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RF Coaxial Couplers for High-Intensity Linear Accelerators

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RF COAXIAL COUPLERS FOR HIGH-INTENSITY LINEAR ACCELERATORS

by

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ABSTRACT

Two rf coaxial couplers that are particularly suitable for intertank connection of the disk-and-washer accelerating structure for use in high-intensity linear accelerators have been developed. These devices have very high coupling to the accelerating structure and very low rf power loss at the operating frequency, and they can be designed for any relative particle velocity $\beta > 0.4$. Focusing and monitoring devices can be located inside these couplers.

I. INTRODUCTION

In high-energy linear accelerators, it is often advantageous to couple accelerating cavity chains together around focusing elements, power feed points, or beam diagnostic equipment. The high-energy (>100-MeV) part of the Clinton P. Anderson Meson Physics Facility (LAMPF) accelerator uses bridge couplers both to bridge quadrupole focusing elements and beam diagnostic equipment and to provide a convenient power feed point.[1,2] The couplers are circular pieces of cylindrical waveguide excited in the TM_{010} mode, and the field is stabilized by stems mounted on the waveguide wall. It was necessary to determine the number of stems needed, their exact lengths, and the positions at which they would provide the stablest operation and suppression of possible degenerate TE modes in the cavity. Because of its complexity, experimental tuning of such a coupler is difficult. However, performance of these couplers has been satisfactory.

Rectangular waveguide was used as a bridge coupler in the design of the meson factory linac in Moscow.[3] Their study showed that a TE_{10n} mode is most suitable for rectangular rf coupler operation.

The disk-and-washer (DAW) accelerating structure is characterized by very strong intercell coupling, which makes it insensitive to various types of perturbations. Therefore, the bridge connection between the tanks should be made using devices of intrinsically high coupling. The cylindrical and rectangular rf waveguide couplers mentioned above have to be connected to the main accelerator structures by resonators at each end, so the coupling to the structures is small. To preserve the high coupling advantage of the DAW structure required a device that could provide strong intertank coupling and also permit possible use of focusing devices between the tanks. We have found that rf coaxial couplers can meet these requirements and are particularly suited to axially symmetrical cavities, like the DAW cavity. The radial field lines at the DAW periphery make transition into a coaxial line ideal, and the circular symmetry of the coaxial line and the DAW provides an excellent match within reasonable dimensions.

II. RF COAXIAL COUPLERS

An rf coaxial coupler consists of two coaxial cylinders whose open ends are connected to the accelerating structures (see Fig. 1). Because coaxial couplers are axially symmetrical, the most natural connections are to axially symmetrical cavities such as the DAW cavity. Because the coupling is through a relatively large area, the electromagnetic fields overlap, the DAW cavity modes merge smoothly into the coaxial coupler modes, and strong coupling results. During standing-wave operation of the biperiodic chain of cavities, the coaxial coupler can be considered as a third type of cavity that couples biperiodic chains together. In an

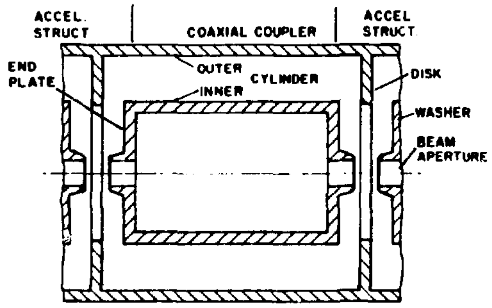


Fig. 1. The rf coaxial coupler.

infinitely long system with many coaxial couplers, this appears to be a triperiodic system.

Tuning such a system involves making a single dispersion curve with no stop band and no tilting of the on-axis field. It can be done by tuning a section of the biperiodic DAW structure first, and then adding a coaxial coupler and tuning it to the operating frequency so that it fits between the sections of the structure. Generally, only one coaxial coupler mode is coupled to the operating mode of the structure. The coaxial coupler can be considered a coupled system of two coupling cavities interconnected by a "bridging" coaxial cavity. The coupling cavities are connected directly to the biperiodic DAW accelerating structure and are intrinsically a continuation of the system. Therefore, it is important to tune not only the coaxial cavity "bridge" but also the coupling cavities.

