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A SMALL DIAMETER STANDING WAVE LINEAR ACCELERATOR STRUCTURE

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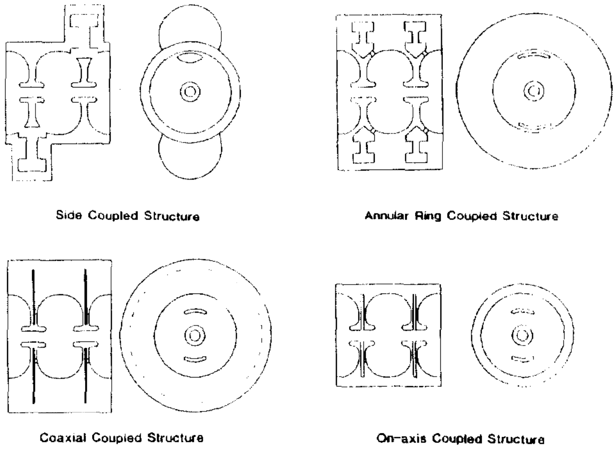
Abstract

A compact, small diameter, standing-wave linear accelerator structure suitable for industrial and medical applications is presented. The novel structure utilizes a new type of coaxial cavity as the coupling cavity for $\pi/2$ mode, standing-wave operation. This structure offers a significant reduction in overall diameter over the side-coupled, annular ring, and existing coaxial coupled structures, while maintaining a high shunt impedance and large nearest neighbor coupling (high group velocity). A prototype 4 MeV, 36 cm long, S-band accelerator incorporating the new structure has been built and tested. Theoretical accelerator design parameters, as well as experimental results, are presented.

INTRODUCTION

Compact electron linear accelerators with energies up to 50 MeV have been widely used for radiation therapy and industrial radiography since early 1960. Recently emphasis has been placed on more efficient, compact, and cost-effective designs to reduce the size and cost of these systems. For standing wave, $\pi/2$ mode linear accelerators, the coupling cavities allow for flexibility of design, since they are unexcited in steady state operation. Existing standing-wave accelerator coupling cavities can be classified into four general design types: side cavity, on-axis, coaxial, and annular ring structures. These four structures are shown schematically in Figure 1 and important features are summarized in Table I.



Side Coupled Structure

Annular Ring Coupled Structure

Coaxial Coupled Structure

On-axis Coupled Structure

Figure 1. Various Standing Wave Linear Accelerator Structures

Since the side cavity structures are off-axis, they do not influence the design of the accelerating cells, enabling side coupled accelerators to attain high efficiencies. Side coupled structures, however, have the disadvantages of increasing the effective diameter of the accelerator guide and the number of machining and assembly steps required.

TABLE I TYPICAL PARAMETERS FOR S BAND $\frac{\pi}{2}$ MODE STANDING WAVE ACCELERATOR STRUCTURES

	Side Coupled	On-axis	Standard Coaxial	Annular Ring	New Design
Effective Diameter	16.5 cm	8.4 cm	12.6 cm	14.0 cm	8.4 cm
Minimum Web Thickness Between Accelerating Cells	3 mm	9 mm	9 mm	5 mm	9 mm
Maximum Nearest Neighbor Coupling: K_1	5 %	20 %	25 %	18 %	25 %
Nearest Neighbor Coupling / Next Nearest Neighbor Coupling $= \frac{K_1}{K_2}$	30	200	–	–	110

Cylindrically symmetric cavities - the on-axis, coaxial, and annular ring designs - have the advantage of being machined directly into the opposite side of an accelerating cell, thereby eliminating multi-piece assembly and prebrazing. Construction costs can be substantially reduced. Existing designs, however, all have disadvantages. The radius of an on-axis coupling cavity is comparable to the radius of the accelerating cavity, but the structure is susceptible to the excitation of parasitic and beam blowup modes, which reduce the overall accelerator efficiency and beam stability[1]. On-axis structures are also sensitive to thermal detuning, a result of the thermal deformation of the web between accelerating cells.[2] Coaxial structures eliminate the direct interaction of the electron beam with the coupling cavity, but existing designs increase the effective guide diameter 60% to 80%. The coaxial structure is also more resistant to thermal detuning. Current designs consist of narrow cylindrical cavities sandwiched between accelerating cells, which operate at a coaxial TM_{010}-like mode.[3,4] Coaxial cavities use magnetic coupling and have strong nearest-neighbor coupling with small next-nearest-neighbor coupling, which improves power flow and increases the mechanical tolerances allowed. Annular ring designs have the same size disadvantage as the existing coaxial structures, along with increased machining complexity.

