VARIABLE-ENERGY DRIFT-TUBE LINACS*

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Summary

Practical applications of ion linacs are more viable now than ever before because of the recent development of the radio-frequency quadrupole accelerating structure, as well as other technological advances developed under the Pion Generator for Medical Irradiations program. This report describes a practical technique for varying the energy of drift-tube linacs and thus further broadening the possibilities for linac applications. This technique involves using the post couplers (normally used to flatten and stabilize the electric fields) to create a step in the fields, thus terminating the acceleration process. In the examples given for a 70-MeV accelerator design, when using this technique the energy is continuously variable down to 20 MeV, while maintaining a small energy spread.

Introduction

Practical applications of proton and ion linacs are more viable now than ever before because of the development of the radio-frequency quadrupole (RFQ) accelerating structure and other accelerator technology that we have proposed as an integrated system in our PIGMI (Pion Generator for Medical Irradiation) design.[1] Although many of these applications would benefit from a variable-energy option, drift-tube linacs (DTL) are not noted for this property.

The only variable-energy scheme in routine use involves turning off later portions of the linac to provide a few discrete energies from multitank linacs. Many applications require more discrete energies than normally are available from this scheme. The PIGMI technology advocates single-tank, post-coupled DTLs for simplicity and reliability. Any multitank arrangement to provide energy variability is a step backward in linac technology.

Post couplers have a special property in that they can introduce a step in the electric fields. Modest perturbations to the symmetry of the post-coupler/drift-tube geometry can introduce few-percent cell-to-cell changes in the fields across the post coupler. Several such perturbations on adjacent post couplers can introduce a sizable reduction in the fields over the region of a few cells. Such steps in the fields can be used to drop the beam out of synchronism with the accelerating fields and provide a variable-energy capability for the single-tank, post-coupled DTL.

Performance

Some examples of the field distributions that could be established in a 100-cell, post-coupled DTL are shown in Figs. 1, 2, and 3. Figure 1 shows

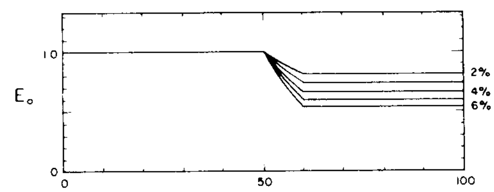

Fig. 1. Ten 2, 3, 4, 5, and 6% perturbations beginning at cell 50.

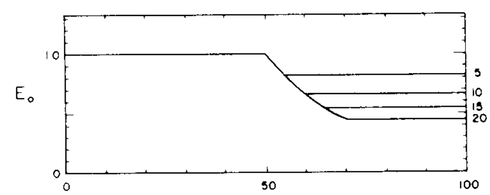

Fig. 2. Five, ten, fifteen, and twenty 4% perturbations beginning at cell 50.

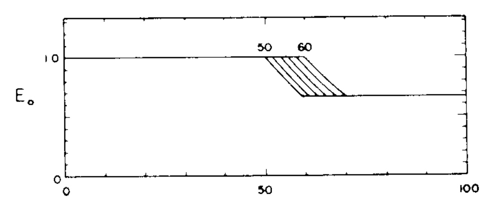

Fig. 3. Ten 4% perturbations beginning at cells 50, 52, 54, 56, 58, and 60.

the field distributions that result when 10 adjacent post couplers, beginning at cell number 50, are set for perturbations of from 2, 3, 4, 5, and 6%. Figure 2 shows the field distributions that result when 5, 10, 15, and 20 post couplers are set for 4% perturbations, beginning at cell 50. Figure 3 shows the resulting field distributions when 10 post couplers are set for 4% perturbations beginning at cells 50, 52, 54, 56, 58, and 60.

