BEAM DYNAMICS IN THE LOW ENERGY END OF PIGMI*

D. A. Swenson
University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87544

ABSTRACT

The high frequency, high accelerating gradient and low injection energy of the PIGMI design all serve to compound the beam containment problem in the first few meters of the structure. A suitable solution based on alternating phase focusing will be presented. The physical properties of the structure and the properties of the beam within it will be described.

It is a primary thesis of the PIGMI Program at LASL[1] that by raising the frequency and accelerating gradient of proton linac structures, a new breed of proton linacs will emerge that are smaller, shorter, less expensive and more reliable. For such linacs, a smaller and less expensive injector is highly desirable, which implies a lower injection energy. These three changes compound dramatically the problem of beam containment in the first few meters of the structure: The higher frequency reduces the volume of the drift tube where we normally place the magnetic quadrupole lenses, the higher gradient increases the need for radial focusing, and the lower energy further reduces the effect of the focusing magnetic fields in comparison to the defocusing effect of the rf electric fields.

It is essentially hopeless to try to solve this radial focusing problem with static magnetic quadrupole fields. Accelerator builders have shied away from electrostatic quadrupole fields, and probably for good reason. Solenoid focusing is equally hopeless.

The basic dynamics problem in the high-gradient low-energy end of such linacs is the magnitude of the defocusing component of the rf electric fields when operated in the usual phase stable mode. By changing the sign of the phase at which the particles cross the gaps, this powerful defocusing component can be turned around into a powerful radial focusing component. By alternating the phase at which the particles cross the gap, it is possible to alternately focus and defocus the longitudinal and radial phase spaces in such a way as to accelerate the beam and to contain it without dependence on additional focusing fields.

This possibility, called alternating phase focusing (APF), was recognized soon after the discovery of the alternating gradient focusing. Early investigations were restricted to symmetrical, and later assymmetrical, biperiodic phase sequences.[a] Many investigators concluded that the stable phase areas were small and of little practical interest. More recently, there has been a revival of interest in this focusing principle in connection with high gradient prospects of superconducting structures, and the difficult focusing situations in heavy-ion linacs. The Russians seem to have found some interesting structures in the late sixties and studies of these are in progress.

About a year ago I began looking for a suitable alternating phase focusing sequence.[2] In order to make practical judgments, it was necessary to conceive of practical ways to realize an alternating phase focusing situation. I constrained my studies to a standing wave drift tube loaded structure where there is, on the average, one gap per $\beta\lambda$ of length, that is, where the particles are exposed to the rf fields once and only once per rf period. These structures look very much like drift tube loaded structures designed by committee, where there was somewhat less than full agreement on the lengths of the drift tubes.

Particles which cross linac-type gaps at the peak of the accelerating voltage ($\phi = 0$) get the maximum acceleration possible, and little in the way of longitudinal or transverse focusing or defocusing. Particles which cross linac-type gaps at $\phi = -90°$ get no acceleration, but lots of longitudinal focusing and transverse defocusing, and particles which cross linac-type gaps of $\phi = +90°$ get no acceleration, but lots of transverse focusing and longitudinal defocusing. Particles which cross gaps between these limits get varying amounts of acceleration, and longitudinal and transverse focusing and defocusing. 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. This means that drift tubes can be fabricated smaller and shorter than ever before, allowing the structure to be extended to higher frequencies and to lower energies than currently possible.

Upon exploring the parameter space, I quickly found the array of phase sequences shown in Fig. 1, ranging from two-gap periodicities at the top to eight-gap periodicities at the bottom. Within each periodicity, the sequences are arranged in order of decreasing acceleration factor. To the right of each sequence, there are a number of dots corresponding to suitable excitations for the sequence ranging from 0 to 16 MV/m. The asterisks represent the excitations that exhibit the maximum longitudinal stability. The two columns on the right

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*To be supported by The National Cancer Institute of the U.S. Department of Health, Education and Welfare.

[a]See Reference 2 for related bibliography.

side of the figure give the normalized emittance ($\beta\gamma ab$) of a beam whose maximum diameter is one centimeter, and the total widths of the longitudinal acceptance.