A coaxial coupling cavity extends the zero field drift tube region between adjacent accelerating cavities, thereby reducing the efficiency of the accelerator. Coaxially coupled structures, however, attain a higher percentage of theoretical shunt impedance[5]. Consequently, accelerator efficiencies comparable to those of side coupled structures can be obtained if the web between accelerating cells is not increased more than a few millimeters. The size disadvantage of the annular ring and existing coaxial designs exemplifies the problem of developing a new coaxial design which 1) has a diameter comparable to an accelerating cavity, 2) does not significantly increase the web thickness, and 3) has large K_1 and small K_2. In this paper, a new coaxial cavity design is presented, and low power tests of a prototypical accelerator using this design are summarized.

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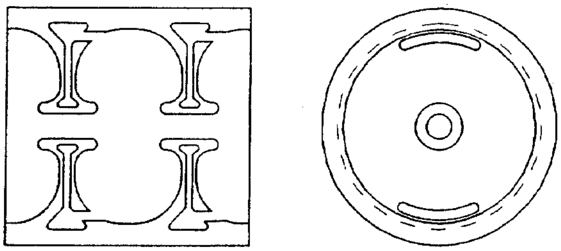

Figure 2. Schematic Illustration of New Coaxial Coupled Standing Wave Linear Accelerator Structure

The Coaxial Coupled Accelerator

The Coaxial Coupling Cavity Design

The new structure, designed to operate at 3000 MHz, is presented schematically in Figure 2. It consists of a small radius, coaxial structure with enlarged triangular areas which fill the unused areas between accelerating cavities and increase the magnetic induction in those regions. In essence, the geometry enhances the intrinsic field distribution of a simple coaxial cavity in the TM_{010}-like mode, while reducing the cavity to smaller overall dimensions. The flat area between the enlarged end regions acts as an effective capacitor and concentrates the electric field in that region, away from the coupling slots, similar to a reentrant cavity. The concentration of the magnetic field provides an ideal coupling opportunity. Two slots are cut 180° opposite each other, thereby preserving symmetry about the beam axis. Relatively small slots can provide adequate nearest neighbor coupling, K_1, and the next nearest neighbor coupling, K_2, can be made negligibly small by rotating the slots 90° at each cell. The design also allows for a very high K_1 to be obtained while keeping K_2 to an acceptable value, by increasing the slot width and arc length.

The coupling cavity fills the web between two accelerating cavities. Several dimensional constraints were imposed upon the design. First, the cavity radius was to be approximately equal to that of the coupled accelerating cavity. Second, the coupling cavity gap could not be less than 3 mm to maintain reasonable mechanical tolerances. Third, a minimum wall thickness of 3 mm was to be maintained at all points for mechanical stability and thermal conduction.

Before the coupling cavity was designed, an accelerating cavity with a 9 mm web thickness was optimized for maximum shunt impedance, using the cavity program LALA[6]. A cavity with inner radius 3.58 cm and theoretical shunt impedance per unit length of 124 MΩ/m was designed. The cavity code LACC was then used to design the coaxial coupling cavity, subject to the constraints listed above[7]. The program was used to arrive at a cavity 5% higher in frequency than the operating frequency, because of the anticipated effect of the coupling slots. The size and location of the coupling slots were determined using the LACC magnetic field values. A coupling slot of arc length 45° and width 5 mm was selected and located along the outer edge of the cavity.

A half coupling cavity cut to the LACC design dimensions resonated at 3160 MHz without the coupling slots and 3015 MHz with the slots. In the full cavity, however, the coupling slots on opposite walls are rotated 90° and this lowers the full cavity frequency to 3000 MHz. Machine tuning to within ± .2 MHz of the desired frequency was easily accomplished by increasing the diameter to lower the frequency or increasing the capacitive gap to increase the frequency.

The Accelerator Design

The prototype accelerator was designed to match the performance characteristics of an existing side coupled structure, the L1000-A accelerator built by Varian Associates. It consists of 7 1/2 accelerating cavities and was designed for optimum performance at 4 MeV output energy. A beam simulation program was used to develop the buncher configuration for the guide, using the LALA field profiles. An injection voltage of 15 kV was used, with variable field gradients. A three-cell buncher with cell length 44.8 mm was selected. The resulting output energy spectra are given in Figure 3. The overall length of the guide is 35.9 cm. RF power from a magnetron is introduced at the 5th full accelerating cavity. The peak rf power delivered at the guide is 2.3 MW, with a 4.3 μsec pulse width. Table II summarizes the accelerator design parameters.