A coaxial coupler can be designed to operate in the TEM mode or in one of the higher order modes. We have investigated the properties of both types by use of SUPERFISH.[4] We used the optimized DAW cavity parameters[5,6] and the optimized geometry. The SUPERFISH code can calculate modes and field distributions for multicell systems, and we used this feature to calculate the coaxial bridge properties and derive proper dimensions for its optimum performance. For the calculation, we added a coaxial coupler to one end of the DAW chain, and we assumed symmetry about the center of the bridge cavity to reduce computer time. The length of the bridge cavity is adjusted to give it proper resonance. For the TEM mode, the resonant length of a coaxial cavity shorted at both ends is $\ell = m_1(\lambda/2)$ where m_1 is an integer and λ is the wavelength that corresponds to the operating frequency.

Of course, for an accelerator the bridge coupler length is not a free parameter. The particles travel from one tank to another through the coaxial coupler at velocity β, and the phase shift of the electromagnetic fields in the cavities adjacent to the coaxial coupler must be either 0 or π, with the additional restriction that the particles see an accelerating field in both cavities adjacent to the coaxial coupler. Thus the distance between the centers of these cavities must be

$$L = m\beta(\lambda/2) \quad , \tag{1}$$

where m is an even or odd integer, depending on the number of field variations, m_1, in the coaxial coupler. The acceleration condition requires $m_1 = m - (2n + 1)$, $n = 0, 1, \ldots$. The resonance conditions in the coaxial line require that the coaxial coupler length $\ell = m_1(\lambda/2)$ or, if ℓ_1 is the length of the DAW cavity $[\ell_1 = \beta(\lambda/2)]$,

$$\ell = L - \ell_1 \quad . \tag{2}$$

Thus

$$m_1(\lambda/2) = m\beta(\lambda/2) - \ell_1 \quad . \tag{3}$$

There are only a few β values for which m and m_1 are both integers. Usually the coaxial coupler frequency must be adjusted slightly. This can be done by loading the coupler by means of metallic or dielectric rings, which virtually means slowing the wave. Then the coaxial coupler length is

$$\ell = m_1\beta_1(\lambda/2) \quad , \tag{4}$$

where β_1 is the effective wave velocity of the modified coaxial line. Equation (3) becomes

$$m_1\beta_1(\lambda/2) = m\beta(\lambda/2) - \ell_1 \quad . \tag{5}$$

There is no strict boundary between the cavity and coaxial coupler.

Assuming large overlapping of fields between the DAW cavity and the coaxial coupler, we can assume ℓ_1 as small as

$$\ell_1 = \beta(\lambda/4) \quad , \tag{6}$$

and we have

$$2m_1\beta_1 = \beta(2m - 1) \quad , \tag{7}$$

TABLE I

β_1 AS A FUNCTION OF β FOR DIFFERENT m AND m_1 VALUES

		β_1		
β	m	(m_1 = m - 3)	(m_1 = m - 5)	(m_1 = m - 7)
0.4	4	1.4		
	5	0.9		
	6		2.2	
	7		1.3	
	8		1.0	
	9			1.7
	10			1.27
	11			1.05
	12			0.92
0.5	5	1.13		
	6	0.92		
	7			
	8		1.25	
	9		1.06	
	10		0.95	
	11			1.31
	12			1.15
	13			1.04
	14			0.96
0.6	5	1.35		
	6	1.10		
	7	0.98		
	8			
	9		1.28	
	10		1.14	
	11		1.05	
	12		0.99	1.38
	13			1.25
	14			1.16
	15			1.09
	16			1.03
	17			0.99
0.7	7	1.14		
	8	1.05		
	9	0.99		
	10		1.33	
	11		1.23	
	12		1.15	
	13		1.09	
	14		1.05	
	15		1.02	
	16		0.99	1.21
	17			1.16
	18			1.11
	19			1.08
	20			1.05
	21			1.03
	22			1.00
0.8	10	1.09		
	11	1.05		
	12	1.02		
	13	1.00	1.25	
	14		1.2	
	15		1.16	
	16		1.13	
	17		1.10	
	18		1.08	
	19		1.06	
	20		1.04	
	21		1.03	
	22		1.01	
	23		1.00	