Table I gives the field reduction factors for all combinations of 5, 10, 15, and 20 post couplers set for perturbations from 2 to 10%. In all cases where the total perturbation is large enough to drop the fields in the high-energy end of the linac below the level required for synchronous acceleration, the beam will exit the linac at a reduced energy with some energy spread. The resulting energies and energy spreads for a range of perturbations near the center of a typical 100-cell, 70-MeV DTL are given in Tables II-VI. Higher

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Table I

FIELD-REDUCTION FACTORS FOR SOME COMBINATIONS OF THE NUMBER AND SIZE OF THE INDIVIDUAL POST-COUPLER PERTURBATIONS

Step Size		Number of Steps 5	10	15	20
2%	0.98	0.9039	0.8171	0.7386	0.6676
3%	0.97	0.8587	0.7374	0.6333	0.5438
4%	0.96	0.8154	0.6648	0.5421	0.4420
5%	0.95	0.7738	0.5987	0.4663	0.3585
6%	0.94	0.7339	0.5386	0.3953	0.2901
7%	0.93	0.6957	0.4840	0.3367	0.2342
8%	0.92	0.6591	0.4344	0.2863	0.1887
9%	0.91	0.6240	0.3894	0.2430	0.1516
10%	0.90	0.5905	0.3487	0.2059	0.1216

Table II

AVERAGE ENERGY AND ENERGY SPREAD IN MeV AS A FUNCTION OF THE NUMBER AND ORIGIN OF 2% FIELD STEPS

Origin of Perturbations	Number of 2% Steps 5	10	15	20
50	69.7 ±3.1	42.6 ±2.3	39.8 ±1.3	39.1 ±1.1
51	69.0 ±4.4	43.5 ±2.2	40.8 ±1.3	40.4 ±1.1
52	70.3 ±2.4	44.3 ±2.4	41.4 ±1.3	41.1 ±1.1
53	70.3 ±1.4	45.5 ±2.4	42.7 ±1.3	41.9 ±0.9
54	70.6 ±0.4	46.6 ±2.1	43.6 ±1.4	43.2 ±1.1
55	70.5 ±0.7	47.2 ±2.0	44.2 ±1.2	43.9 ±1.3
56	70.3 ±0.9	48.3 ±2.5	45.4 ±1.3	44.6 ±0.9
57	70.1 ±3.0	50.0 ±2.5	46.7 ±1.6	46.1 ±1.1
58	70.7 ±0.2	51.1 ±2.6	47.4 ±1.6	46.9 ±1.6
59	70.7 ±0.3	52.0 ±2.7	48.6 ±1.0	48.1 ±1.1

Table III

AVERAGE ENERGY AND ENERGY SPREAD IN MeV AS A FUNCTION OF THE NUMBER AND ORIGIN OF THE 3% FIELD STEPS

Origin of Perturbations	Number of 3% Steps 5	10	15	20
50	46.7 ±4.7	36.9 ±1.0	36.2 ±0.6	36.2 ±0.6
51	47.8 ±4.9	38.1 ±1.2	36.9 ±0.9	36.9 ±0.8
52	48.4 ±4.6	38.8 ±1.1	37.9 ±0.8	37.9 ±0.6
53	50.1 ±5.8	40.0 ±1.2	38.7 ±1.0	38.8 ±0.9
54	50.8 ±5.0	40.8 ±1.2	39.7 ±0.6	39.7 ±0.6
55	52.1 ±4.9	41.5 ±1.1	40.5 ±1.0	40.6 ±0.9
56	53.0 ±5.6	42.9 ±1.2	41.4 ±0.9	41.4 ±0.8
57	54.1 ±5.8	43.7 ±1.4	42.4 ±0.6	42.3 ±0.5
58	56.6 ±6.4	44.6 ±1.1	43.5 ±1.2	43.4 ±1.0
59	57.8 ±6.3	45.9 ±1.3	44.4 ±1.0	44.3 ±0.9

energies result when the perturbations are moved toward the high-energy end of the linac, and lower energies result when the perturbations are moved toward the low-energy end of the linac.

In permanent-magnet focused linacs advocated by the PIGMI technology, a lower limit to the energies exists for which this scheme is suitable and below which the beam becomes unstable in the quadrupole-focusing system. In the 70-MeV linac example, this limit is about 20 MeV. For energies below 20 MeV, provisions can be made to extract the beam at some intermediate point along the structure where the low-energy beams still are stable in the quadrupole-focusing system. With beam extraction at 25 MeV, beam energies as low as 8 MeV are stable.

