Conf-770313--2

LA-UR 77-604

TITLE: LOW-ENERGY LINAC STRUCTURE FOR PIGMI

AUTHOR(S): Donald A. Swenson
James E. Stovall

SUBMITTED TO: 1977 Particle Accelerator Conference

los alamos
scientific laboratory
of the University of California
LOS ALAMOS NEW MEXICO 87545

Form No. 836
St. No. 2629
1/75

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

LOW-ENERGY LINAC STRUCTURE FOR PIGMI*

By

Donald A. Swenson and James E. Stovall
University of California, Los Alamos Scientific Laboratory
P. O. Box 1663, Los Alamos, NM 87545

Summary

The higher radio frequency (450 MHz) and lower injection energy (250 keV) of the PIGMI (Pion Generator for Medical Irradiations) linac design seriously compound the problem of beam containment in the first few meters of the structure. The conventional quadrupole-focused, drift-tube linac represents the best solution for beam energies above 8 MeV but because of the small space available for quadrupoles in the PIGMI designs, cannot provide the required focusing at lower energies. A satisfactory solution to this focusing problem has been found based on pure alternating phase focusing for the first few MeV, followed by a smooth transition to a pure permanent magnet quadrupole-focused structure at 8 MeV. The structure and its calculated performance are described.

Introduction

The National Cancer Institute is supporting a program of accelerator development at the Los Alamos Scientific Laboratory aimed at the extension of proton linac technologies to produce the most suitable Pion Generator for Medical Irradiations (PIGMI). The program is currently in the first year of a three-year program, and is progressing well.[1]

An optimized design of a pion generator suitable for a radiotherapy program at a major medical center has been established. It consists of a 250-keV injector, followed by a 40-meter-long drift-tube linac that accelerates the proton beam to 150 MeV, and a 95-meter-long coupled-cavity linac that accelerates the beam to its final energy of 650 MeV, where the average beam current of 100 microamperes impinges on one or more targets producing abundant quantities of π^- mesons for radiotherapeutic applications.

The major innovations in this program include: higher-frequency structures (450 and 1350 MHz), higher accelerating gradients (5-8 MV/m), lower injection energy (few hundred keV), waveguide manifold rf distribution, alternating phase focusing for the first few meters, followed by permanent-magnet quadrupole focusing for the remainder of the linac, and an improved coupled-cavity linac structure for the high-energy portion of the facility.

The move to higher frequencies and higher gradients compounds dramatically the problem of practical fabrication of the drift-tube linac structure at lower energies (below 5 MeV). The higher frequency reduces the volume of the drift tubes where we normally place the magnetic quadrupole lenses, the higher gradient increases the need for radial focusing, and the lower energy further reduces the space available for magnetic lenses and the effect of the focusing magnetic fields in comparison to the defocusing effect of the rf electric fields. It was known from the beginning of the project that some fundamental development in accelerator-focusing schemes would be required in this low-energy region in order to take full advantage of the higher frequencies and gradients in the higher-energy portions of the machine.

The prime contender to satisfy the accelerating and focusing requirements in the region below 5 MeV is the concept of alternating phase focusing (APF). An array of such structures has been developed[a] which shows promise for acceleration of protons and heavy ions at higher frequency and from lower energies than currently possible with magnetically focused drift-tube linacs. In these structures, the transverse, as well as the longitudinal, focusing forces are produced by the rf fields. By arranging the drift-tube lengths, and hence gap positions, in an appropriate way, in a more or less conventional standing wave drift-tube linac, the particles can be made to experience acceleration and a succession of focusing and defocusing forces which result in satisfactory containment of the beam in the six-dimensional phase space without dependence on additional focusing fields.[4]

The PIGMI Prototype

The major piece of equipment to be designed, fabricated, and tested under the PIGMI program is the operating prototype of the low-energy end of the proposed design, complete with a proton beam and diagnostic gear to evaluate its performance. Steady progress is being made on the design of this prototype. The PIGMI prototype involves a 250-kV Cockcroft-Walton power supply, a proton ion source and accelerating column, a buncher cavity and solenoid lens to prepare the beam for injection into the linac, and a prototype of the low-energy portion of the PIGMI linac structure.

