VARIABLE ENERGY STANDING WAVE LINEAR ACCELERATOR STRUCTURE

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Summary

A variable-energy, single-section, side-coupled standing-wave linear accelerator structure is presented. This new structure provides a simple, reliable technique of continuously varying charged-particle beam energy over a wide range without degrading the energy spectrum. Theoretical and experimental results of this new technique are described. Application to medical and industrial linear accelerator technology has been demonstrated.

Introduction

Standing-wave linear accelerators are widely used for medical (radiation therapy) and industrial (radiography) applications. Most of these single-section accelerators are optimized for energy spectrum at one beam energy. It is highly desirable to obtain a beam of charged particles with a narrow spread of energy, this energy being variable over a wide range.

Radiation therapy accelerators typically produce x-rays in one of three energy ranges: 4-6 MeV (low energy), 8-12 MeV (medium energy) and 15-25 MeV (high energy). Depending upon the location of tumors, the optimum treatment can be performed by choosing the right x-ray energy. A multi-energy accelerator would allow optimum treatment at a larger range of tumor depths with a single machine. Similarly, a multi-energy industrial radiography machine would significantly increase the useful range of subject thickness.

One approach to varying the beam energy over a wide range is to cascade sections of linear accelerator guides which are independently excited from a common RF source with independent control of amplitude and phase.[1,2,3] Another approach is the double-pass single-section linear accelerator which uses a movable reflecting magnet to obtain phase variation between passes.[4] However, these techniques are rather complicated and the results are often costly and perhaps less reliable. Moreover, the techniques do not necessarily provide the wide range of energy variation desired without spectrum deterioration.

This paper presents a new technique which provides a simple, reliable method of varying the energy over a wide range without degrading the energy spectrum.

Structure Description

The geometry of the first few accelerating cavities of a single-section standing-wave accelerator guide, or "buncher", is designed to bunch the injected beam to minimize the energy spread for the desired accelerating electric field. For maximum efficiency, this field is nearly constant along the beam axis. The optimum bunching condition can be easily destroyed by changing the accelerating electric field for a given buncher geometry. The structure described here allows the accelerating electric field in the buncher to be kept constant while varying the magnitude and sign of the accelerating field in the rest of the accelerating guide.

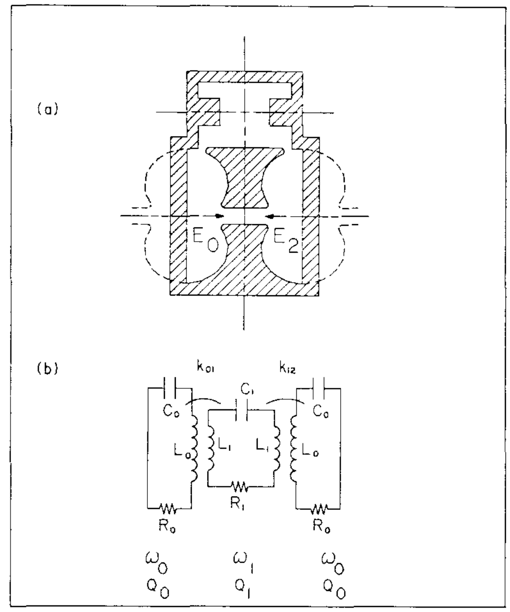

Figure 1. (a) Simplest structure of side-coupled standing-wave accelerator.
(b) Equivalent circuit.

The side-coupled standing-wave accelerator structure which was developed at Los Alamos has many advantages.[5] Not the least among these is the tenacity with which the structure holds the relative fields in the accelerating cavities constant. The simplest structure using this concept is shown in Fig. 1(a). The coupling cavity which is unexcited at $\pi/2$ mode operation is removed from the beam axis. The technique described here is to utilize this off-axis unexcited side coupling cavity to vary the relative magnitude and/or sign of the accelerating fields of adjacent centerline cavities.

Typically, all cavities are longitudinally symmetrical to assure that the couplings between centerline and side-coupling cavities are equal, to provide constant accelerating electric field along the guide. This symmetry is indicated in Fig. 1(a).

The equivalent circuit of the structure is shown in Fig. 1(b). For $\pi/2$ mode operation, this equivalent circuit leads to the following relationship between coupling factors (K_{01} and K_{12}) and accelerating field amplitudes (E_0 and E_2):

$$\frac{E_2}{E_0} = -\frac{K_{01}}{K_{12}} - \frac{2}{K_{01}\,K_{12}\,Q_0\,Q_1}$$

as K Q $\gg$ 1, it is clear that varying the ratio K_{01}/K_{12} will result in an accelerating-field amplitude step. We have demonstrated that if this circuit is imbedded in a longer structure, the same step will result. Thus, providing independent control of accelerating fields in adjacent centerline cavities of a standing-wave accelerator guide is reduced to varying the ratio K_{01}/K_{12}. We have chosen to provide for this variation in the side cavity, since variation of side-cavity frequency and loss has no first-order effect on accelerator operation. Also, mechanical access is more convenient since the side cavity is located outside of the centerline accelerating cavities.