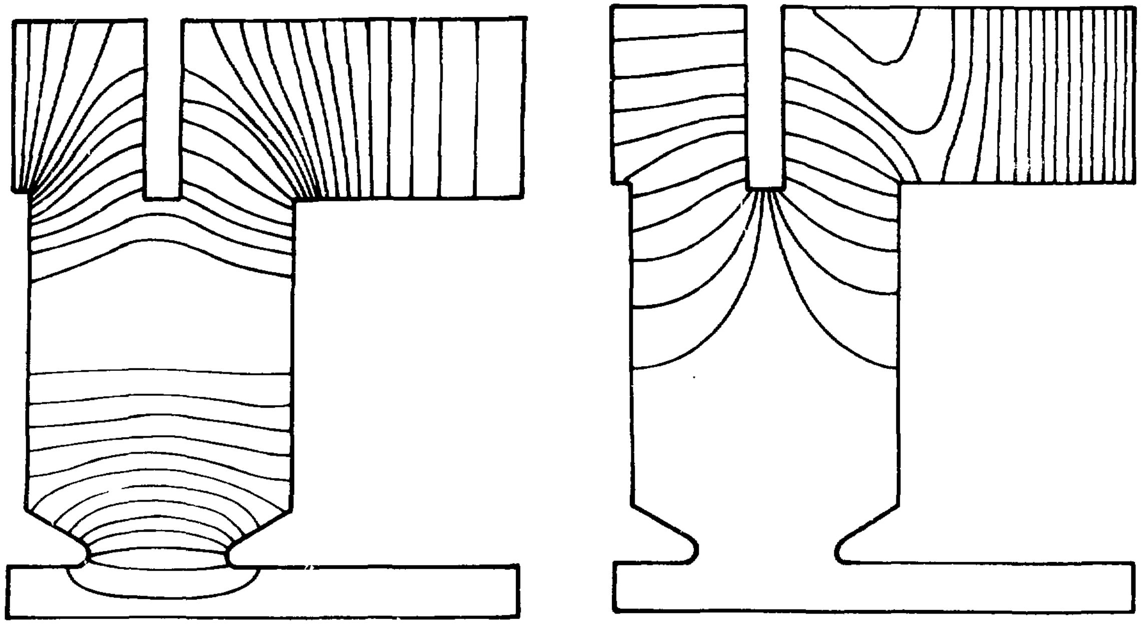
from which we can express

$$\beta_1 = \frac{\beta(2m - 1)}{2m_1} . \qquad (8)$$

For m >> 1, β_1 approaches β. The value, β_1, should be close to 1 so that the least adjustment is necessary.

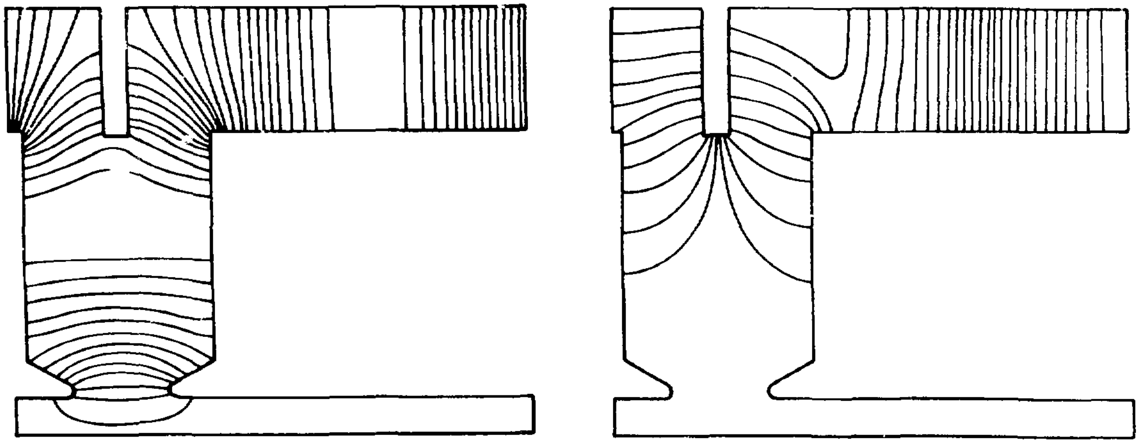
Table I lists a few values for β_1, which show that one can find $\beta_1 \backsim 1.0$ for practically all β values. At lower β values, $m_1 < m$ is preferred; at higher β values, m_1 closer to m is preferred. This, of course, is advantageous, because then the coaxial coupler length can be chosen appropriately for any β value.