The linac portion of the PIGMI Prototype has recently been defined. It consists of a single tank, loaded with 64 drift tubes, which accelerates a proton beam from 0.25 MeV to 8.9 MeV in a total length of 2.64 meters. The tank is divided into four sections as shown in Fig. 1.

The first section has no quadrupole lenses among its 28 drift tubes, and is entirely dependent on the APF principle for beam confinement. The APF sequence employed here is of the $+\phi\ +\phi\ -\phi\ -\phi$ sequence, where ϕ begins at about 72° and tapers at a rate of 0.25 degrees per gap throughout the APF and Quad Ramp sections.

The last section is essentially a scaled-down version of a conventional quadrupole-focused Drift-Tube Linac (DTL), and accelerates the beam from 7.1 to 8.9 MeV in a distance of 34 cm for an average acceleration rate of better than 5 MeV/meter.

The middle two sections form a transition between the APF section and the DTL section. In the Quad Ramp sec-

*Supported by the National Cancer Institute of the Division of Cancer Research Resources and Centers of the U. S. Department of Health, Education, and Welfare.

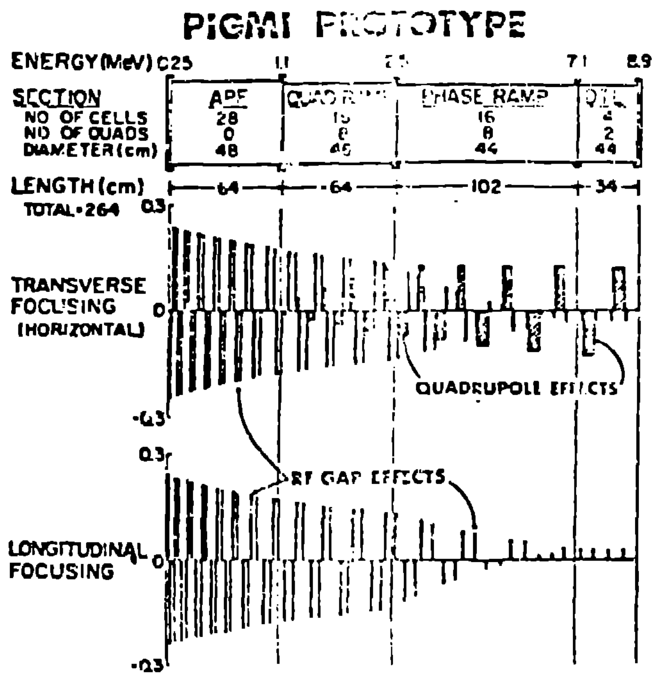

Fig. 1.
PIGMI prototype focusing effects.

tion, permanent-magnet quadrupole lenses are introduced into every other drift tube in a +0−0 configuration. In the Phase Ramp Section, the gap phases are rapidly transformed from the APF sequence used in this prototype to a constant stable phase angle of −20°, suitable for the DTL section.

In the transition region, there is a mixture of both APF and quadrupole focusing. It is important that they be mixed in such a way that the transverse acceptance in the horizontal and vertical planes are roughly similar. One consequence of this is that the net focal properties of the quadrupoles in the horizontal plane must be similar to the net focal properties of the quadrupoles in the vertical plane, a fairly common condition on quadrupole focused transport systems. Another consequence, which is not so common, is that the spatial distribution of the APF and quadrupole focusing elements must satisfy some basic symmetries. Symmetry arguments suggest that the quadrupole distributions must have odd symmetry about a point of even symmetry in the APF distribution.

The nearest that one can come to a point of even symmetry in the APF sequence adopted for PIGMI is the midpoint between the $+\phi$'s or the midpoint between the $-\phi$'s. These points correspond to the midpoints of the medium-length drift tubes. If the quadrupole distribution is to be odd about these points, and if we exclude the possibility of multiple quadrupoles in a single drift tube, the medium-length drift tubes must be void of quadrupoles. This is unfortunate because the medium-length drift tubes represent approximately one-half of the available space for the introduction of quadrupole focusing elements.

The only spaces left for quadrupoles are in the long drift tubes between the $-\phi$ and $+\phi$ gaps, and in the short drift tubes between the $+\phi$ and $-\phi$ gaps. If the quad distribution is to be odd about the quadless, medium-length drift tubes, the quads in the short drift tubes must be of one sign (+, for example), and the quads in the long drift tubes must be of the other sign (−). If the quadrupoles in the long drift tubes make use of the available space, the gradient of those quads must be less than that in the short drift tubes so that the focal effects of the two can be similar.