Table I shows that five 2% perturbations give a field reduction factor of only 0.9039, which is not low enough to drop the particles out of synchronism with the accelerating structure. The left-hand column of Table II confirms that situation, showing the average energy in each case to be close to the unperturbed value of 70 MeV. All

Table IV

AVERAGE ENERGY AND ENERGY SPREAD IN MeV AS A FUNCTION OF THE NUMBER AND ORIGIN OF 4% FIELD STEPS

Origin of Perturbations	Number of 4% Steps: 5	10	15	20
50	39.1 ±1.9	34.8 ±0.8	34.2 ±0.5	34.4 ±0.4
51	40.3 ±2.1	35.4 ±0.7	35.1 ±0.7	35.2 ±0.7
52	41.2 ±2.1	36.4 ±0.9	35.9 ±0.6	36.1 ±0.6
53	42.2 ±2.1	37.2 ±0.9	36.8 ±0.8	36.8 ±0.8
54	43.7 ±2.0	38.4 ±0.8	37.8 ±0.5	38.0 ±0.5
55	44.2 ±2.1	39.1 ±0.8	38.6 ±0.8	38.7 ±0.8
56	45.1 ±2.2	40.1 ±0.8	39.4 ±0.5	39.6 ±0.5
57	46.6 ±2.2	40.9 ±1.1	40.4 ±0.8	40.4 ±0.7
58	47.2 ±2.0	41.9 ±0.7	41.3 ±0.9	41.5 ±0.8
59	48.5 ±2.9	43.0 ±1.0	42.3 ±0.5	42.3 ±0.5

Table V

AVERAGE ENERGY AND ENERGY SPREAD IN MeV AS A FUNCTION OF THE NUMBER AND ORIGIN OF 5% FIELD STEPS

Origin of Perturbations	Number of 5% Steps: 5	10	15	20
50	36.5 ±1.2	33.3 ±0.7	33.0 ±0.5	33.2 ±0.6
51	37.1 ±1.1	34.0 ±0.5	33.8 ±0.5	33.9 ±0.5
52	38.4 ±1.4	34.9 ±0.7	34.8 ±0.8	34.9 ±0.7
53	39.0 ±1.4	35.7 ±1.2	35.6 ±0.5	35.7 ±0.4
54	40.4 ±1.4	36.8 ±0.8	36.5 ±0.7	36.7 ±0.7
55	41.0 ±1.4	37.7 ±0.6	37.4 ±0.4	37.5 ±0.5
56	42.1 ±1.5	38.5 ±0.9	38.1 ±0.6	38.4 ±0.6
57	43.3 ±1.6	39.4 ±0.6	39.1 ±0.5	39.3 ±0.5
58	43.8 ±1.5	40.3 ±0.7	39.9 ±0.4	40.1 ±0.5
59	44.9 ±1.4	41.3 ±0.9	40.9 ±0.7	41.1 ±0.8

other combinations in Table I show an energy reduction capability. However, those combinations with field reduction factors exceeding 0.8 yield the largest energy spreads in Tables II-VI. Ten 4% perturbations give a field reduction factor of 0.6648 which will yield a relatively well-defined energy-reduction capability with root means square (rms) energy spreads of 1 MeV or less.

All of the field distributions in Fig. 1 would require proportional control of the magnitude of the perturbations on the individual post couplers. The field distributions in Figs. 2 and 3 would require only binary control of the number and location of the post couplers producing perturbations of fixed magnitude. The latter scheme offers considerable mechanical, operational, and cost advantages and has enough flexibility to yield any desired energy, within the limits of the beam-transport system, to a resolution of 1 MeV or less and an energy spread of ±1 MeV or less.

Mechanical Features

A perturbation of fixed magnitude at selected post couplers can be realized by fitting each post coupler with a mechanical positioner having a well-defined home position (power off) and well-defined alternate position (power on). Both positions must be capable of fine adjustment during initial setup. The home position represents the unperturbed situation and is adjusted to achieve symmetry in the post-coupler/drift-tube geometry. In the home position, the post coupler forces a uniform field distribution across the post coupler. The alternate position represents the perturbed situation and is adjusted to achieve a certain degree of asymmetry in the post-coupler/drift-tube geometry. In this position, the post coupler introduces a step of the prescribed magnitude in the field distribution across the post coupler.