Figure 2 shows TEM mode coaxial coupler field lines and DAW cavity field lines calculated using SUPERFISH. The wavelength, λ = 20 cm, corresponds to the resonant frequency, f_r = 1500 MHz, of our experimentally tuned DAW cavity.[6] The accelerating and coupling modes of the DAW cavity are coupled to the coaxial coupler TEM mode, as shown in Figs. 2(a) and 2(b), respectively. Total coupler length, ℓ, is $\lambda/2$, and for β = 0.66 (β of the DAW cavity) the other parameters are β_1 = 1.0, m_1 = 1, and m = 2. Neither the field patterns nor the frequencies are changed, as Figs. 3(a) and 3(b) show, when the coaxial coupler length is increased by $\lambda/2$,



(a) (b)

Fig. 2. Field lines in TEM mode coaxial coupler, $\ell = \lambda/2$, $f_r = 1500$ MHz, with coupling to the DAW (a) cavity accelerating mode and (b) cavity coupling mode.



(a) (b)

Fig. 3. Field lines in coaxial coupler TEM mode, $\ell = \lambda$, $f_r = 1500$ MHz, coupled to the DAW (a) cavity accelerating mode and (b) cavity coupling mode.

except that the field lines of the half-wavelength are added to the overall field pattern of the coupler.

Figure 4 shows field lines in a full-length coaxial coupler. Here $\beta_1 = 1$, $m_1 = 3$, $m = 6$, and $\beta = 0.66$.

It is possible to calculate other dispersion frequencies and their field lines in the coaxial coupler plus DAW cavity system by using SUPERFISH, as was done for the DAW structure itself.[6] The full system length, cavity-coupler-cavity, must be included in the calculations, which become cumbersome and time-consuming. However, we were interested in calculating the coupling coefficient between the DAW cavity and coaxial coupler, so we calculated the 0 and π modes of such a configuration. The calculated frequencies were $f_0 \doteq 1000$ MHz and $f_\pi \cong 1700$ MHz. Using the first-order approximation, we calculate the coupling coefficient from

$$k = \frac{f_\pi^2 - f_0^2}{f_\pi^2 + f_0^2} \quad . \tag{9}$$

For the calculated frequencies, we have $k \sim 0.5$, which indicates that coupling between the cavity and coaxial coupler is approximately the same as coupling between the accelerating and coupling cavities of the DAW structure.