The length, gradient, and locations of the quadrupoles in the PIGMI prototype are shown by the hatched rectangles in Fig. 1. The quads are ramped on in the Quad Ramp section to a maximum gradient of 6 kG/cm in the short quads, and approximately half of that in the long quads which are approximately twice as long. The gradients of the short quads are held at 6 kG/cm in the Phase Ramp sections, as the APF effects are ramped off, bringing the short and long quads to the same length and gradient by the end of the section. In the DTL sections, the quads have a conventional +0−0 configuration.

It is important to insure that during the transition from the APF to DTL structure the focal properties do not approach an unstable situation and that the acceptance is not unduly restricted. The transformation matrix for each period of the transition region, consisting of two accelerating gaps, two focusing gaps, and one long and one short quadrupole lens having alternate gradients, has been evaluated for a range of magnet gradients. Evaluation of the transfer matrices yields not only the limits of stability but also the oscillation amplitude associated with each period.

Each period was evaluated for the nominal velocity β associated with the period neglecting acceleration. The results of the period analysis are shown graphically in Fig. 2, and although these curves were generated for a particular linac, they are similar in interpretation to the more general stability curves of Smith and Gluckstern[4] concerning periodic quadrupole focusing.

If we let r represent the radius of the beam envelope having a normalized emittance η, we can express the beam size in terms of the parameter β_c (beta Courant[5])

$$r = \sqrt{\beta_c \eta / \beta\gamma} \; , \qquad (1)$$

where $\beta\gamma$ is the normalized momentum. Values of $\beta_{c,max}$ then correspond to the point in the period where the radial excursion of the beam is a maximum. For convenience, we make β_c unitless by dividing by $\beta\lambda$, the fundamental unit of length in linac structures. The contours in Fig. 2 of constant $\beta_{c,max}/\beta\lambda$ therefore correspond to constant values of maximum beam size r_{max}, for a given normalized emittance η. For a given bore radius $R = r_{max}$, to pass a beam of emittance η, the following inequality must hold:

$$\beta_{c,max}/\beta\lambda \le \gamma R^2/\lambda\eta \; . \qquad (2)$$

In the early part of the PIGMI prototype we see that essentially no amount of quadrupole focusing affects the acceptance. The inflection point in each curve (connected by a dotted line) indicates the point at which the maximum beam size shifts from the center of a focusing gap to the center of a focusing quadrupole. Beyond this point, the acceptance is a strong function of the magnetic gradient.

The quadrupole law chosen for the PIGMI prototype is indicated by a dashed line superimposed on the stability diagram. The normalized acceptance in the APF section

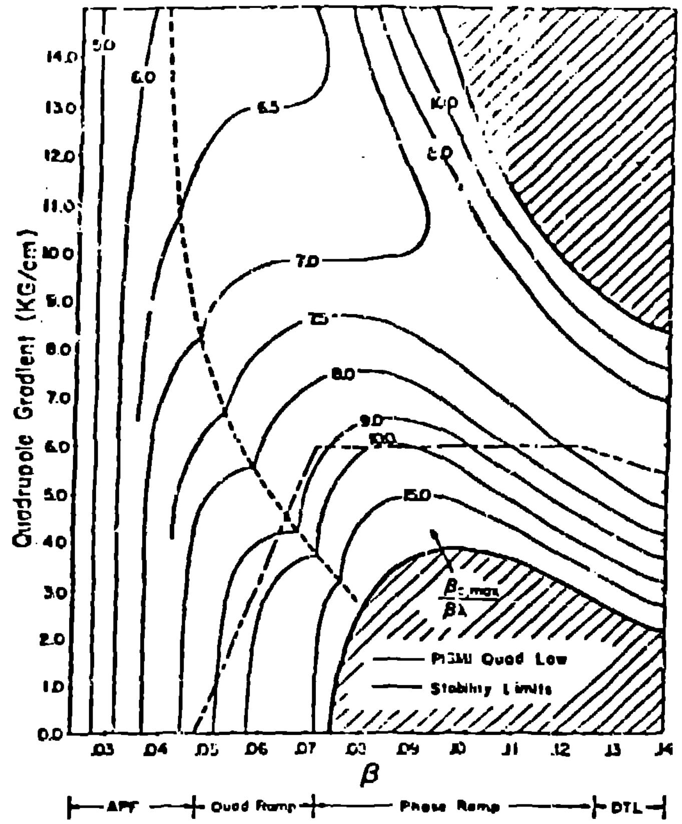

Fig. 2.
Stability region for the PIGMI prototype.

