BEAM DYNAMICS DESIGN OF A PION LINAC*

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Abstract

We have conducted a study of a superconducting linac to accelerate pions produced at LAMPF from 400 or 500 MeV to 925 MeV kinetic energy. For such a linac, it is necessary 1) to keep the machine as short as practical in order to minimize the loss of beam due to particle decay, and 2) to tailor the beam to achieve the maximum flux within the desired momentum bite at the exit. The interplay of these and other considerations with the transverse and longitudinal beam dynamics is discussed, and is illustrated with the simulated performance of reference pion-linac designs.

Introduction

A proposed linear accelerator for pions ("Pilac") would extend the capabilities of the Los Alamos Meson Physics Facility (LAMPF). Pilac would accelerate pions from the A2 target in the 800 MeV proton line. The pions would be accelerated from 400 or 500 MeV to 920 MeV kinetic energy, corresponding to a momentum of 1050 Mev/c. This project has the goal of providing a flux of 10^9 pions per second. The linac would use superconducting rf cavities in order to provide large apertures and transverse acceptance, and produce high accelerating gradients without a large cost in rf power.

In order to evaluate different design concepts for this linac, we have used a figure of merit which is the product of two factors: (a) momentum fraction and (b) survival fraction. The momentum fraction is the fraction of particles entering the linac that are within the desired momentum bite (2% full width, for example) at the linac exit. In order to maximize this factor, we may tailor the beam dynamics in the linac to produce a bunch that is wide in phase spread and narrow in energy spread at the linac exit.

The survival fraction is the fraction of particles entering the linac that have not been lost to decay by the time they reach the linac exit. For particles of rest mass E_{rest} (139.567 MeV for pions), kinetic energy W, mean life parameter $c\tau$ (7.803 m for pions), and traveling a distance L, the survival fraction is

$$F_{surv} = e^{-\frac{L}{c\tau\beta\gamma}},$$

where

$$\beta\gamma = \sqrt{\left(\frac{W}{E_{rest}}\right)\left(\frac{W}{E_{rest}} + 2\right)}.$$

For an accelerating section to take the beam from kinetic energy W_1 to W_2, the survival fraction is given by

$$F_{surv} = \left(\frac{E_2 + \sqrt{E_2^2 + E_{rest}^2}}{E_1 + \sqrt{E_1^2 + E_{rest}^2}}\right)^{-\frac{E_{rest}}{c\tau G}}$$

where E is the total energy of a pion

$$E_n = W_n + E_{rest}$$

at the start (E_1) or end (E_2) of the section, and G is the accelerating gradient

$$G = \frac{W_2 - W_1}{L}.$$

Strategies for Linac Design

We have used two design strategies in looking at possible Pilac designs. In the first strategy, designated as the fast-synchrotron-oscillation approach, we attempt to capture and accelerate the whole input bunch, but adjust the design phases along the linac to make the bunch rotate counterclockwise so that it is narrow in energy-phase space at the end (see Fig.1). For the energy gain we need for Pilac, the bunch rotates from the initial tilt at the start of the linac (Mod. 2) to where it is narrow in energy spread (Mod. 6), and then continues to rotate another half turn until it is narrow again at the linac exit. This approach emphasizes the momentum fraction at the expense of the survival fraction.

In the second strategy, designated as the slow-synchrotron-oscillation approach, the initial bunch is rotated slightly, but most of the design phases are chosen near the peak of the accelerating wave, so that the particles are shot through the linac as quickly as possible. This approach emphasizes the survival fraction at the expense of the momentum fraction. (See Fig. 2.)

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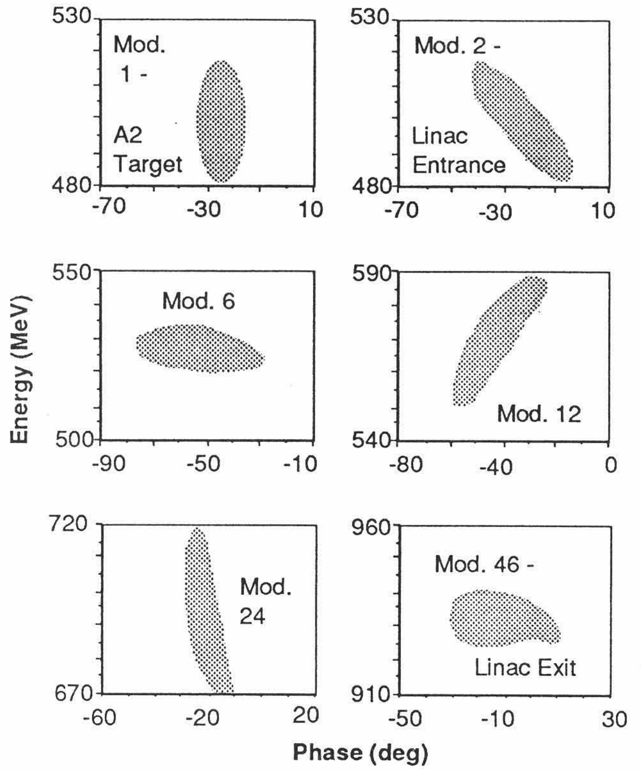