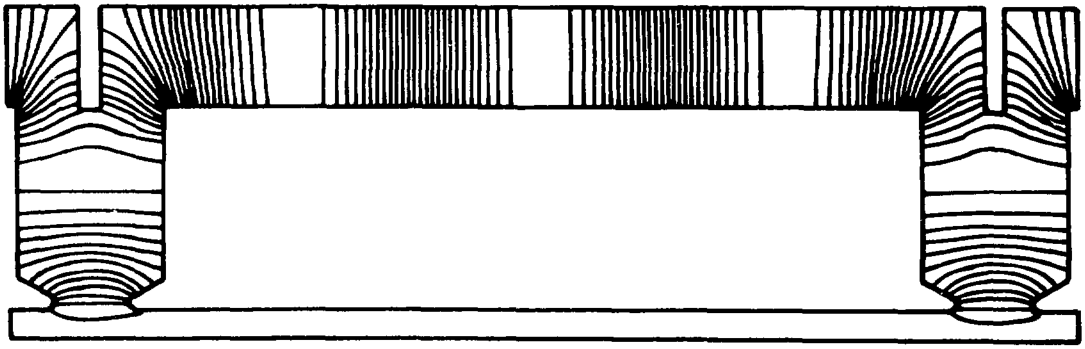


Fig. 4. Field lines in a whole TEM mode coaxial coupler, $f_r = 1500$ MHz.

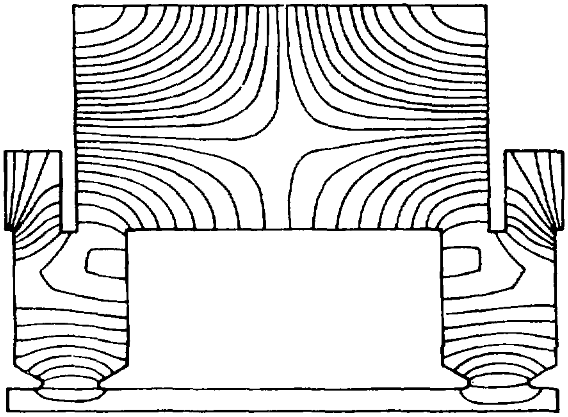


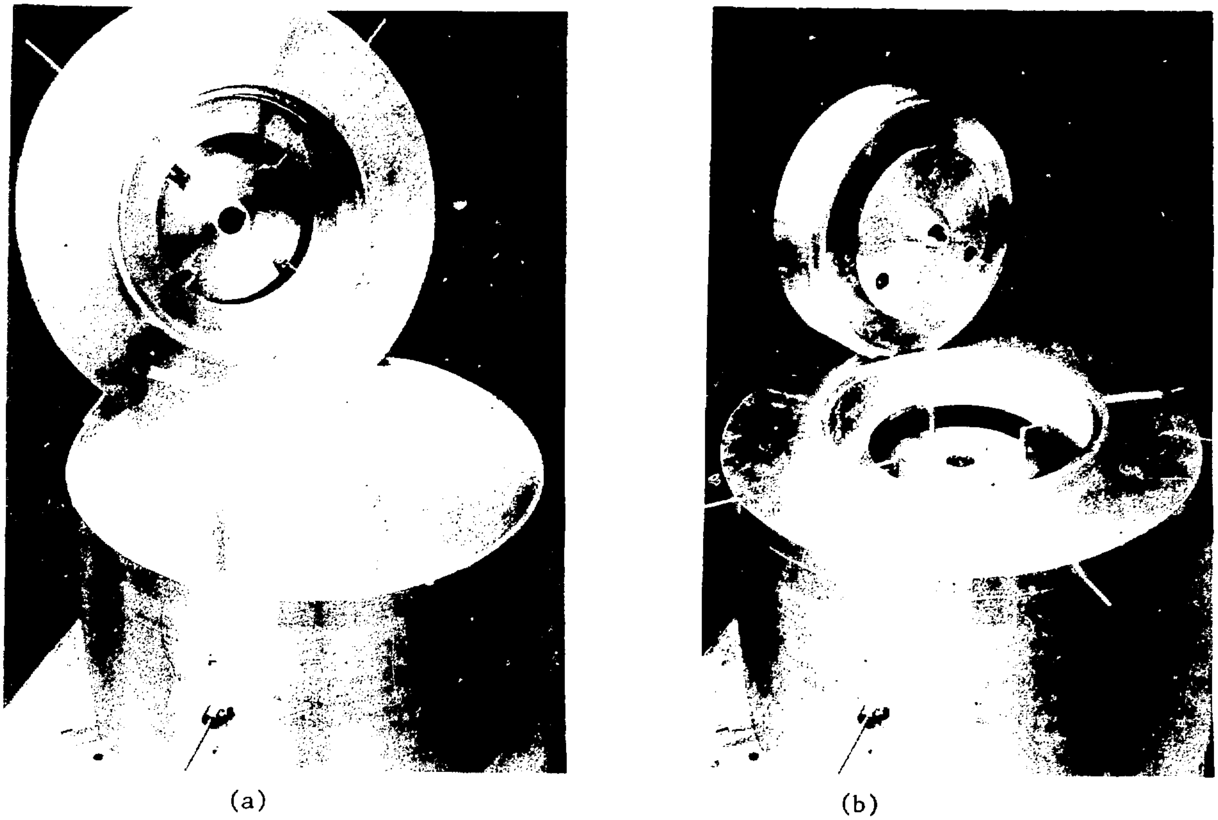
Fig. 5. Field lines in a higher order mode coaxial coupler, f_r = 1500 MHz.

