IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

STANDING WAVE HIGH GRADIENT ACCELERATOR STRUCTURE

Victor A. Vaguine
Varian Associates Inc., Palo Alto, California

Summary

A novel type of standing wave linear accelerator structure has been developed at Varian Associates, Inc. This accelerator is an interlaced combination of two side cavity coupled standing wave substructures. An S-band prototype accelerator guide with two identical substructures and total accelerating length of 10cm has been built and successfully tested with a 2MW magnetron. Significant improvement in maximum permissible accelerating gradient was achieved. Output electron beam energy of 4 MeV and corresponding accelerating gradient of 40 MeV/m were experimentally demonstrated. The shunt impedance of the structure corresponds to 83 MΩ/m.

Introduction

In many areas of application of linear accelerators, it is important to obtain the highest possible acceleration of charged particles per unit length. This is especially true in applications where available space is restricted. An example is the medical straight ahead electron linear accelerator of the type employed in radiation therapy. Here, a compact accelerator structure, including an electron gun and a target, is installed in the restricted space of the x-ray head in a rotating gantry. Additional space is required for radiation shielding, vacuum system, primary collimator, variable jaws, radiation dose monitoring chamber and flattening filter. The advantages of having a short accelerator structure with a very high accelerating gradient are significant in this application. This would permit production of high output electron energy in a therapy machine with a large available distance between the beam target and a patient. As a result, one would obtain the optimized clinical value of x-ray radiation - deep penetration and small skin dose - with a relatively simple and inexpensive machine that can be rotated completely around a patient lying on a treatment couch of convenient height.

LASL Standing Wave Structure

The maximum permissible accelerating gradient in a given structure is determined by the RF breakdown threshold. It is convenient to express the quality of the structure relative to maximum permissible accelerating gradient in terms of E_p/E_o, where E_o is the average accelerating gradient along the structure and E_p is the maximum RF field on the internal surface of the structure.

Another important characteristic of a linear accelerator structure is its efficiency which can be expressed in terms of shunt impedance.

It is not obvious that optimization of both qualities (maximum permissible accelerating gradient and high shunt impedance) can be achieved in a given structure. One must rather be prepared to think in terms of a compromise, weighing trade-offs between these qualities.

The design of the LASL standing wave side coupled cavity linear accelerator is an example of such trade-offs. The concept, design, optimization and experimental results of the LASL structure are well known (see, for example, the article by E.A. Knapp, B.C. Knapp and J.M. Potter[1]). The conceptual evolution of this structure is shown in Fig. 1 (left side). The fundamental idea of the LASL standing wave design is the removal of the coupling (unexcited) cavities from the beam path, and the expansion of the accelerating (excited) cavities to occupy the entire structure length. This approach also made it possible to optimize cavity shape almost independently from intercavity coupling considerations. As a result, LASL structures with impressive shunt impedance have been designed.

However, detailed analysis of the optimized LASL structure shows that one-third of the entire structure length is still occupied by intercavity drift tubes, and hence is not available for active acceleration of the beam. The basic limitation of the LASL structure in the area of high accelerating gradient application results from a very high value of E_p/E_o and hence a relatively low level of RF breakdown threshold. This is due to the strong concentration of highly inhomogenous electric field at the drift noses.

Ideally, one would like to have a structure with $E_p/E_o=1$. An example of such a structure would be a very short cylindrical TM_{010} cavity with two very small beam holes along the central axis. In the case of the LASL design employed by Varian in low energy medical linear accelerators (Clinac 4), $E_p/E_o=3.76$, which is far greater than the above mentioned ideal case. Measurements of E_p/E_o were accomplished by an accurate surface perturbation technique described by the author earlier[2]. The maximum permissible accelerating field determined experimentally, is only 19.7 MV/m in S-band pulsed operation, with a pulse length of 4 to 5 μsec. Since the factor E_p/E_o is known, it is easy to calculate that the RF breakdown field on the internal surface of this structure reaches approximately 74 MV/m. In order to provide a safety factor, the structure is actually operated with an accelerating gradient of 14.5 MV/m and a maximum surface field of 54 MV/m.

Concept of Varian Accelerator Structure

A novel standing wave linear accelerator structure recently has been developed at Varian Associates, Inc. This structure combines high efficiency and high accelerating gradient capability. It takes the form of two interlaced standing wave side cavity coupled substructures. The conceptual evolution of this approach is shown in Fig. 1 (right side).

