribution system solves many problems related to high power transmission. It is a nearly an ideal mode for reducing power losses and peak RF fields. There is one disadvantage, however, for this power coupler application. Unlike the TEM coax waveguide mode, whose diameter can be reduced to the limits of RF breakdown, the TE_{01} waveguide mode has a minimum cutoff diameter of 220 mm at 1.3 GHz. This is considerably larger than the present 60 mm diameter used in the TTF-3 coupler. However, this diameter can be reduced by placing a coaxial rod of dielectric inside the circular waveguide. This reduces the TE_{01} cutoff diameter and, at the same time, reverses the mode order of TE_{01} and TE_{21} so the TE_{01} mode can propagate while the TE_{21} mode is still cutoff. With this mode ordering, a simple double feed launcher can couple the input rectangular TE_{10} mode to the TE_{01} mode. An model of this configuration is shown in Figure 3.

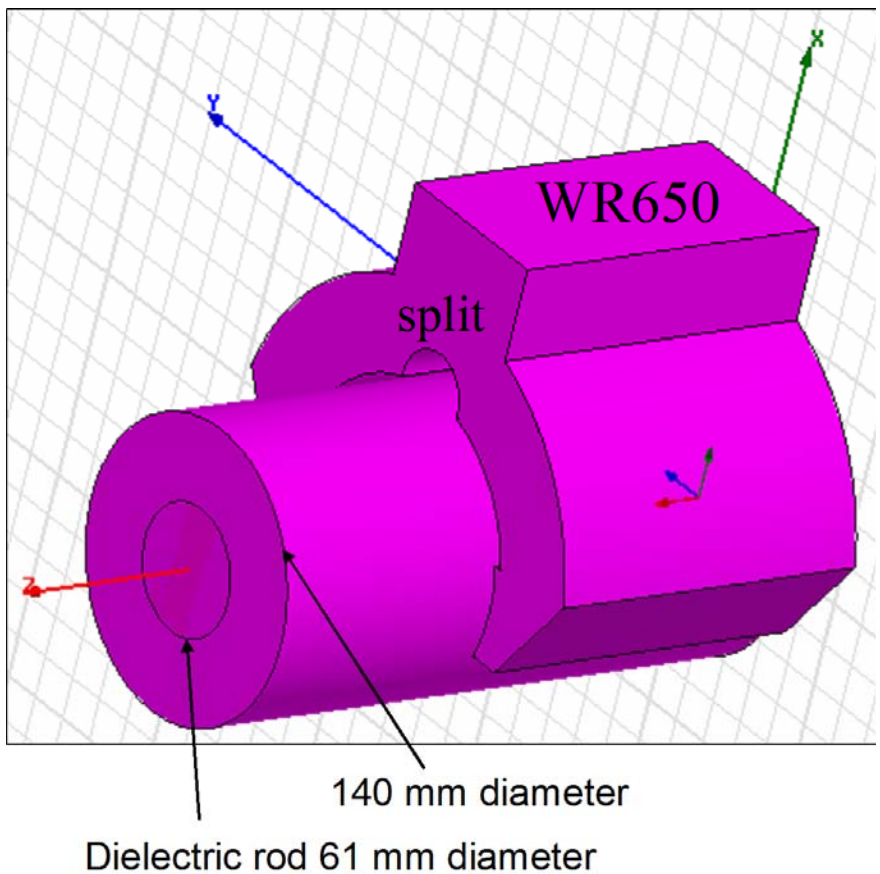

Figure 3 Double feed coupler from rectangular TE10 mode to circular TE01 mode in coaxial dielectric loaded waveguide.

This simple configuration provides excellent coupling between the input TE_{10} mode and the circular TE_{01} mode. Using Ansoft's High Frequency Structure Simulator (HFSS) to calculate the S parameters of a prototype design, a transmission coefficient of 0.998 and reflection coefficient of 0.004 was obtain by modifying only the feed coupler geometry (no irises). The mode purity was better than 99%. For an input power of 500 kW (twice the nominal power per cavity in the ILC), the peak field in the dielectric was only 0.38 MV/m, which is quite small and would require minimal processing.

The dielectric material used in the computation was high purity alumina with relative permittivity of 9.4 and a loss tangent of 3 X 10^{-5}. The calculated loss using this material is only 0.1-0.2% higher than that for the TEM mode in the existing TTF-3 coupler, depending on the length (300-450mm).

The computations of the mode transducer show it to be ideal for the power coupler, but high power tests are desirable to verify the predicted performance and lack of multipactoring problems. CCR generated a mechanical design, constructed and assembled two transducers with plans for high-power testing of the coupler as part of the Phase I program. A picture of the initial assembly of the coupler is shown in Figure 4.