corresponding to the 5.0 contour would be 0.48 cm mrad for a bore radius of 4 mm. If the bore radius remained constant, a bottleneck would occur at $\beta = 0.85$. However, the bore is tentatively programmed as a linear function of β such that a minimum acceptance of $\eta = 0.37$ cm mrad occurs around $\beta = 0.05$ at a bore radius of 5 mm. In addition, we see that the focusing law lies well inside the stable region.

The performance of the prototype design was further evaluated using PARMILA program, a multiparticle linac dynamics code. The transverse acceptance of the prototype has been calculated using a multiparticle technique and found to be only 10% smaller than expected from the stability diagram, a reasonable discrepancy considering the approximations assumed in generating the stability curves. It is interesting to note that the acceptance is identical in both transverse planes indicating that the transition region does not contain an assymetrical bottleneck.

Additional multiparticle runs have been performed to study the effects of coupling and space charge. In this case, continuous monoenergetic beams having a normalized transverse emittance of 0.10 cm mrad have been transformed from the buncher at the exit of the accelerating column, through a solenoid lens to the linac, and then accelerated to 8.9 MeV. Even at peak beam currents of 30 mA the capture efficiency is calculated to be better than 60%.

The geometrical and dynamical parameters of each of the 64 cells of the prototype are given in Table I, where PHI is the phase of the rf when the design particle arrives