Two things are immediately obvious from this array of sequences:

1. The range of suitable excitations for a given sequence is relatively narrow, and

2. The optimum excitation of the sequences decreases as periodicity increases.

The results in Fig. 1 are based on a formulation of the dynamics which did not, and could not conveniently, include the coupling terms between the transverse and longitudinal dynamics. Nevertheless, these results, which are described more systematically in Ref. 2, serve as a significant guide into the parameter space for more sophisticated studies.

More Sophisticated Study for PIGMI

The sequence that we are currently studying for PIGMI has a periodicity of 4, starting with -72 -72 72 72 and changing gradually by .2 degrees per gap towards $\phi = 0$.

Specifically, the structure has a resonant frequency of 450 MHz and an axial electric field of 6 MV/m. The injection energy is 250 keV (β = .023). The first 40 cells have a total length 1.057 meters, and accelerate the beam to 1.776 MeV. The gap phases vary gradually from ± 72 degrees at the beginning to ± 64 degrees at the end. Table I gives these and other details on the sequence, where T is the transit time factor, V is the volts across the gap, and EL is the cell length.

The transit time factor is a strong function of the bore radius for the very short cells. The relationship was determined from a series of cavity calculations using the new SUPERFISH[3] program. In the shortest cells, T = .452 for a bore radius of 4 mm, and T = .342 for a bore radius of 5 mm. In the longer cells of this series, T = .824 for a bore radius of 4 mm, and T = .777 for a bore radius of 5 mm. In our present studies we have taken the bore radius to be 4 mm at 250 keV enlarging to 5.4 mm at 1.776 MeV. Figure 2 shows the geometry of the shortest cell, the longest cell, and a composite of the first eight cells of this sequence. The 8-cell composite was run on SUPERFISH, resulting in a resonant frequency of 451.46 MHz, and the electric field pattern shown in the figure.

The general linac particle dynamics code, PARMILA, has been modified to handle the APF structure. This formulation of the dynamics has all the important coupling terms between the transverse and longitudinal dynamics. The code can generate a variety of distributions for the initial coordinates of the particles in the 6-dimensional phase space, and can follow these particles through the structure while producing a variety of performance data.

The structure presented in this paper evolved from a series of PARMILA runs where the structure was changed slightly between runs while the effect of each change was noted. The major judgements in this process were based on outputs of the type shown in Fig. 3. At the top of this figure are the xx' and ϕw phase spaces that succeed in traversing the structure. Below these phase spaces are the x and ϕ profiles with one line of output per cell. It is easy to see the periodicity of four in both the transverse and longitudinal focusing. Figure 4 gives some indication of the wavelengths of the transverse and longitudinal oscillations within the structure.

In order to make a valid analysis of the coupling and space charge effects, it is necessary to simulate a realistic beam simultaneously in both the transverse and longitudinal phase spaces. This is most easily done prior to the buncher where the longitudinal phase space is simple (all phases, no energy spread). This, however, necessitates the inclusion of the buncher and the low energy transport system in the description of the structure to be analyzed.

The beam from the ion source and the beam in the APF structure have circular symmetry. In order to maintain circular symmetry throughout this region, we have chosen to use a single solenoid lens to focus the beam from the buncher to the linac.

Figure 5 shows the performance of the buncher-solenoid-APF linac combination with all the important coupling terms, but with zero beam current (space charge). The buncher is a simple, single cavity system with a peak voltage of 2.4 kV located 80 cm in front of the linac. The solenoid has a focal length of 20 cm. The percentage of the beam captured by this system is ~62%, which compares well with conventional linacs with single cavity buncher systems.

No significant deterioration in performance is noted when the beam current (space charge) is increased to 30mA. To accommodate this space charge, the optimum buncher voltage is 2.7 kV and the optimum solenoid focal length is 19 cm.

The next stage of our studies will be to match this structure to a permanent-magnet quadrupole-focused structure by a gradual turn-off of the APF effect, and a gradual turn-on of the quadrupole focusing.