As in the case of the LASL design, coupling (unexcited) cavities are removed from the beam path and the first substructure is produced. Rather than expanding the accelerating (excited) cavities through the entire length of the accelerator, the first substructure is combined with an identical second one. As a result, one obtains the Varian standing wave accelerator structure: a combination of two independent substructures, each operating at the $\pi/2$-mode, and each with an independent RF input coupler. As shown in Fig. 2, the side cavities are positioned along the structure in two transverse planes in comparison with the LASL design, in which side cavities are placed in the one plane only.

Proper operation of the Varian guide requires that both substructures be tuned to the same resonant frequency, RF power from the RF source must be divided equally between the two substructures, and a phase difference of $\pi/2$ between these two RF power inputs must be provided in order to obtain synchronization between the accelerating fields and the charged particles and to achieve maximum acceleration.

The "natural" technical means for obtaining the equal input RF power division with the proper phase relationship is a 3db hybrid coupler. The properties of the 3db hybrid coupler exactly match the input RF power requirements: the RF power is divided into two equal parts, with a phase difference of $\pi/2$. As shown in Fig. 3, the 3db hybrid is connected to two adjacent input coupler cavities. The sign of the $\pi/2$ phase difference between the two substructures can be determined by selecting which of the two input ports of the hybrid is used for introducing RF power from the source. Switching the input between these two ports reverses the direction of acceleration. An additional useful feature of the proposed design, especially in pulsed operation, is that reflected power from both substructures goes into the load on the fourth port of the hybrid. As a result, the RF power source is provided with additional protection.

Both substructures should be tuned to the same frequency. If the resonant frequencies of the two substructures are slightly different and equal to f_1 and f_2 respectively, and the frequency of the RF power source is selected to be $f_o=\frac{1}{2}(f_1+f_2)$, the resulted accelerating gradient is reduced by the factor:

$$F=1-\tfrac{1}{2}\left(1+\frac{\pi^2}{16}\right)Q_L^{\,2}\left(\frac{f_1-f_2}{f_o}\right)^2 ,$$

where Q_L is the loaded Q-factor of each substructure. Typical parameters of an S-band structure, operating under the condition in which the RF power dissipated in the structure is equal to the RF power absorbed by beam loading, are f_o=3000 MHz and Q_L=3000. In order to provide $F>0.95$, one must tune both substructures to within $|f_1-f_2|\leq 0.25$ MHz, which is readily achievable.

The internal cavity configuration of the Varian structure is shown in Fig. 2, together with the LASL geometry for comparison. In the case of a small hole approximation with TM_{010} pill-box geometry, one can easily estimate the shunt impedance ZT^2 and E_p/E_o. Taking into account the fact that the effects of sidewall rounding and coupling slots are approximately equal and opposite, one obtains $ZT^2=85\ \frac{M\Omega}{m}$ and $E_p/E_o=1.23$ for the case of λ=10cm and d/D=0.88. The small hole approximation represents a practical case. Hence, one would expect an increase in maximum permissible accelerating gradient by approximately a factor of three relative to LASL design without compromising the shunt impedance.

Fabrication and Test of V-guide Prototype

A short experimental S-band linear accelerator of the Varian type has been built from OFHC copper for design verification studies. The parameters of this accelerator are listed in TABLE I. Parameters of the LASL Clinac-4 structure are also included for comparison. Thickness of intercavity dividing walls is 3mm. The resonant frequency of the substructures has been tuned within 30 kHz.

Electron energies in excess of 4 MeV have been produced with an input peak RF power of 2 MW. Operation with full available RF power at the accelerating gradient of 42 MeV/m has shown no evidence of internal RF breakdown.

Acknowledgments

The author wishes to express his appreciation to A. McEuen and L. Bean for their assistance and valuable contributions in the course of developmental work.

References

1. E.A. Knapp, B.C. Knapp, and J.M. Potter, Rev. Sci. Instr. 39, 979 (1968).
2. V. Vaguine, CERN Yellow Report, CERN 71-4, (1971).