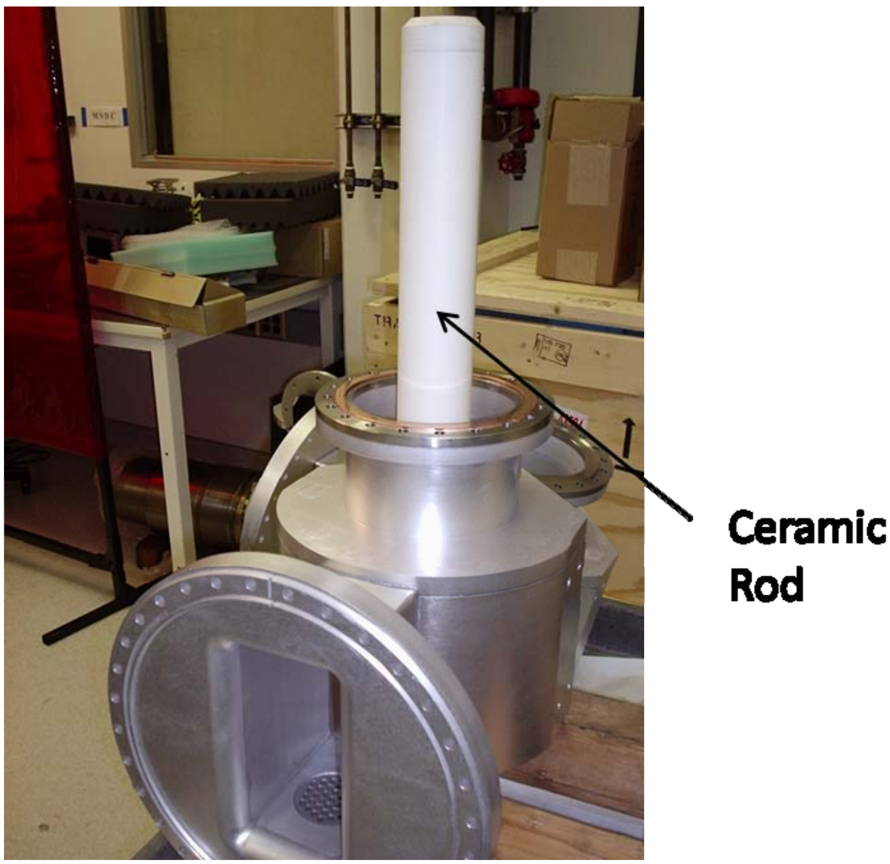

Figure 4 Initial assembly of the TE_{10} to TE_{01} mode transducer.

The two couplers were assembled in “back-to-back” configuration along with the two SLAC supplied L-Band windows required for connection to the high power test set. The complete assembly with couplers and windows is shown in Figure 5.

The S-parameters of this configuration was measured with a vector network analyzer. The return loss was very good (-24 dB), especially considering this measurement was for the configuration of two converters and two windows. The insertion loss of the entire assembly was also very low (1.1%).