TABLE II DATA SUMMARY

Accelerator Length	35.9 cm
Number of Cavities	7½
Frequency	2997 MHz
Coupling: Nearest Neighbor (K_1)	3.3 %
Next Nearest Neighbor (K_2)	.03 %
RF Peak Power	2.3 MW
RF Pulsewidth	4.3 μ sec
E peak/Eo	8.1
Transit Time Factor	.916
Theoretical Qo	16,000
Theoretical ZT^2/L	124 MΩ/m

	Design	Measured
Qo	14,400	13,500
Qext	7,200	6,600
βo = Qo/Qext	2.0	2.05
ZT^2/L	111 MΩ/m	105 MΩ/m

Both the coupling and accelerating cells were accurately tuned by machining, in order to make post-braze tuning of the guide unnecessary. The accelerating cells were tuned to within ± 0.1 MHz of the desired frequency. The desired frequencies were determined from the dispersion measurements of successive stacks of 2, 4, and 6 half cells. The coupling half cavities were tuned to within ± 0.2 MHz of 3009 MHz,, which gave full cell frequencies of approximately 2994 MHz. Because of the sensitivity of the large capacitive region of the cavity to gap length, the effect of the braze had to be allowed for. The full cavity frequency varies 240 MHz/mm of additional spacing between half cells. The braze process adds 20 microns of copper between cells on average, resulting in an increase of approximately 5 MHz.

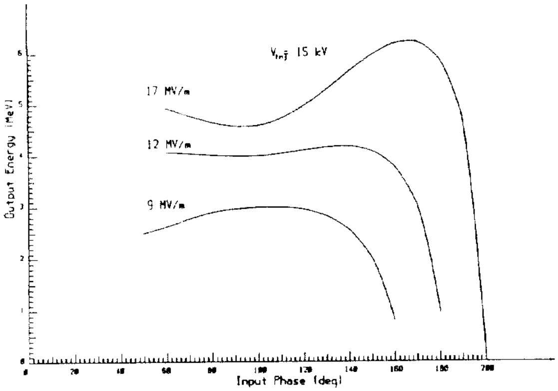

Figure 3. Energy Spectra of New Coaxial Coupled Standing Wave Accelerator, as a Function of Input Phase for Several Field Gradients

Experimental Results

The measured and theoretical dispersion curves for the brazed guide are shown in Figure 4. The theoretical curve assumes a biperiodic structure with $f_{accelerating}$ = 2996.69 MHz and $f_{coupling}$ = 3000 MHz. The bead drop data is shown in Figure 6. The guide had a measured Q of 13,500 and Q_{ext} of 6,580, with a coupling factor, β_0 , of 2.05. The nearest neighbor coupling, K_1 was 3.3% and the next nearest neighbor coupling was 0.04%. The coupling cavity frequencies were 3001.5 MHz, ± 1.5 MHz. Before and after brazing length measurements of the guide indicated a greater than average increase per cell, approximately 30 microns. This explains the high coupling cavity frequency, which is apparent in the dispersion curve. The accelerating cells remained tuned to within ± 0.1 MHz of a fixed frequency. These frequency variations were acceptable and no post-braze tuning of the guide was done. High power tests of the accelerator are currently being undertaken.

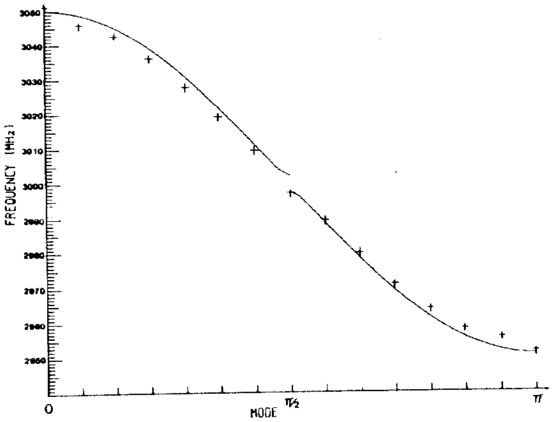

Figure 4. Dispersion Curve for New Coaxial Coupled Standing Wave Accelerator Structure

Conclusion

A new, small diameter coaxial coupling cavity which fits entirely in the web between accelerating cavities was developed. A compact, standing wave, linear accelerator incorporating the new cavity was designed, assembled, and tested. In addition to smaller size and less weight, the accelerator offers various advantages over existing structures. The component cells are simpler to machine and assemble. No post-braze tuning of the accelerator is required. For equal size coupling slots, higher values of K_1 with lower values of K_2 are obtained. Low power tests indicated the properties of the assembled prototype accelerator were in good agreement with the design calculations.

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