TABLE I

PIGMI PROTOTYPE CELL PARAMETERS

NC	PHI	WS	BETA	T	QS	QL	CL	LSUM
0		.250	.023		0.000	6.000		
1	-72.00	.266	.024	.457	0.000	1.660	1.076	1.83
2	71.75	.282	.025	.461	0.000	1.225	1.526	3.86
3	71.50	.294	.025	.469	0.000	.755	1.320	5.12
4	-71.25	.307	.026	.476	0.000	1.278	1.355	6.48
5	-71.00	.326	.026	.484	0.000	1.036	2.076	8.56
6	70.75	.347	.027	.495	0.000	1.350	2.124	10.68
7	70.50	.362	.028	.503	0.000	.845	1.475	12.15
8	-70.25	.378	.028	.510	0.000	1.410	1.509	13.66
9	-70.00	.402	.029	.519	0.000	2.030	[illegible]	15.98
10	69.75	.425	.030	.530	0.000	1.500	2.314	18.32
11	69.50	.447	.031	.540	0.000	.947	1.627	19.96
12	-69.25	.466	.032	.547	0.000	1.576	1.62[illegible]	21.64
13	-69.00	.497	.033	.557	0.000	2.287	2.548	24.18
14	68.75	.520	.034	.569	0.000	1.676	2.615	26.80
15	68.50	.552	.034	.579	0.000	1.063	1.826	28.63
16	-68.25	.577	.035	.587	0.000	1.752	[illegible]	30.50
17	-68.00	.615	.036	.597	0.000	2.409	2.828	33.33
18	67.75	.655	.037	.609	0.000	1.865	[illegible]	36.23
19	67.50	.684	.038	.620	0.000	1.193	2.624	38.27
20	-67.25	.724	.039	.628	0.000	1.959	2.055	40.37
21	-67.00	.761	.040	.639	0.000	2.759	[illegible]	43.51
22	66.75	.811	.042	.652	0.000	2.075	[illegible]	46.73
23	66.50	.847	.042	.66[illegible]	0.000	1.335	2.276	49.61
24	-66.25	.895	.043	.671	0.000	2.170	2.349	51.35
25	-66.00	.943	.045	.682	0.000	3.058	3.426	54.63
26	65.75	1.004	.046	.695	0.000	2.309	3.570	58.41
27	65.50	1.049	.047	.705	0.000	1.505	2.561	62.95
28	-65.25	1.096	.048	.714	0.000	2.415	2.612	63.56
29	-65.00	1.167	.050	.725	-.354	3.387	3.868	67.43
30	64.75	1.248	.051	.738	0.000	2.567	3.519	71.40
31	64.50	1.297	.053	.748	1.500	1.686	2.825	74.23
32	-64.25	1.354	.054	.757	0.000	2.683	2.913	77.15
33	-64.00	1.44[illegible]	.055	.767	-1.073	3.767	4.287	81.43
34	63.75	1.532	.057	.779	0.000	2.850	[illegible]	85.83
35	63.50	1.598	.058	.789	3.000	1.887	[illegible]	88.99
36	-63.25	1.668	.060	.797	0.000	2.978	3.241	92.23
37	-63.00	1.772	.061	.807	-1.818	4.135	4.744	96.98
38	62.75	1.842	.063	.818	0.000	3.150	4.814	101.80
39	62.50	1.962	.065	.827	4.500	2.150	[illegible]	105.35
40	-62.25	2.046	.066	.834	0.000	3.257	[illegible]	108.96
41	-62.00	2.170	.068	.843	-2.566	4.559	[illegible]	114.19
42	61.75	2.300	.070	.852	0.000	3.452	5.344	119.56
43	61.50	2.356	.071	.859	4.800	2.344	3.897	123.45
44	-61.25	2.496	.073	.865	0.000	3.662	4.627	127.46
45	-58.62	2.656	.075	.872	-3.229	4.859	5.485	133.14
46	47.92	2.853	.078	.881	0.000	3.840	5.799	138.94
47	43.39	3.031	.080	.888	6.000	2.950	4.527	143.46
48	-51.54	3.180	.082	.894	0.000	4.136	4.724	148.19
49	-49.12	3.407	.085	.899	-3.814	5.178	6.269	154.05
50	29.81	3.707	.089	.903	0.000	4.373	6.367	160.77
51	25.28	3.972	.092	.906	6.000	3.729	5.401	166.17
52	-41.04	4.201	.094	.907	0.000	4.744	5.119	171.81
53	-39.41	4.495	.097	.906	-4.478	5.562	6.871	178.69
54	11.69	4.863	.101	.903	0.000	5.000	7.040	185.73
55	9.17	5.200	.105	.897	6.000	4.070	6.449	192.18
56	-32.13	5.572	.108	.890	0.000	5.429	6.733	198.91
57	-29.71	5.659	.111	.881	-5.238	5.918	7.560	206.40
58	-6.42	6.260	.115	.869	0.000	5.671	7.726	214.20
59	-10.94	6.642	.118	.855	6.000	5.726	7.248	221.80
60	-22.43	7.010	.122	.839	0.000	6.115	7.893	229.69
61	-20.00	7.391	.125	.822	-5.904	6.235	8.231	237.93
62	-20.00	7.772	.128	.803	0.000	4.392	8.418	246.34
63	-20.00	8.152	.131	.783	5.716	6.544	8.624	254.97
64	-20.00	8.531	.134	.761	0.000	6.092	8.824	263.79

TOTAL LENGTH = 263.791

at the center of the gap, WS and BETA are the energy and velocity of the design particle after crossing the gap, T is the transit time factor, QS is the quadrupole gradient in kG/cm, and QL and CL are the quadrupole and cell lengths respectively.

REFERENCES

1. D. A. Swenson, Los Alamos Scientific Laboratory Progress Report for the PIGMI Program at LASL, LA-6714-PR, for the Period Ending December 31, 1976.

2. E. A. Knapp and D. A. Swenson, "The PIGMI Program at LASL," Proc. 1976 Proton Linear Accel. Conf., AECL-5677, 115 (1976).

3. D. A. Swenson, Particle Accelerators, 7, 61 (1976).

4. D. A. Swenson, "Beam Dynamics in the Low-Energy End of PIGMI, Proc. 1976 Proton Linear Accel. Conf., AECL-5677, 234 (1976).

5. L. Smith and R. Gluckstern, RSI. 26, 220 (1955).

6. E. D. Courant, M. S. Livingston, and H. S. Snyder, Phys. Rev. 88, 1190 (1952).