Calculated field lines in one mode of the higher order mode coaxial coupler are shown in Fig. 5. The same conditions are applied to the length of this coupler as to that of the TEM mode coupler. The mode frequency also can be adjusted by changing the inner and outer cylinder radii while keeping the coupler length constant.

III. RESULTS

We built experimental models of a TEM mode coupler and a higher order mode coupler. We tuned both to the resonant frequency, f_r = 1500 MHz, of our tuned DAW cavities.[6] Then we connected sections of the DAW structure to each end of the coupler, as shown in Fig. 6. Four T-shaped supporting stems held the inner part of the coupler in the correct position. Because the supports caused perturbations in the cavities, we had to retune the cavities and the coupler to f_r = 1500 MHz. The TEM mode coupler was retuned by changing its length, and the cavity was retuned by a small change in its gap length. The higher order mode coupler was adjusted by changing its inner and outer cylinder diameters. The tuning procedure was the same as that for the DAW cavity described in Ref. 6. We measured dispersion frequencies and the on-axis field distribution using the bead-pull technique.

When the coupler is not tuned to the frequency $f = f_r$, a stop band occurs in the dispersion frequency curve and rf power is not transmitted so well through the coupler in the $\pi/2$ mode. A smaller field appears in the second accelerating section than in the first section if tuning was by nonsymmetric loading of the coaxial coupler. While tuning the couplers, we measured the system mode frequencies and constructed the dispersion curves, from which we then determined the stop-band width.



(a) (b)

Fig. 6 Coaxial coupler and DAW structure connection showing the (a) end flange with a disk lifted and (b) end flange in place with one DAW module on the top.

When the stop band closed, we measured the on-axis field distribution in both the TEM and higher order mode couplers. The distributions are shown in Figs. 7(a) and (b), respectively. The different end-cell distribution shapes are caused by different size beam holes in the end plates.

The rf power loss in the coupler is proportional to the square of the field in it. We measured the field in the coupler by the bead-pull technique, and found that it was about two orders of magnitude less than the field in the accelerating cavities, which indicates a very low rf power loss in the coupler.

