A VARIABLE DIRECTIONAL COUPLER FOR AN ALTERNATE ILC HIGH-POWER RF DISTRIBUTION SCHEME*

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Abstract

We describe the design and functionality of an RF directional coupler for which the power division between the output ports is mechanically variable. In an alternate power distribution scheme for the ILC, power is delivered to cavities in pairs, through hybrids. Four pairs, or eight cavities, are fed from one waveguide feed, from which one fourth, one third, and one half of the power is coupled out at consecutive directional couplers. Three such feeds are powered by a single 10 MW klystron. Experience suggests that cavities considered useable will display some variation in the operational accelerating gradient they can sustain. With fixed distribution, the klystron power must be kept below the level at which the weakest cavity out of 24 receives its power limit. This problem can be solved by installing variable attenuators, but that means wasting precious power. With adjustable coupling, distribution can be optimized for more efficient use both of available power and of the accelerating cavities. This novel device, feeding cavities paired by similar performance, can provide such benefit to the ILC.

INTRODUCTION

The baseline design for the International Linear Collider (ILC) includes approximately 16,080 9-cell superconducting cavities in the main linacs. These are installed eight to a cryomodule. To minimize the number of expensive power sources needed, 10 MW L-band klystrons will be used to power three cryomodules, or 24 cavities, each.

At each cryomodule, the RF is divided amongst the cavities by a set of directional couplers connected in series. The first directional coupler taps off $^1/_8$ of the power, the second $^1/_7$, and so on. In this scheme, seven different directional coupler designs are required to feed nominally equal power into each cavity.

Between this distribution line and each standing-wave cavity, a high-power circulator is included to absorb power reflected from the cavity during the fill time and emitted during discharge. Without circulators, this power would go back into the feeding line toward the klystron. How much of a problem this presents would depend on how the reflections from all the cavities add up. As has been suggested by Tantawi [1], with proper spacing of the eight cavities, the reflections can be made to cancel at the input to the line. That is, the phases can be distributed such that the phasor sum (assuming equal amplitude) is zero. The power is then completely absorbed in the loads attached to the fourth ports of the directional couplers.

Due to their expense, roughly 30% of the high-power RF the distribution cost, it is highly desirable to eliminate the need for circulators. The approach mentioned above places forward and backward phasing requirements on a whole set of cavities. This is complicated when in some sets spacing is broken up by a quadrupole magnet.

We consider here an alternate approach, less rigidly locked to the overall distribution design, in which cavity reflections are canceled in pairs. This can be accomplished by feeding pairs of cavities through 3-dB hybrid directional couplers, the same way high-Q resonant cavities or delay lines are fed in SLED [2] type pulse compression systems, respectively. In this case, the reflections are directed into a load on the hybrid's fourth port. The power for each pair is extracted from the main feed line through a string of directional couplers, now reduced in number to three.

We further propose a common manufacturing design for these distribution couplers with the coupling mechanically adjustable to provide the various required values. Such an adjustable coupler opens the possibility of fine tuning to customize the distribution within each cryomodule.

This adjustability can be a great benefit to the machine efficiency. With the state-of-art accelerating gradient for superconducting cavities being pushed in the ILC design, it is expected that there will be some spread in sustainable

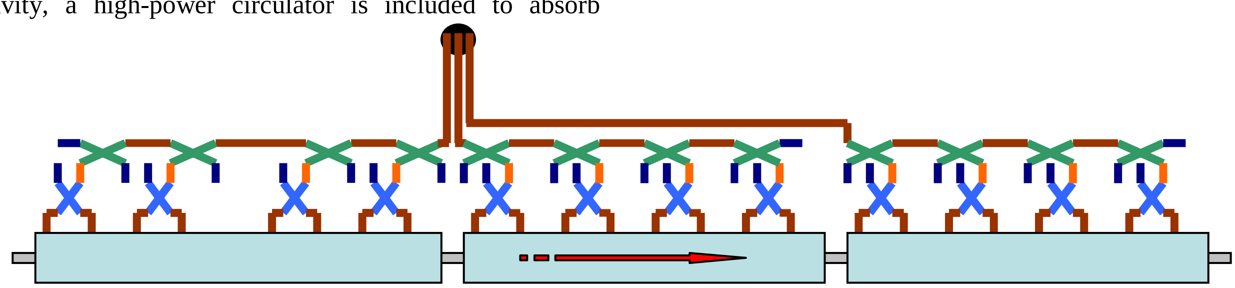

Figure 1: Schematic of alternative high-power RF distribution scheme from one klystron to three cryomodules. The adjustable couplers are shown in green and the hybrids in blue. Loads are dark blue and flexible waveguide orange. Extra space is shown in the middle of the first cryomodule for a quadrupole magnet. Additional devices near each cavity coupler, such as three-stub tuners, are not shown.