REFERENCES

1. D. A. Swenson, "The PIGMI Program at LASL," this proceedings.

2. D. A. Swenson, "Alternating Phase Focused Lines," to be published in Particle Accelerators.

TABLE I
APF CELL PARAMETERS

APFOUT SUBROUTINE 1 RUN= 828

NC	PHI	WS	BETA	EZ	T	V	QS	QL	EL
I		.250	.023						
1	-72.0	.266	.024	6.00	.455	.113	0.000	1.664	1.879
2	71.8	.283	.025	6.00	.462	.116	0.000	1.225	1.926
3	71.6	.294	.025	6.00	.468	.079	0.000	.754	1.320
4	-71.4	.307	.026	6.00	.474	.081	0.000	1.278	1.354
5	-71.2	.326	.026	6.00	.480	.125	0.000	1.836	2.076
6	71.0	.346	.027	6.00	.488	.128	0.000	1.356	2.128
7	70.8	.360	.028	6.00	.495	.088	0.000	.841	1.464
8	-70.6	.375	.028	6.00	.500	.090	0.000	1.414	1.503
9	-70.4	.399	.029	6.00	.507	.138	0.000	2.025	2.293
10	70.2	.423	.030	6.00	.516	.141	0.000	1.500	2.350
11	70.0	.441	.031	6.00	.523	.097	0.000	.937	1.624
12	-69.8	.459	.031	6.00	.529	.100	0.000	1.563	1.667
13	-69.6	.487	.032	6.00	.536	.152	0.000	2.232	2.530
14	69.4	.517	.033	6.00	.545	.156	0.000	1.658	2.593
15	69.2	.538	.034	6.00	.552	.108	0.000	1.043	1.800
16	-69.0	.561	.035	6.00	.558	.111	0.000	1.727	1.847
17	-68.8	.595	.036	6.00	.566	.167	0.000	2.457	2.790
18	68.6	.631	.037	6.00	.575	.172	0.000	1.830	2.858
19	68.4	.657	.037	6.00	.583	.120	0.000	1.159	1.993
20	-68.2	.683	.038	6.00	.589	.123	0.000	1.907	2.044
21	-68.0	.725	.039	6.00	.597	.184	0.000	2.703	3.073
22	67.8	.768	.040	6.00	.607	.189	0.000	2.019	3.148
23	67.6	.799	.041	6.00	.615	.132	0.000	1.288	2.205
24	-67.4	.831	.042	6.00	.621	.136	0.000	2.103	2.261
25	-67.2	.881	.043	6.00	.629	.203	0.000	2.970	3.382
26	67.0	.933	.045	6.00	.639	.208	0.000	2.225	3.463
27	66.8	.970	.045	6.00	.647	.146	0.000	1.429	2.436
28	-66.6	1.009	.046	6.00	.653	.150	0.000	2.316	2.497
29	-66.4	1.068	.048	6.00	.662	.223	0.000	3.259	3.717
30	66.2	1.130	.049	6.00	.671	.228	0.000	2.448	3.805
31	66.0	1.174	.050	6.00	.679	.161	0.000	1.583	2.688
32	-65.8	1.221	.051	6.00	.686	.165	0.000	2.548	2.754
33	-65.6	1.291	.052	6.00	.694	.245	0.000	3.571	4.079
34	65.4	1.364	.054	6.00	.703	.250	0.000	2.690	4.174
35	65.2	1.417	.055	6.00	.711	.178	0.000	1.751	2.961
36	-65.0	1.472	.056	6.00	.717	.182	0.000	2.797	3.032
37	-64.8	1.555	.058	6.00	.725	.268	0.000	3.906	4.469
38	64.6	1.641	.059	6.00	.734	.274	0.000	2.950	4.571
39	64.4	1.704	.060	6.00	.742	.195	0.000	1.933	3.255
40	-64.2	1.776	.061	6.00	.748	.222	0.000	3.615	3.699