Fig. 1. Evolution of the bunch in energy-phase space for the fast-synchrotron-oscillation approach.

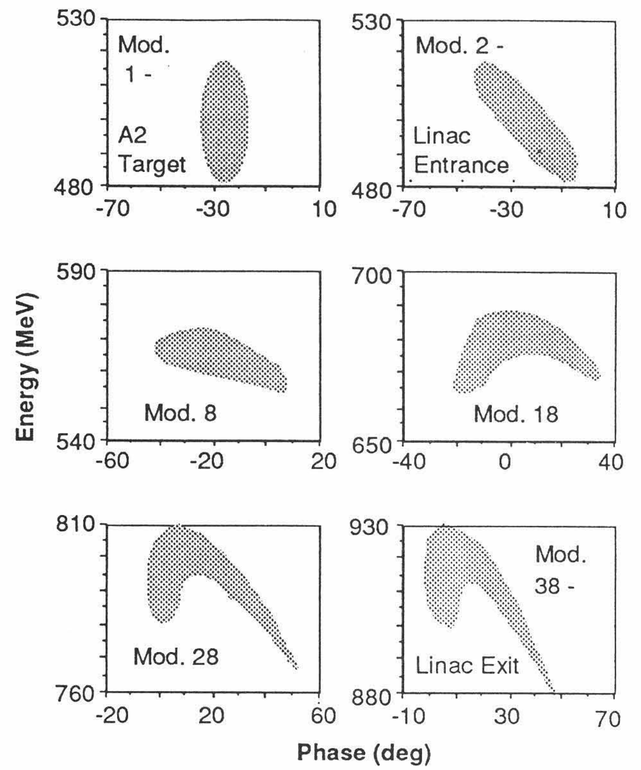

Fig. 2. Evolution of the bunch in energy-phase space for the slow-synchrotron-oscillation approach.

In either of these approaches, we attempt to choose the design phases of the rf cavities to maximize the number of particles in the desired dp/p bite at the linac exit. We have used the following approximate procedure to find these rf phases. We choose the design phases such that the trailing edge of the phase spread lies on a straight line in a plot of phase vs cavity number, as shown in Fig. 3. This allows the optimization to be done with only two parameters, the phases at the start and end of the straight line. In fact, the optimization is reduced to a one-parameter search for a given number of cavities, since after one end of the line is specified, the value at the other end must be set to give the desired output energy for the linac. Putting the trailing edge of the phase width on the straight line tends to move the design phase (at the middle of the bunch) away from the peak when the bunch is wide in phase, thus putting the bunch on a more linear part of

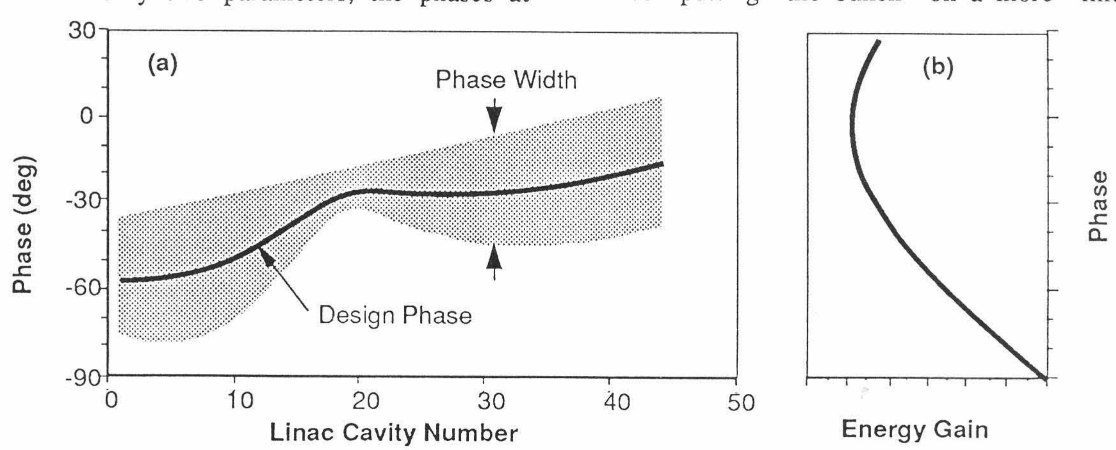

Fig. 3. The design phases are such that the trailing edge of the phase width is on a specified line, as shown for a representative case in (a). The accelerating wave is shown in (b).