Table VI

AVERAGE ENERGY AND ENERGY SPREAD IN MeV AS A FUNCTION OF THE NUMBER AND ORIGIN OF 6% FIELD STEPS

Origin of Perturbations	Number of 6% Steps 5	10	15	20
50	34.7 ±1.0	32.3 ±0.6	32.3 ±0.5	32.3 ±0.5
51	35.3 ±0.9	33.1 ±0.5	33.0 ±0.4	33.2 ±0.4
52	36.4 ±1.0	33.9 ±0.4	33.9 ±0.4	34.0 ±0.5
53	37.1 ±1.2	34.8 ±0.7	34.7 ±0.5	34.8 ±0.6
54	38.4 ±1.2	35.6 ±0.6	35.6 ±0.4	35.7 ±0.5
55	39.0 ±1.1	36.6 ±0.8	36.4 ±0.6	36.5 ±0.6
56	40.3 ±1.1	37.3 ±0.7	37.3 ±0.4	37.5 ±0.4
57	41.0 ±1.3	38.2 ±0.7	38.1 ±0.6	38.3 ±0.6
58	41.9 ±1.1	39.2 ±0.6	39.1 ±0.6	39.2 ±0.5
59	43.3 ±1.2	40.1 ±0.5	39.9 ±0.3	40.2 ±0.7

The need for a controllable eccentricity in the post-coupler geometry was recognized in the earliest days of post couplers. Originally, the eccentricity was conceived as a way to achieve flat field distributions and effective symmetry in the post-coupler/drift-tube geometry. The original scheme was based on an eccentric tab mounted on the end of the post coupler, where the degree of asymmetry was controlled by rotation of the post coupler.

For a device requiring frequent movements and vacuum and radio-frequency (rf) contact integrity, a motion based on a flexible joint is preferred to the rotary motion of the original scheme. By pivoting the post coupler at the outer wall, only a modest flexure would be required to provide the desired asymmetry. A few-convulation bellows can provide a suitable vacuum seal and rf contact, but sliding vacuum seals and rf contacts would be unacceptable. For all stationary joints, O-rings and Metex-rings are acceptable.

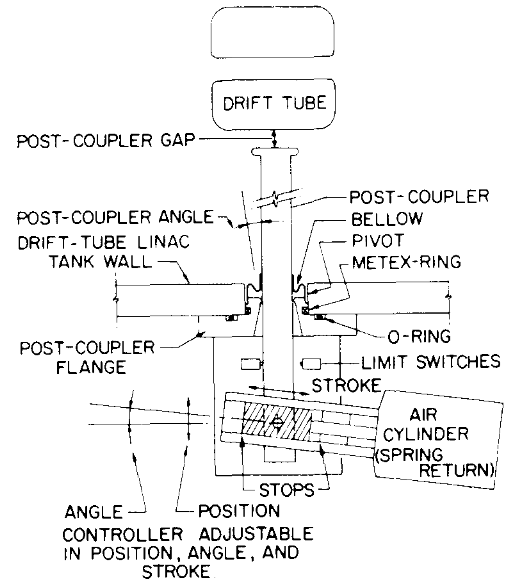

Fig. 4. A possible post-coupler positioner.

Figure 4 suggests a possible post-coupler positioner with features to enhance its effectiveness. An air cylinder with spring return is a convenient force to move the post coupler from the home position to the alternate position. Electrically operated air valves can provide a suitable interface to a control system. The mechanical linkage must have two well-defined positions, with each position capable of fine adjustment during initial setup. In addition, limit switches would provide data to the control system to confirm that the desired action has occurred.

Given a suitable mechanical positioner on each post coupler, the selection of energy from the DTL reduces to the excitation of the controllers on some preselected set of post couplers. The resulting change in the field distribution probably would change the impedance match to the rf power source. Some accommodation of this perturbation may be necessary.

Conclusions

A scheme is described in this paper to provide a variable-energy capability for the drift-tube linac, thus broadening the interest in this device for practical applications. The scheme is based on the use of post couplers to introduce steps in the accelerating fields, at specified points in the linac, to terminate the accelerator process and to produce beams of a variable energy. A relatively simple mechanical configuration for the post coupler is suggested.

REFERENCES

1. D. A. Swenson, "PIGMI: A Pion Generator for Medical Irradiations," Los Alamos National Laboratory Mini-Review LAL-81-6 (February 1981).