TOTAL LENGTH = 105.707

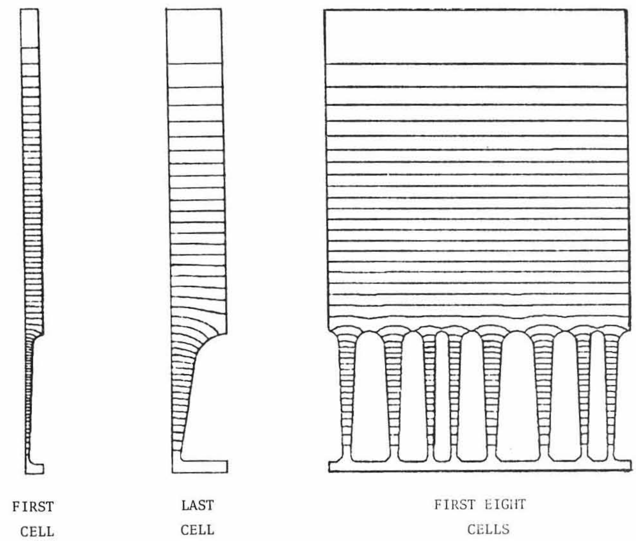

Fig. 2. First, Last and First Eight Cells of Sequence.

PERIOD	SEQUENCE (degrees)	ACCEL. FACTOR	FIELD FACTOR F (MV/m) 0 4 8 12 16 20	X X' (βγ ab) (cm-mrad)	φ W (total) (deg keV)
2	-60 60 -65 55 -70 70	.500 .498 .342		3.23 2.58 2.93	70x200 86x130 74x100
3	-90 30 30 -90 40 40	.577 .511		1.83 3.60	58x134 52x160
4	-90 0 90 0 -60 -60 60 60 -70 -70 60 60	.500 .500 .421		1.71 1.45 1.38	60x120 50x 58 70x 96
5	-90 -30 60 60 -30 -90 -90 30 90 30	.546 .346		0.72 1.18	60x 60 70x 64
6	-90 -90 0 60 60 0 -90 -90 0 70 70 0 -90 -90 0 90 90 0	.500 .447 .333		0.84 0.96 1.13	65x 54 70x 50 60x 50
7	-90 -90 0 40 70 40 0	.553		1.11	45x 26
8	-90 -90 -30 30 60 60 30 -30 -90 -90 -30 30 90 90 30 -30	.558 .433		0.62 0.81	62x 30 70x 32

Fig. 1. Array of Basic APF Phase Sequences.

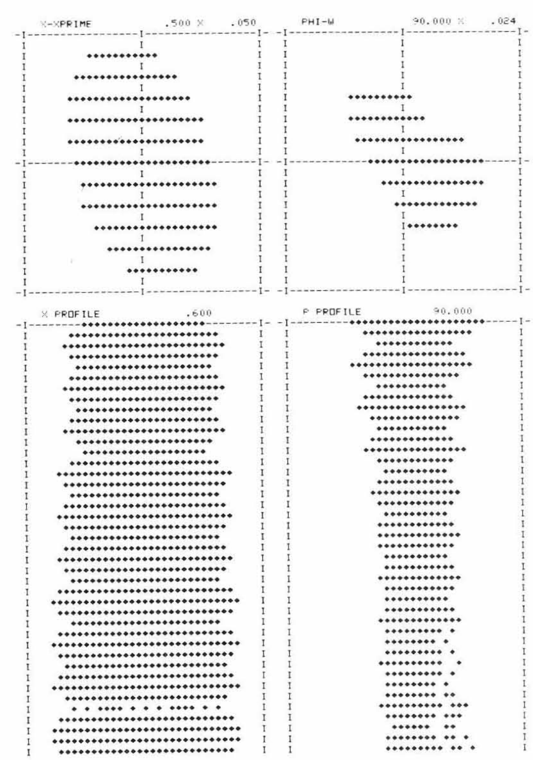

Fig. 3. Performance of APF Linac Section.

