NOVEL ACCELERATOR STRUCTURE COUPLERS*

C.D. Nantista, V.A. Dolgashev, and S.G. Tantawi, SLAC, 2575 Sand Hill Rd., Menlo Park, CA 94025, USA

Abstract

Recent experience with X-band accelerator structure development has shown the rf input coupler to be the region most prone to rf breakdown and degradation, effectively limiting the operating gradient. A major factor in this appears to be high magnetic fields at the sharp edges of the coupling irises. As a first response to this problem, couplers with rounded and thickened iris horns have been employed, with improved performance. In addition, conceptually new coupler designs have been developed, in which power is coupled through the broadwall of the feed waveguide. A prototype "mode converter" coupler, which launches the TM_{01} mode in circular waveguide before coupling through a matching cell into the main structure, has been tested with great success. With peak surface fields below those in the body of the structure, this coupler represents a break-through in the NLC structure program. The design of this coupler and of variations which use beamline space more efficiently are described here. The latter include a coupler in which power passes directly through an iris in the broad wall of the rectangular waveguide into a matching cell and one which makes the waveguide itself an accelerating cell. We also discuss techniques for matching such couplers.

INTRODUCTION

RF power is typically coupled into accelerator structures by magnetic coupling through a pair of iris apertures in thin-walled interfaces between the ends or narrow walls of rectangular waveguides and a coupling cell [1]. In the development of high-gradient structures for future linear colliders, much attention has been demanded by the limitations imposed by rf breakdown and surface damage [2], [3]. Although high-field regions such as iris tips and slots throughout these structures are vulnerable to breakdown, couplers have been seen to represent a sort of bottleneck. In the past couple of years, this has led us to explore ways of reducing the surface fields in structure couplers. We here present and discuss some solutions to the coupler problem.

FAT-LIPPED COUPLER

Post-processing autopsies of test structures have revealed gross deterioration of the “horns” or ridges of waveguide to coupler cell irises. This confirmed a connection between processing damage and pulsed heating due to large surface currents [4]. The problem was most obvious in structures where the horn edges had been made sharp (~0.08 mm radii). The most straight-forward remedy to the problem of coupling iris pulsed heating is to round the iris edges with increased radius. Figure 1 shows a coupler geometry of the type which performed poorly and a modified coupler with a 3 mm thick, full-radiused waveguide iris. This redesign reduced the peak surface magnetic field by ~50% and the pulsed heating by a factor of four. The coupler cell wall is given a racetrack shape to compensate for the larger quadrupole distortion of the fields [5].

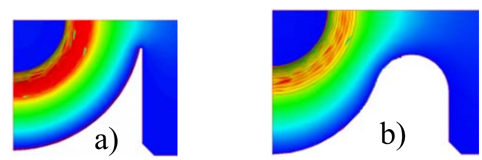

Figure 1: Quarter cross-section of a) thin-irised coupler and b) fat-lipped coupler with reduced pulsed heating.

MODE-CONVERTER COUPLER

Greater reduction of coupler fields requires a qualitative change of design. The mode-converter coupler was adapted from a set-up designed to test and study single cells of various geometries and materials. To test the performance of these cells without being limited by coupler field enhancement, we had decided to couple on axis from a circular TM_{01} mode waveguide. A TM_{01} launcher was thus designed. Between two such launchers could be inserted a simple, symmetric structure consisting of the travelling-wave test cell sandwiched between two lower-field matching cells.

The TM_{01} Mode Launcher

After electric fields were found to be too high in an initial wrap-around style mode launcher, a simpler design was conceived. It consists of a WR90 waveguide, to be fed symmetrically from both ends, opening through its broad wall into a perpendicular 0.900” diameter circular waveguide. Matching the diameter to the rectangular guide width keeps the fields low while avoiding unnecessary overmoding. The only other propagating mode, the fundamental TE_{11}, even when not excluded by symmetric feeding, is poorly coupled compared to the TM mode. A simple matching element completes this launcher or mode converter. This can be an iris in the circular waveguide or, as shown in Fig. 2, a set of matching bumps (or posts) in the rectangular waveguide.

The edge of the junction, where the walls of the rectangular and circular guides meet, is rounded to minimize electric field enhancement. For the singe-cell tests, a smaller hole, opposite the circular waveguide, opens into a cutoff viewport. In adapting this mode

* Work supported by the U.S. Department of Energy under contract DE-AC03-76SF00515.

converter into a coupler for an actual beamline structure, this viewport becomes the beampipe.