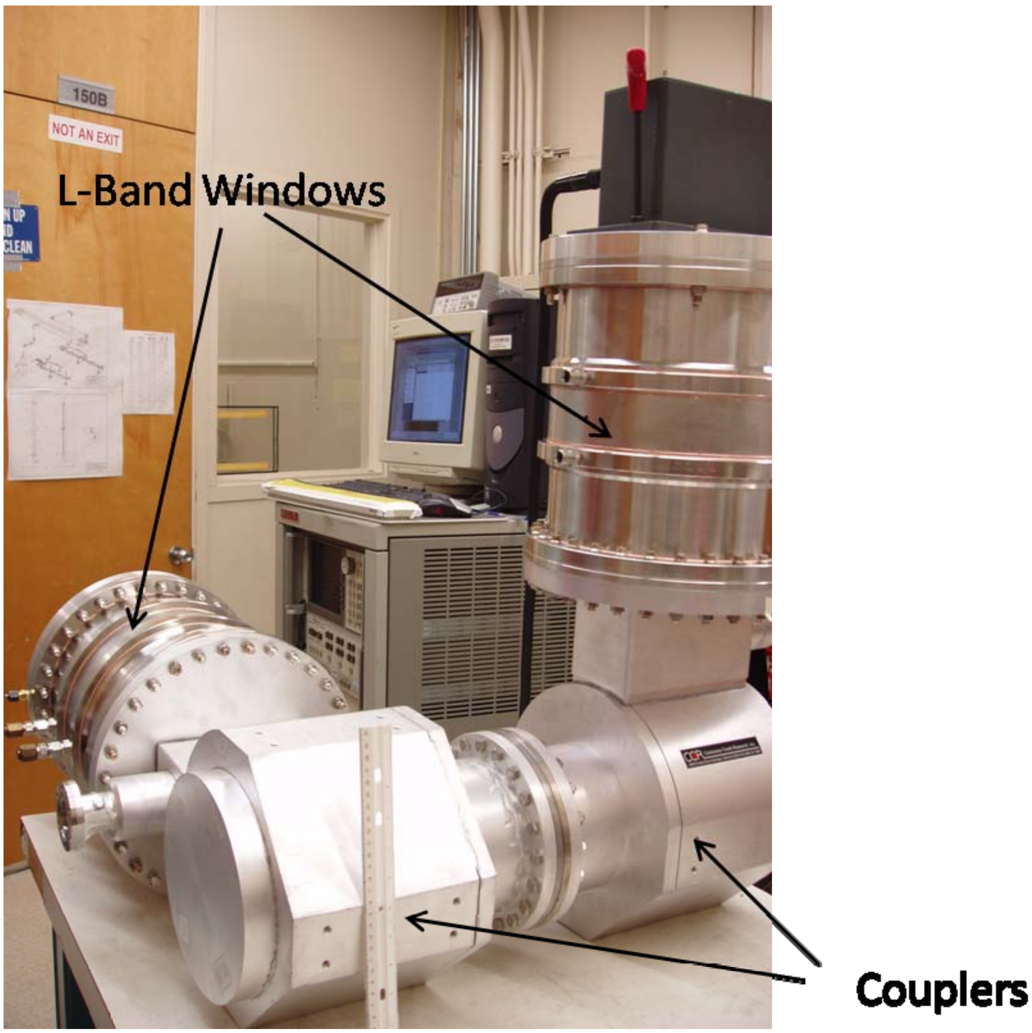

Figure 5 Two back-to-back couplers with L-band windows.

Unfortunately, due to contractual issues between the DOE and SLAC there was a three-month delay to the start of the Phase I program. This delay resulted in insufficient time in the program to complete the final high power test (500kW) of the coupler at SLAC.

III. Design of Thermal Break Window

It is very desirable to introduce a physical break in the coupler between the warm coupler and superconducting cavity to minimize coupler heat load. Such a break can be obtained by a window configuration shown in Figure 6. For typical low-order modes such as the TE_{11} the introduction of a gap between the window faces would have unacceptable power loss because of edge field diffraction. However, the TE_{01} mode has zero electric field on the wall and a no longitudinal currents so the diffraction losses are negligible for small gap sizes (order of wavelength). For example, the loss across a gap of 2 cm, a length much larger than necessary for good thermal isolation, is less than 0.001%.

The gap does introduce a reflection that depends on the window thickness and gap spacing. However, an iris or a simple step transition can match the reflection. An example of matching using a step transition is transition is shown in Figure 6. The gap thickness, window thickness and step transition length were 5, 40.6 and 104.4 mm respectively. The return loss for this configuration is -37dB. For an input power of 500 kW (twice the nominal power per cavity in the ILC), the peak field in the dielectric was only 0.38 MV/m, which is quite small and would require minimal processing time.

Another matching solution can be obtained by a combination of the gap and window thickness. A demonstration of this approach can be seen by examining the return loss versus gap distance in Figure 7. An excellent match is obtained at a gap distance of 12 mm for the window thickness of 20mm.Once again the fields are quite low, being 0.37 MV/m for an input power of 500 kW.