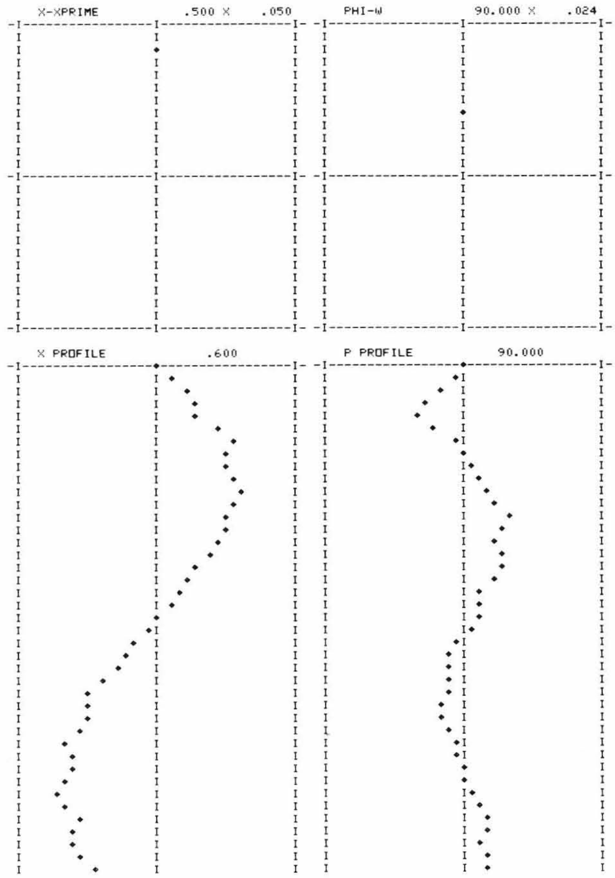

Fig. 4. Single Particle Oscillations.

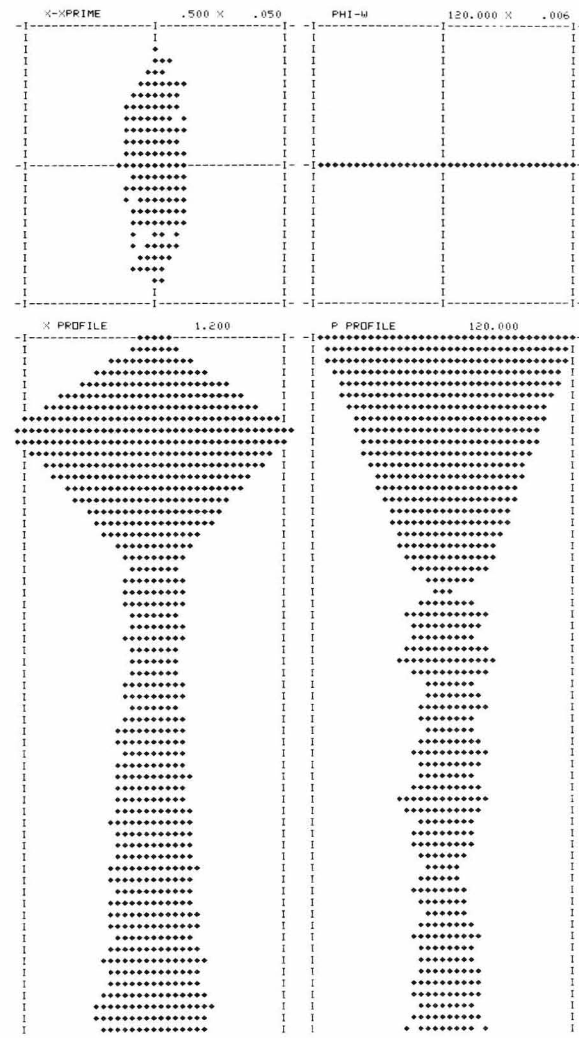

Fig. 5. Performance of Buncher-Solenoid-Linac Combination.

DISCUSSION

D. Johnson, FNAL: You alluded to the fact that you couldn't consider coupling between the two planes. However, it seems to me that that does decrease the acceptance quite a bit. Can you say something about that?

Swenson: These latter calculations did have the proper coupling. I must thank John Staples of Berkeley for pointing out an error of a factor of 4 in the coupling coefficient, but that has been corrected in these calculations. It's just that this neat display of the possible sequences gets messed up if you try to mix in coupling of the phase spaces. If you consider those as starting points for further investigations then these further investigations have gone through a process of optimization of the structures with the coupling terms. In each possible application the importance of the coupling terms depends on the brightness of the ion source, the radius of the beam, the currents that you want, the gradients that you think you can get and so forth.