Figure 2 shows the geometry of the mode converter with electric and magnetic field plots from HFSS. For a power flow of 50 MW, the peak surface electric field is 35 MV/m and the peak magnetic field is 100 kA/m. The match, quite broad relative to structure bandwidths, is shown in Figure 3.

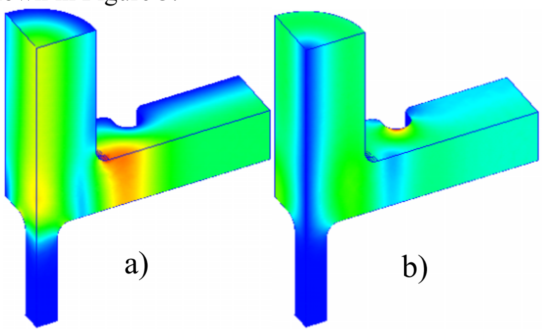

Figure 2: Quarter geometry of TM_{01} mode converter with a) electric field and b) magnetic field plots.

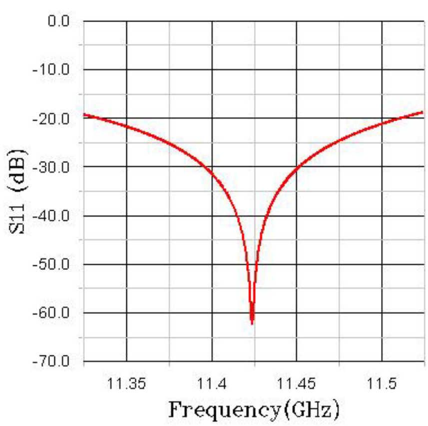

Figure 3: Simulated frequency response of X-band TM_{01} mode converter.

Designing Matching Cells

Use of this universal mode converter in any given input or output coupler requires design of a customized cell to match the circular waveguide into the disk-loaded structure. This cell has fields higher than in the mode converter itself, but can typically be designed to have surface fields below those in the main structure cells, so that the coupler is no longer a weak link. To determine the matching cell dimensions for a travelling-wave structure, one can use the following approach based on symmetrized models and single-mode cascading.

First, one models a symmetric structure composed of one or more structure cells, with the central one symmetrized—for example cells 1, 2, 3, 2, and 1, with the diameter of cell 3 adjusted if necessary to account for the fact that it has the same iris dimension on either side (normally changing in a constant gradient structure). Using a field solver such as HFSS, this model is simulated, with a port at each end of the circular waveguide diameter, to determine the scattering matrix. This is repeated with the central, symmetric cell doubled and then tripled.

If one converts the scattering matrix to a transmission matrix and cascades it between those of an undetermined matching element and its reflection as $T^{tot} = T^m T T^{m(1\leftrightarrow 2)}$, the condition for a match, $T_{21}^{tot} = 0$ (or $S_{11}^{tot} = 0$), yields the following equation for the amplitude of the matching reflection as a function of the phase as seen looking out from the modelled port:

$$\left|S_{22}^m\right| = \frac{\cos\left(\phi_{11} + \phi_{22}^m\right)}{\left|S_{11}\right|} - \sqrt{\left[\frac{\cos\left(\phi_{11} + \phi_{22}^m\right)}{\left|S_{11}\right|}\right]^2 - 1},$$

where the ϕ's are phases of scattering matrix elements.

Plotting the solution to this equation over the ϕ_{22}^m region where it is pure real for the cases of one, two, and three symmetrized cells, one finds that the curves intersect at a unique point. Since this match is independent of the number of central cells, it must be a travelling wave match to the periodic structure represented by that cell. A matching iris can now be designed to give this desired reflection amplitude, and from its simulated reflection phase its proper spacing from the first structure iris can be determined. This defines the matching cell. Figure 4 shows an example with electric fields.

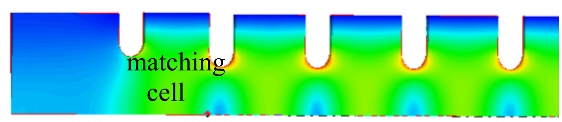

Figure 4: Circular waveguide (left) matched to a TW periodic structure through a matching cell with field plot.