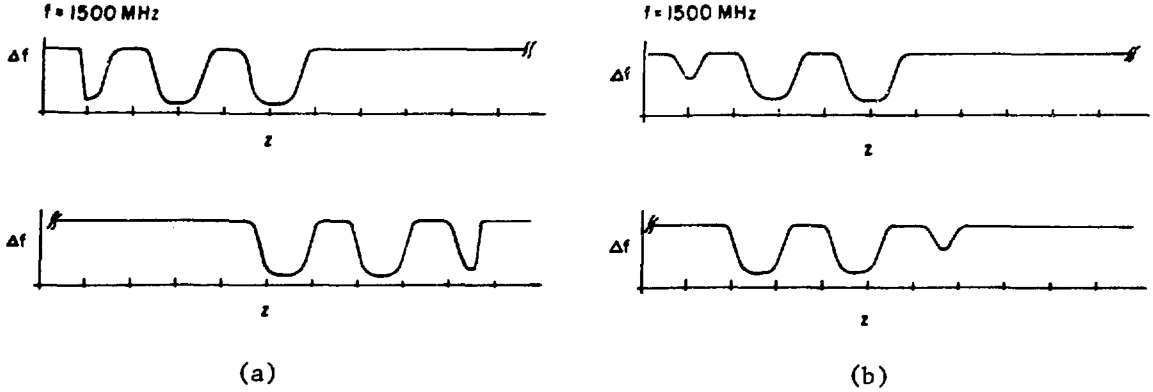


Fig. 7. On-axis field distribution in the DAW accelerating structure and a coupler as measured by the bead perturbation technique with the (a) TEM mode coupler and (b) higher order mode coupler.

In long accelerating structures transverse electric modes may be excited and travel with the beam, causing beam blowup. This effect can be very serious because it limits beam current intensity in the accelerator. We studied this problem in our system with the coaxial coupler and found that the asymmetrical TE_{11} mode does not couple to the coupler modes, so it is not transmitted through the coupler. This filtering effect might be used successfully in high-current operation of an accelerator where the probability of TE_{11} mode excitation is high.

Another advantage of the coaxial coupler is the ease and simplicity of feeding rf power into the structure, especially compared to the difficulty of connecting a high-power transmission line directly to an accelerator cell. Connecting a waveguide directly to the coaxial coupler so that the rf power is distributed symmetrically out of both sides of the coupler is much simpler and easier. We studied this connection experimentally. Coupling was through an aperture in the coupler wall located at a maximum of the magnetic field. We changed the aperture size until we got good matching. Then we measured the on-axis field distribution and found it to be the same as that measured using small coaxial pickup probes.

The coaxial couplers with or without rf power ports also can be used for rf power transmission from one tank to another. We used two coaxial couplers to connect three DAW accelerating sections. The rf signal was fed into one of the couplers while we picked up a signal at the other one. Figure 8 shows the on-axis field distribution in the whole system and clearly shows the feasibility of using these coaxial couplers in accelerator design.

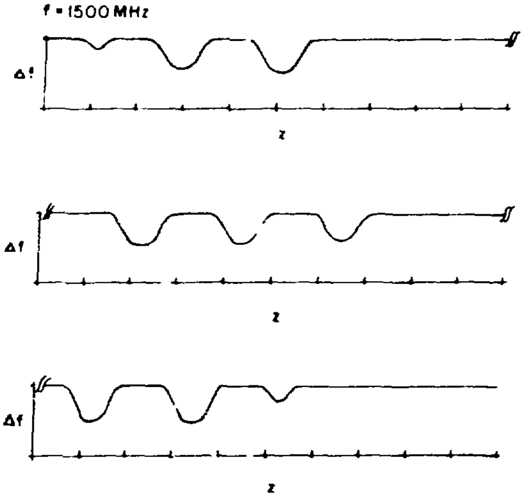


Fig. 8. On-axis field distribution in the DAW accelerating structures with both TEM and higher mode couplers.

IV. CONCLUSIONS

Radio-frequency coaxial couplers are efficient members of the family of units designed for high-energy linear accelerators, and they could be considered for use in synchrotron acceleration systems. Focusing devices such as permanent magnet quadrupoles and beam-monitoring devices can be installed within the inner cylinder. Their very good power transmission and small power loss make coaxial couplers particularly suitable for accelerators where high rf power levels are required to develop high gradients and/or to deliver energy to a high-intensity beam. The rf power from individual sources can be fed into each coupler or to every second one (or to any other sequence), depending on the total power required. If one rf power source shuts down, the power of the other sources can be increased enough so that accelerator operation can continue. The reliability of such a system is thus very high.

The coupler length must be such that the relative particle velocity β and the wave phase shift are matched. The coupler is tuned together with the structure; coaxial coupler tuning is not difficult, and no field stabilizing stems are required. Beam blowup modes of the structure are not coupled to the coupler modes so they are not transmitted from tank to tank. This filtering effect can be very useful in high beam current accelerators.

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