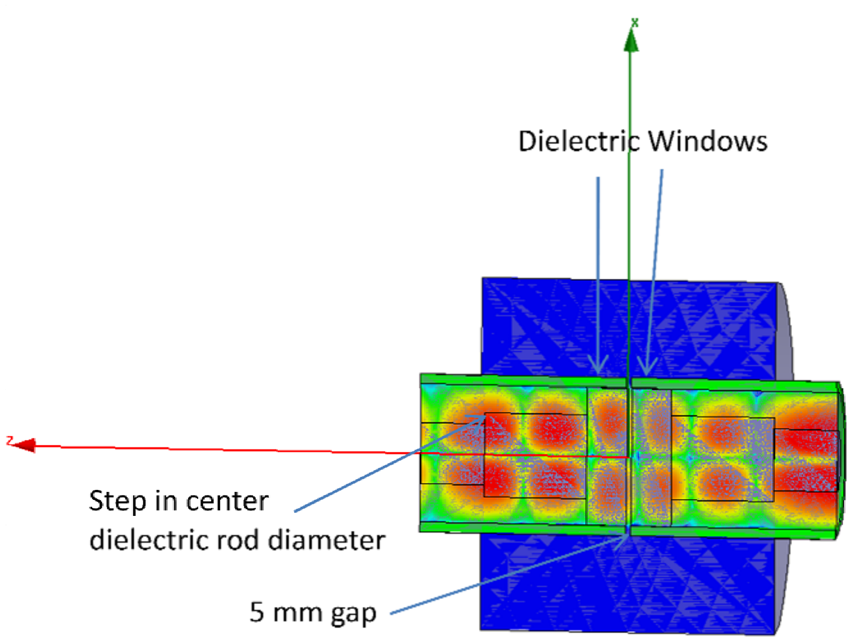

Figure 6 HFSS calculated plot for thermal break window design.

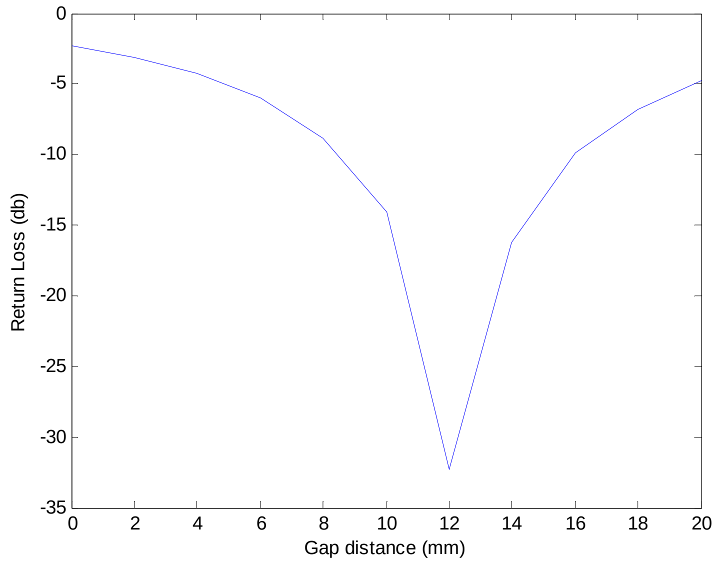

Figure 7 Return loss versus gap length for window thickness of 20mm.

IV. Prototype Design for Cavity Coupler

The waveguide power is coupled into the accelerator cavities through the drift tube region by evanescent field coupling. The coupling will be tuned by the use of a 3-stub tuner external to the power coupler. Coupling the power into the cavity will require conversion of the cylindrical TE_{01} mode to the coax TEM mode. This conversion will be difficult since these modes are "absolutely" orthogonal. Furthermore, the converter must be compact to fit in the inner envelope of the cryostat. Since the wavelength is 230 mm, adiabatic coupling would require too much length. Several design approaches have been evaluated for this coupler. Preliminary designs for the coupler baed on the following three approaches had been generated and discarded as they all required too much volume in the cryostat:

1) The first configuration considered was the use of the input coupler as depicted in Figure 2. The TE_{01} mode in the rectangular waveguide would couple evanescently to the TM_{01} mode in the superconducting cavities.

2) A second configuration consisted of a converter using metal plates along the axis of the waveguide to create four sector waveguides. The propagation constant in each sector can be changed by modifying the radius of the inner coax dielectric. The phase of the RF in one sector can be shifted relative to that of an adjacent sector by propating over a length of $\pi/\Delta\beta$, where $\Delta\beta$ is the difference in the propagation constants between sectors. In the example shown in Figure 8, the first section shifts the relative phases of the TE_{01} modes in the sector guides to couple to the TE_{21} mode. Then a second section shifts the phase in the TE_{21} sector guides to couple to the TM_{01} mode. The TM_{01} mode is then converted to the TEM mode by transitioning to a metal inner conductor.

3) The third configuration that was considered was splitting the input circular TE_{01} waveguide and, using two intermediary rectangular waveguide sections, converted to a TEM mode in a split output coax section. A mirror image is paired to form the complete converter (Figure 9).