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gradients among the cavities produced, probably at least five percent with a long lower tail. One cannot afford to set the acceptance bar too high, or the yield will suffer, impacting cost and schedule. With a system of fixed nominal couplings, however, the weakest cavity in a set of 24 will limit the power level at which the klystron can be run, forcing the rest of the cavities to operate below their potential and impacting the gradient. If a variable attenuation or (with circulator) reflection is added at each cavity (e.g. a 3-stub or E-H tuner), the cavities can all be run at their capacities, but at the cost of power efficiency, since some power is deliberately discarded. Adjustable coupling allows one to optimize the amount of klystron power that a set of cavities can fruitfully receive.

PAIR FEEDING

When power is fed into a four-port hybrid with identical loads on the two coupled ports, any reflected signals cancel in the input port and add constructively in the fourth port. This can be used to direct power reflected from paired up ILC cavities into loads. Circulators are then not needed to avoid unacceptable reflections to the klystron, as has been noted by Katalev and Choroba [3]. The hybrid port isolation and the load match, or more specifically their combined effect, would need to provide sufficient isolation between the two cavities to avoid problems.

Assuming this can be done, this scheme imposes a condition on the cavity spacing. The relative phase between output ports of a hybrid is–π/2. If the cavities are fed symmetrically from the midpoint between their inputs, then for the RF to be phased to the relativistic beam requires:

$$-\frac{\pi}{2} = -k_0 P + 2n\pi \quad \text{or} \quad P = \frac{(2n + 1/2)\pi}{k_0}, \qquad (1)$$

where P is the spacing, k_0 the free space wavelength ω/c, and n an integer. For a choice of n=11, P=1.326 m, very close to the current design spacing.

The layout of this two-stage distribution scheme is shown Fig. 1. The number of directional coupler/hybrids and loads required is the same as in the linear series distribution. Strictly for power division, this would be the number of cavities fed minus one. Here an extra in each line is shown to allow for discarding excess power at the end. In this alternative, however, only four couplings, rather than seven are required for a set of eight cavities. With the variable design described below, only two types of device need be fabricated. The 3 dB hybrids that provide the second stage of splitting should be of a compact design with fixed coupling to effectively perform their function. Accordingly, cavities should optimally be grouped in pairs that can take approximately the same amount of power.

VARIABLE COUPLER CONCEPT

Our variable coupler design can be mechanically adjusted to give anywhere from zero to full coupling. The same component can thus provide the nominal ¼, $^1/_3$, and ½ couplings required in the above distribution scheme. Further, it can be adjusted in each case to give more or less of the total energy in the waveguide line, depending on the gradient capacity of the individual cavity pairs, This opens up the possibility of considerable savings in efficiency. An important feature of the adjustment is that it does not change the phase of the transmitted or coupled power, only the split.

The coupler is based on the degenerate polarizations of the TE_{11} mode in circular waveguide. The four ports of the device are in standard WR650 rectangular waveguide. At either end, two ports couple one into each of these modes in a circular section. A middle section, connected to the ends by rotatable flanges, transitions from circular to elliptical cross-section and back again. It is matched for both TE_{11} polarizations, with respect to the axes of the ellipse, but with a phase length difference of π. Power from a given port will excite a mode to whose polarization the axes of the central section are rotated at some angle α. This mode will project onto the normal modes of the central section and the relative phase of the components will be reversed by the time it reaches the far end where they become once more degenerate. This has the effect of rotating the polarization by an angle 2α. Fig. 2 illustrates this effect. A similar rotator for TE_{12} was described in [4]. The power is thus divided between the normal modes of the end section, and gets split accordingly between its output ports. This mechanism has been considered, in a different configuration, for decoupling CLIC cavities [5].

For a given rotation of the central section relative to the fixed upright end sections, the coupling C=P_c/P_i, i.e. the ratio of coupled to input power, is seen to be simply

$$C = \sin^2 2\alpha . \qquad (2)$$

So for nominal fractional couplings, it would be adjusted according to Table 1.

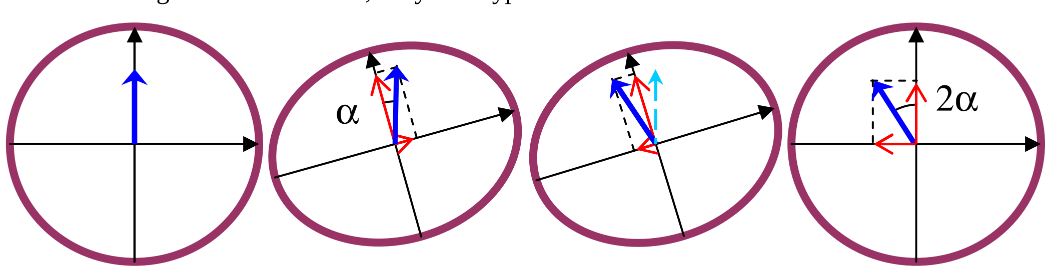

Figure 2: Illustration of mode rotation through the central piece as the cross-section changes. Note the π relative phase reversal of the elliptical basis components.