TABLE I

Parameters of SW Structures

	LASL (C-4)	Varian (V-guide)
Resonant Frequency (MHz)	2998	2998
Accelerating Length (cm)	27.5	10
Number of accelerating cavities	5½	2x2
Number of side cavities	5	2
Beam Aperture (mm)	10	3
Coupling Coefficient	0.03	0.02
Transit Time Factor (β=1)	0.771	0.918
Shunt Impedance ZT^2 (MΩ/m)	78	83
Q_o-factor	15,500	11,300
Max. Perm. Accel. Grad. ($\frac{MV}{m}$)	19.7	58.3
Operating Accel. Grad. ($\frac{MV}{m}$)	14.5	40
Input RF power at 4 MeV with no Beam Loading (MW)	0.75	1.80

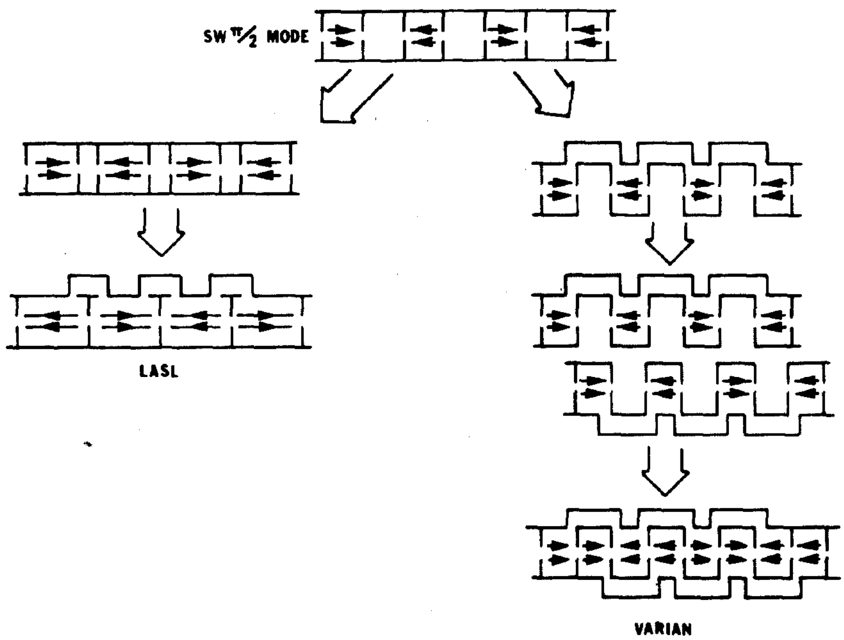

Fig. 1 Conceptual evolution of LASL (left side) and Varian (right side) standing wave accelerator guides.

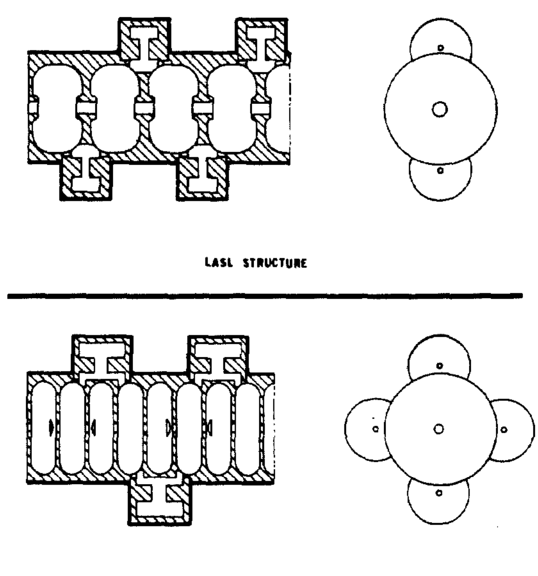

Fig. 2 A cross sectional view of LASL (top) and Varian (bottom) structures.

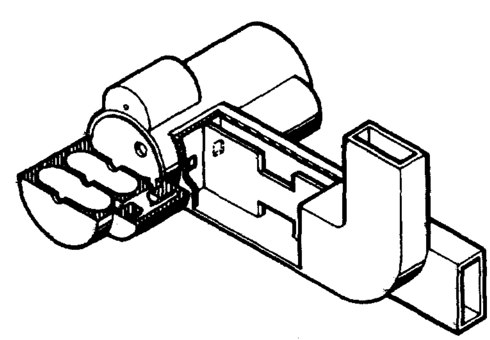

Fig. 3 Varian linear accelerator guide with 3db hybrid power divider.