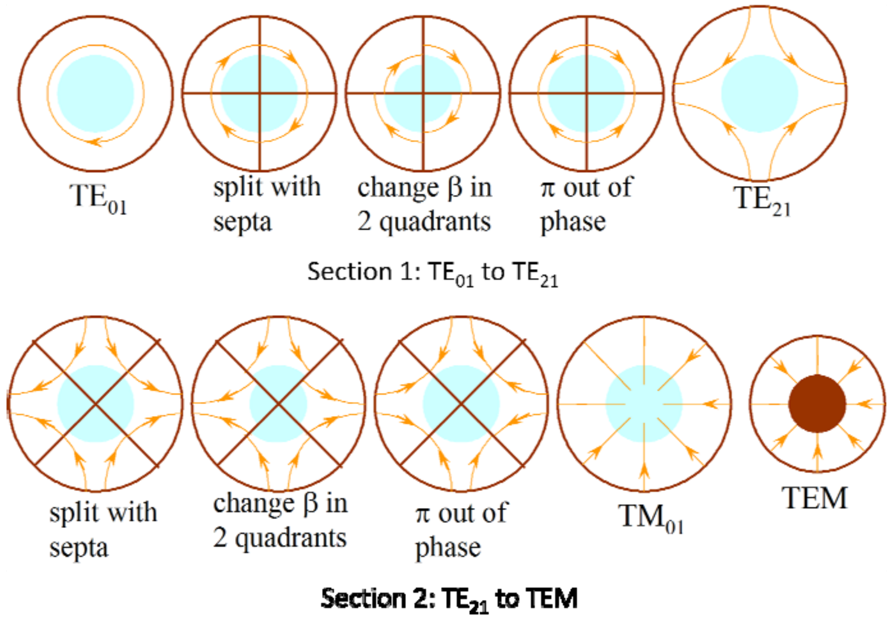

Figure 8 Cross-sections for a converter constructed using metal plates and variations coax rod radius.

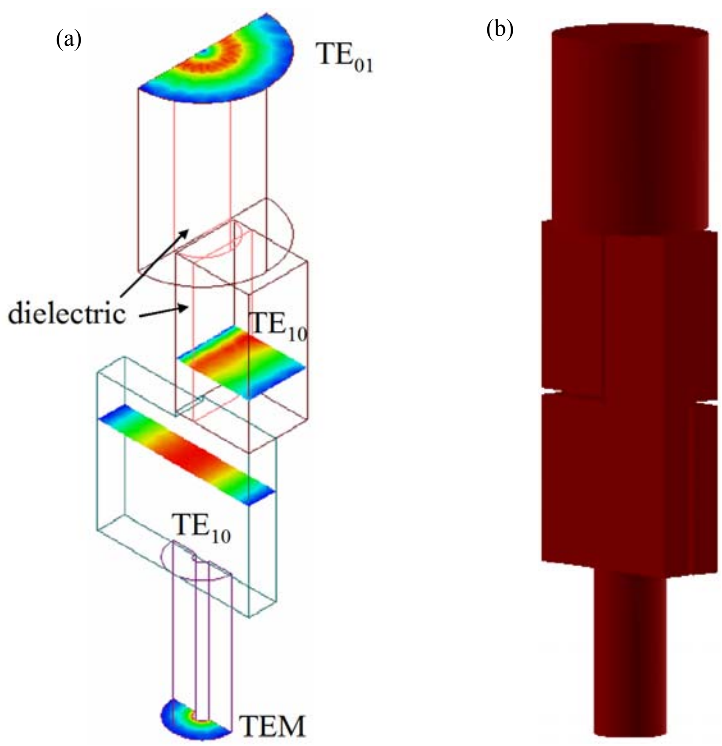

Figure 9 Coax TE01 to coax TEM mode converter using inter-mediary rectangular TE10 mode sections. (a) Wire frame view of one converter half. (b) Solid view of two converter halves paired together to form whole converter.

V. Summary

The Phase I study has established that the TE_{10} to TE_{01} mode transducer and thermal break window could provide part of a successful design approach for a superconducting cavity coupler. The designs are considerably less complex than those of existing couplers. The field levels are very low, and the lack of surface electric field will eliminate multipactor in the TE_{01} region, allowing for fast rf processing. We have constructed a prototype TE_{10} to TE_{01} mode transducer and it will be tested in the near future to confirm the computational results.

Unfortunately, we were unable to obtain a satisfactory design of the last necessary component for the coupler (TE_{01} to TEM mode transducer). Several approaches were investigated but they all required too much volume in the cryostat. We have developed a new approach for the coupler design based on a magnetron vane structure operating in the pi-mode. This approach should be very compact since it does not use adiabatic transformation of the fields. However, we expect that a significant number of iterations of this structure will have to be examined in order to find a design that has couples the two modes strongly without unacceptably high-field gradients. The work required for this design was beyond the scope of the Phase I project.