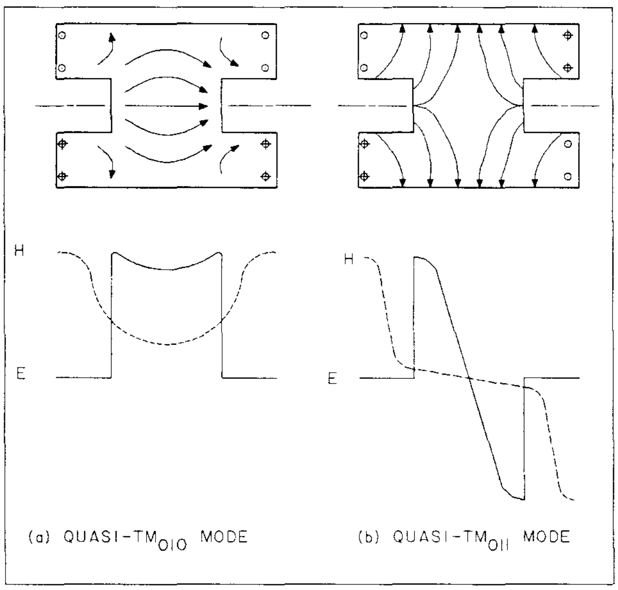

Figure 2. Electric and magnetic field distribution for longitudinally symmetric cavity.

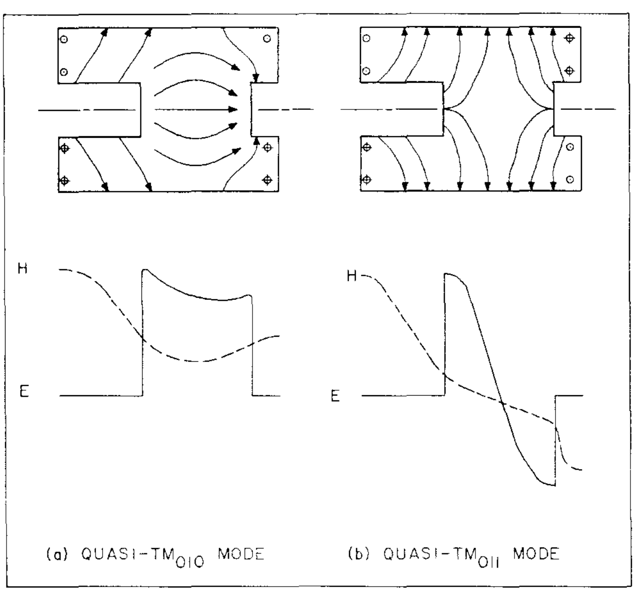

Figure 3. Electric & magnetic field distribution for longitudinally asymmetric cavity.

Variation of Coupling Ratio

The side-coupling cavity is magnetically coupled to the accelerating centerline cavities through the coupling apertures. The field distributions in the side-coupling cavities without coupling apertures shown in Fig. 2. If the distribution of magnetic field within the side cavity were made asymmetrical, a variation of coupling ratio K_{01}/K_{12} would result.

There are several ways to induce this magnetic field asymmetry within the side cavity. One technique is to lengthen one center post and shorten the other as shown in Fig. 3(a).[6] The resultant asymmetrical field distribution is schematically shown in the same figure. The resonant frequency of the side cavity can be held constant by keeping the proper relation between post lengths. It must be noted that if a cavity resonant mode such as the one described in Fig. 3(b) were excited, the relative sign of the accelerating fields in the adjacent centerline cavities would reverse.[7]

Figure 4 shows the relationship of accelerating electric field ratio and side cavity post length variation for the quasi-TM_{010} mode resonance case. To maintain the desired resonant frequency, one has to move both posts simultaneously. This relation is also shown in Fig. 4. By introducing this kind of side cavity in a longer accelerator at a particular location, one can produce the desired step of magnitude and sign in the axial electric field distribution, yet preserve the $\pi/2$ mode resonant conditions.