the wave. When the bunch is narrow, it is allowed to ride higher toward the crest, as nonlinear effects are less important then.

Comparison of 402.5 and 805 MHz Linacs

We have looked at reference designs for both 402.5 and 805 MHz rf cavities. In order to compare these designs, we made the following assumptions. The initial beam at the A2 target was assumed to have a time spread of 60 ps, a momentum spread of 2.8 or 5.6% FW, a transverse emittance of 150 pi mm-mrad, and be transported 12.5 m before entering the linac. The rf cavities were assumed to have 5 cells each, and the linac to use quad doublets for focusing. Space was allowed between cavities for couplers, flanges, and bellows. At points where focusing magnets were needed, space was allowed for transitions to room temperature and miscellaneous vacuum and diagnostic equipment. The space for these was a function of the beam aperture size. The maximum accelerating gradient E_0T was assumed to vary as the surface area of the cavity to the -0.2 power (an empirical relation). This gives $E_0T=13.2$ MV/m for 805 Mhz cavities, corresponding to 10 MV/m for the 402.5 Mhz cavities.

The procedure for each frequency was as follows: First the number of cavities per quad doublet was chosen to make the beam fill the aperture for a 0.5 T pole tip field. Then the cavity design phases were optimized for minimum dp/p at the linac exit. This was then repeated for larger apertures until the spacing between cavities needed to keep the cavity-to-cavity coupling small dominated the survival fraction.

Calculated Performance

The calculated results for the 402.5 MHz and 805 MHz Pilacs for acceleration from 500 to 920 MeV are given in the tables below. The beam had an initial dp/p of 5.6% FW. The survival fraction (S.F.), momentum fraction (M.F.) for 2% FW dp/p at the linac exit, and combined figure of merit (SF*MF) are given for each design. The 402.5 MHz Pilac listed in Table I had to be quite long in order to obtain a bunch that was rotated enough to be narrow in energy spread at the exit. Hence the survival fraction for this case was small. For the 805 MHz cases, the constraints on cavity-to-cavity spacing made the survival fraction start to fall off as the beam aperture diameter was increased above 10 cm. The optimum design based on the combined figure of merit SF*MF for these cases has an aperture of about 13 cm.

TABLE I
Fast-Synchrotron-Oscillation Cases

Freq. (MHz)	Num. Cavs.	Aperture Dia. (cm)	S.F. (%)	M.F. (%)	SF*MF (%)
402.5	36	20	12.5	100.	12.5
805.0	43	10	20.3	100	20.3
805.0	42	10	21.9	94.8	20.8
805.0	44	13	21.2	100	21.2
805.0	42	15	21.0		

The difference in performance is much less pronounced between the 402.5 and 805 MHz slow-synchrotron-oscillation designs listed in Table II. The optimum aperture diameter for a 402.5 MHz Pilac is about 22 cm; for an 805 MHz Pilac, it is about 12 cm.

TABLE II
Slow-Synchrotron-Oscillation Cases

Freq. (MHz)	Num. Cavs.	Aperture Dia. (cm)	S.F. (%)	M.F. (%)	SF*MF (%)
402.5	24	20	26.1	97.8	25.5
402.5	24	22	25.6	96.8	24.8
805.0	36	10	26.9	82.1	22.1
805.0	36	11	29.0	82.3	23.9
805.0	36	13	29.2	82.3	24.0
805.0	36	15	(<27.3)		

Conclusions

For short linacs to accelerate unstable particles, it may be advantageous to sacrifice accelerating bucket area to gain in the number of beam particles surviving. For the linac designs we have examined, the slow-synchrotron-oscillation approach is slightly better than the fast-synchrotron-oscillation method. The slow-synchrotron-oscillation approach is also less dependent on the initial orientation of the beam ellipse in energy-phase space.

A recent re-examination of the linac requirements suggests that the optimum initial energy is around 400 MeV. Future work will include studies to check if the same conclusions apply for acceleration from 400 to 920 MeV.