Table 1: Variable Coupler Nominal Settings

C (coupling)	α (angle)
0	0.00°
1/4	15.00°
1/3	17.63°
1/2	22.50°
1	45.00°

As the angle is changed over the full range of coupling, from 0 to 45 degrees, the phase of the coupled power and that of the transmitted power are unaffected. Since phasing is crucial in an accelerator, this avoids a major headache that could be introduced by a design that used squeezing or length changing to adjust coupling. A sign change, or discrete π phase change, however, can be obtained for the coupled power by simply reversing the angle of rotation. This choice could be helpful in getting the system phased right.

VARIABLE COUPLER DESIGN

The design for the end section has two WR650 ports and one circular port with a radius of 3.634 inches. The transmission port shares the circular guide's axis, and receives the vertical polarization; the coupled port extends perpendicular to the circular guide with its broad wall parallel to it and extracts the horizontal polarization, which is cutoff in the straight ahead port. This perpendicular waveguide extends down below the circular guide in a shorted stub which serves both to help the match into the coupled port and to symmetrize the geometry seen by the vertical mode, which is cutoff in this waveguide. The latter is necessary lest asymmetry couple the mode to the one other propagating circular mode, TM_{01}. The rectangular ports are matched to better than -50 dB with post-like bumps on their side walls. The geometry and functionality are illustrated in Fig. 3.

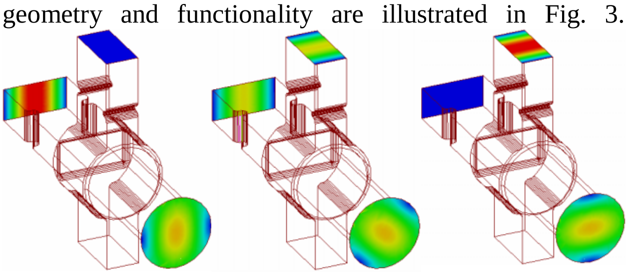

Figure 3: End section. The left and right pictures show the coupling of the vertical and horizontal polarizations to their respective ports. The middle picture shows power in a rotated mode split between output ports.

The mode rotator connects between the circular ports of two end sections. It is a symmetric transition, stepped or tapered between circular ends and interior cross-section(s) that break the degeneracy of TE_{11} polarizations. Its design must satisfy three conditions; it must be matched for transmission of each polarization without parasitic mode coupling, and it must introduce a phase slippage of π between them. Mode rotation through such a design with discrete steps is illustrated in Fig. 4. Sharp edges are to be removed in a redesign.

The integrated four-port directional coupler then looks like Fig. 5. The relative orientation of ports 3 and 4 is an option. The joint between parts must carry currents and be pressure tight as well as RF tight. Adjustment will require loosening the joints.

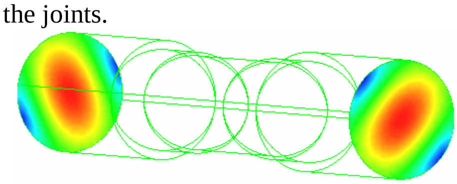

Figure 4: Mode rotator with field plots at ports demonstrating polarization rotation.

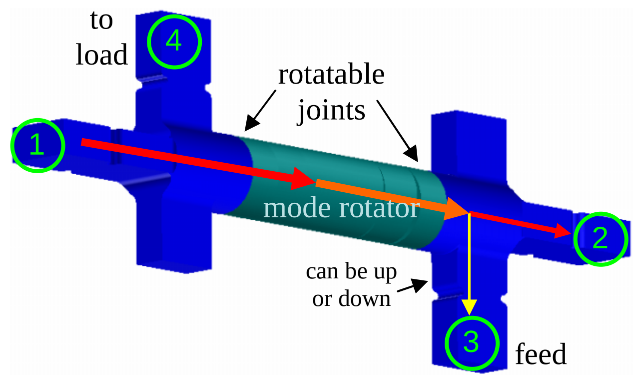

Figure 5: Variable directional coupler.

CONCLUSION

We have briefly described the concept and design of a novel variable directional coupler which allows customized distribution and thus more efficient use of RF power. We've suggested its use in the context of an alternative two-stage RF distribution scheme for ILC in which 3 dB hybrid pairing may allow elimination of expensive circulators We will fabricate and test such a device and hope to employ it in powering a cryomodule at Fermilab in the coming year.

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