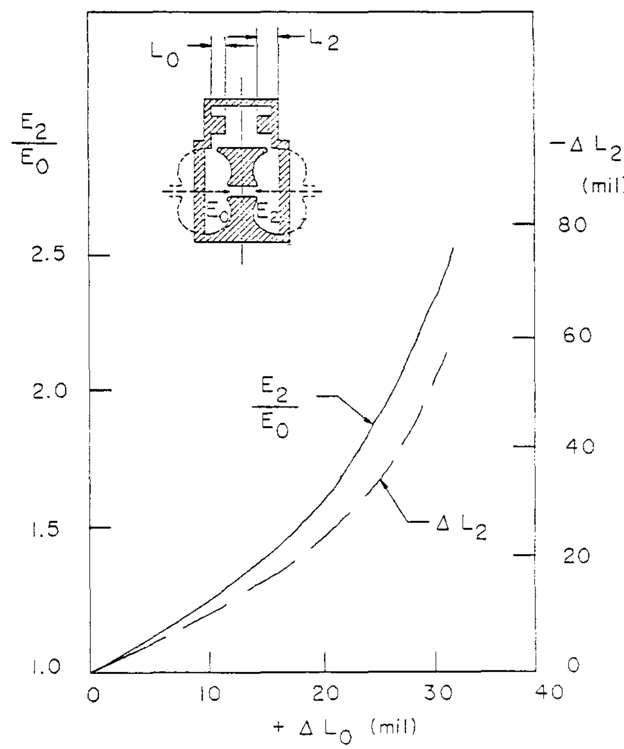

Figure 4. Relationship of field ratio to post-length variation for quasi-TM_{010} mode resonance.

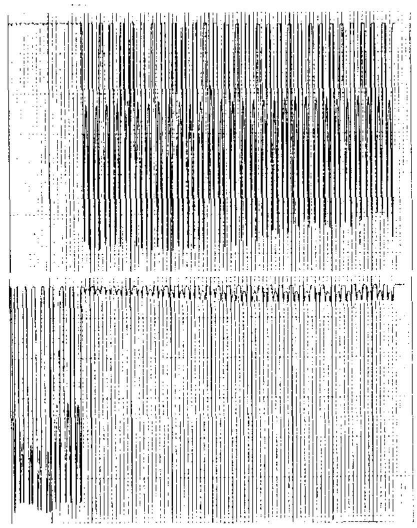

Fig. 5 Axial electric field distribution for (a) high energy mode and (b) low energy mode of Clinac 2500.

Application

Two classes of standing-wave accelerator guides utilizing the concept described have been developed at Varian. They are used in the Clinac 2500 for radiation therapy and in the Linatron 200A for industrial radiography. Table I shows the basic parameters of these two machines.

The Clinac 2500 accelerator guide is capable of operating at two x-ray energies, 24 and 6 MeV, and at several electron energies up to 28 MeV. Fig. 5 shows the accelerating electric field distribution on the beam axis of the Clinac 2500 accelerator guide for the high energy mode (24 MeV) and the low energy mode (6 MeV). The control side cavity is located between the 8th and 9th accelerating cavities. High power experimental results show that the obtainable peak beam currents at 24 MeV and 6 MeV are 50 mA and 180 mA respectively.

Table I. Guide Parameters

Parameters	CL-2500	L-200A
Guide Length (m)	1.9	0.1
No. of cells	1/2 + 36	1/2 + 1 + 1/2
Frequency (MHz)	2856	2997
Effective Shunt Impedance (M Ω/m)	95	65
Qo	16000	13000
RF Power at Guide (MW)		
High Energy Mode	4.5	1.6
Low Energy Mode	2.0	1.6
Coupling Factor K_1	0.04	0.01
Load Line (MeV)		
High Energy Mode	28.5 - 85 i	2.8 - 3.0 i
Low Energy Mode	17.0 - 60 i	1.4 - 1.3 i

The Linatron 200A accelerator guide is designed to operate at 2 MeV and 1 MeV. The switching side cavity is placed between the 2nd and 3rd accelerating cavities. This special side cavity, which uses the resonant-mode conversion technique described before, reverses the sign of the accelerating field. As a result, this guide is capable of operating at two different energy levels without varying the RF input power or the beam current. The Linatron 200A has demonstrated the ability to radiograph steel sections from 38 mm to 200 mm in thickness with 1% sensitivity (1-2T per ASTM E142).

Conclusion

In response to the need for a more versatile single-section accelerator guide, we developed a concept which allows control of the electric field within a guide. The concept allows a step field discontinuity between two accelerating cavities to be varied at will, in a structure in which field relationship is usually invariable. The concept was implemented in several experimental models and two forms of the concept were used in operating guides. These performed as expected. Subsequently, both forms have been used in commercial accelerators, one medical and one industrial, which have been delivered to customers throughout the United States.

Acknowledgements

The authors wish to express many thanks to V. Vaguine for his collaboration and direction, to V. Eliashberg who provided theoretical and computational studies, to A. McEuen who helped to prepare this manuscript and to L. Bean and his staff for providing machining and drafting services.

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