The symmetry technique described here is applicable to more complicated three-dimensional matching problems as well, since the matching element need not be a simple waveguide iris. In practice, this matching method does not always give as small a reflection as desired. It can be used to get close to the desired match. The coupler dimensions can then be optimized using the Kroll method [6], by which the internal reflection from a periodic structure coupler is calculated from the simulated fields in the cells using formulae derived from Floquet's theorem. Since such optimization takes many long field solver iterations, the three iterations (even two would suffice) of the symmetry technique are seen to provide a valuable head start.

BROADWALL (WAVEGUIDE) COUPLER

An undesirable aspect of the mode-converter coupler, where real estate is valuable, is that negligible acceleration is gained over the beamline distance it occupies. This reduces the average effective accelerating gradient of a structure. For use in a linear collider, a more compact coupler is required. With this in mind, it was realized that two matching steps, from rectangular waveguide to circular waveguide and from circular waveguide to disk-loaded structure, are not necessary. The TM_{01} waveguide can be eliminated by direct electric coupling through a circular iris in the WR90 broadwall into a matching cell. We had wondered how short the circular waveguide section could be made before evanescent modes spoiled the independently simulated matches. With the added design cost of having to simulate 90° wedges of the 2-D accelerator cells due to the coupler symmetry, we could in this way reduce its length to zero. Figure 5 illustrates the broadwall coupler.

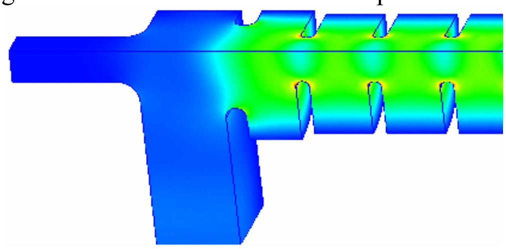

Figure 5: Quarter geometry of a broadwall coupler with electric fields

This single match design also allows the elimination of bumps or posts in the rectangular waveguide ports. The WR90 is then free of obstruction. This is good from the point of view of dipole wakefield damping. One orientation of the lowest TM dipole mode on the coupler axis excites TE_{10} asymmetrically in either arm of the rectangular waveguide; the other excites in-phase TE_{20} waves. Without matching elements, these are free to propagate out, and trapped coupler modes can be avoided.

ACCELERATING WAVEGUIDE COUPLER

Even the broadwall coupler sacrifices some acceleration efficiency for low coupler fields. There is very little field in the waveguide region, and the field in the matching cell may not be quite synchronous. If the couplers represent a small fraction of the structure length and/or allow a higher gradient to be reached in the main cells than otherwise achievable, it may be a viable candidate.

Ideally, however, we would like to reclaim this beamline space for acceleration. This might be accomplished with a more complicated accelerating waveguide coupler similar to that shown in Figure 6. Here partial chokes in the waveguide create a standing wave in the region of the beamline. The height of the waveguide is stepped down to the length of a cell, and the iris coupling it to the main structure is adjusted to achieve the desired phase advance. The waveguide region thus becomes for the beam another cell. The idea is to get significant acceleration here without, in the process, raising field levels at the chokes, or alternative matching elements, back to dangerously high levels.

The waveguide width is also stepped down near the structure axis so that the half guide wavelength $\lambda_g/2$ is equal to the waveguide width. This makes the standing wave field lobe square, eliminating quadrupole asymmetry, which can cause surface electric field enhancement on the iris and beampipe opening. This is similar to "racetracking" in the fat-lipped coupler. Due to their lower fields, it was considered unnecessary in the mode-converter and broadwall couplers.

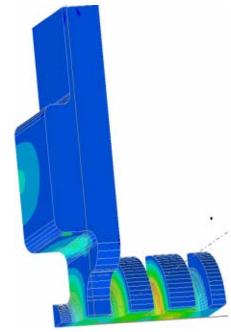

Figure 6: Quarter geometry of an accelerating waveguide coupler with electric fields.

CONCLUSIONS

Several innovative coupler design have been presented. The fat-lipped and mode converter couplers were successfully used for the output and input couplers, respectively, of an experimental X-band structure, allowing it to be processed up to 90 MV/m (400 ns pulse). A subsequent set of structures in the SLAC/KEK program will be tested with mode converter couplers to optimize the main structure parameters. Fermilab will provide additional R&D structures with broadwall couplers. The CLIC structure program at CERN has likewise adopted the mode-converter and broadwall coupler designs for 30 GHz test structures [7].

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