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PRELIMINARY DESIGN AND BEAM-DYNAMICS STUDY OF A FUNNELING LINE HAVING LOW EMITTANCE GROWTH

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ABSTRACT

A theoretical design study has resulted in a conceptual funneling-line design that has a transverse emittance growth limited to only 15% based on beam-dynamics calculations. Two 2-MeV, 100-mA proton beams are funneled from a two-channel, 212.5-MHz radio-frequency quadrupole (RFQ) to a single beam suitable for injection into a 425-MHz linac. The design uses permanent-magnet quadrupoles, dipoles, and combined-function elements. The low emittance growth is obtained by arranging the focusing strength, the periodic structure, and the bending elements so as to minimize abrupt changes in the beam environment with consequent charge redistribution and space-charge-caused emittance growth.

INTRODUCTION

Funneling lines in which two bunched beams of current I and bunch separation $\beta\lambda$ are merged into a single beam of current 2I and bunch separation $\beta\lambda/2$ may be advantageous for a number of different applications. For some of these applications, emittance growth must be kept to a minimum. Insights gained from a previous funneling-line design study,[1] recent advances in beam-dynamics theory,[2] and RFQ design experience at Los Alamos have provided a better understanding of space-charge-induced emittance growth and have shown the necessary ingredients and limitations to obtain low-emittance-growth funneling- and transport-line designs. This paper presents such a design and gives the results of a beam-dynamics study. Although the design is not optimized, the calculational results indicate that emittance growth can be controlled.

DESIGN CONSIDERATIONS

Bongardt[1] has reported the results of a funneling study completed for the German Spallation Neutron Source. Bongardt's line was designed to funnel 100-mA beams of 2-MeV protons from two 100-MHz RFQs into a 200-MHz linac. The average transverse emittance growth in the entire line, including kickers and diagnostics, was $\epsilon_f/\epsilon_i = 2.4$. Bongardt concluded that much of this growth was due to the change in particle distribution as the beam adapted itself to the funneling line. Wangler[2] showed how this occurs; the charge distribution changes rapidly if space-charge forces are not in equilibrium with external focusing forces, and the residual field energy

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for nonuniform beams (the nonlinear field energy) can be transformed to transverse energy of the particles, causing emittance increase.

If the focusing strength or the periodicity (as seen by a beam traversing the various elements of a funneling or transport line) varies so that the average radius of the beam changes, the beam charge distribution also will change as the space-charge forces seek a new equilibrium with the focusing forces. This change in charge distribution results in emittance increase. Thus, we see that if the beam environment (the average focusing and bending strengths and periodicity in the line) could be kept constant, then space-charge-induced emittance growth could be minimized. We assume* that changes in the beam environment, if unavoidable, should be as gradual as possible to try to approach an adiabatic redistribution of charge.

Other causes of emittance growth are energy dispersion in bending elements, spatial nonlinearities of external magnetic and electric fields, and the sine-wave time dependence of bunching and deflecting electric fields. The effect of most of these can be reduced by minimizing beam size in all three dimensions. A small beam radius reduces the effect of nonlinear fields in quadrupoles, bending dipoles, and rebunchers. A short bunch keeps particles in the linear portion of the sine-wave rebuncher field and reduces dispersion caused by the deflecting field in rf deflectors.

In the design presented in this paper, the goal was to keep the focusing strength and periodicity of the funneling line the same as the preceding RFQs; this goal was met only partially. The line was designed to keep beam dimensions as small as possible. Within the bending elements, bunch charge redistribution associated with dispersion was reduced (1) by using a two-channel RFQ with output beams separated by 2.4 cm to substantially reduce bending from that necessary for two completely separate RFQs and (2) by distributing bending throughout the line. No space allocation was made for diagnostics; space could be made available, but it would be necessary to maintain focusing strength and periodicity to avoid excessive emittance growth.

LINE ELEMENTS

A schematic drawing of the funneling line studied is shown in Fig. 1. Parameters of the line elements are given in Table I. The line is 21.5 cm long and consists of two periods. Input beam parameters were provided by an unpublished RFQ design study by Wangler and Mills.* Their design would operate at 212.5 MHz and would produce a 100-mA beam of 2-MeV protons with an average transverse normalized rms emittance of 0.022 π·cm·mrad. In this study, I assumed that the two RFQ output beams would be identical except that the bunches would be 180° out of phase, which would be accomplished by proper phasing of the vane or rod modulations in each RFQ beamline.

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*This information supplied by T. P. Wangler and R. S. Mills, AT-1, Los Alamos National Laboratory.

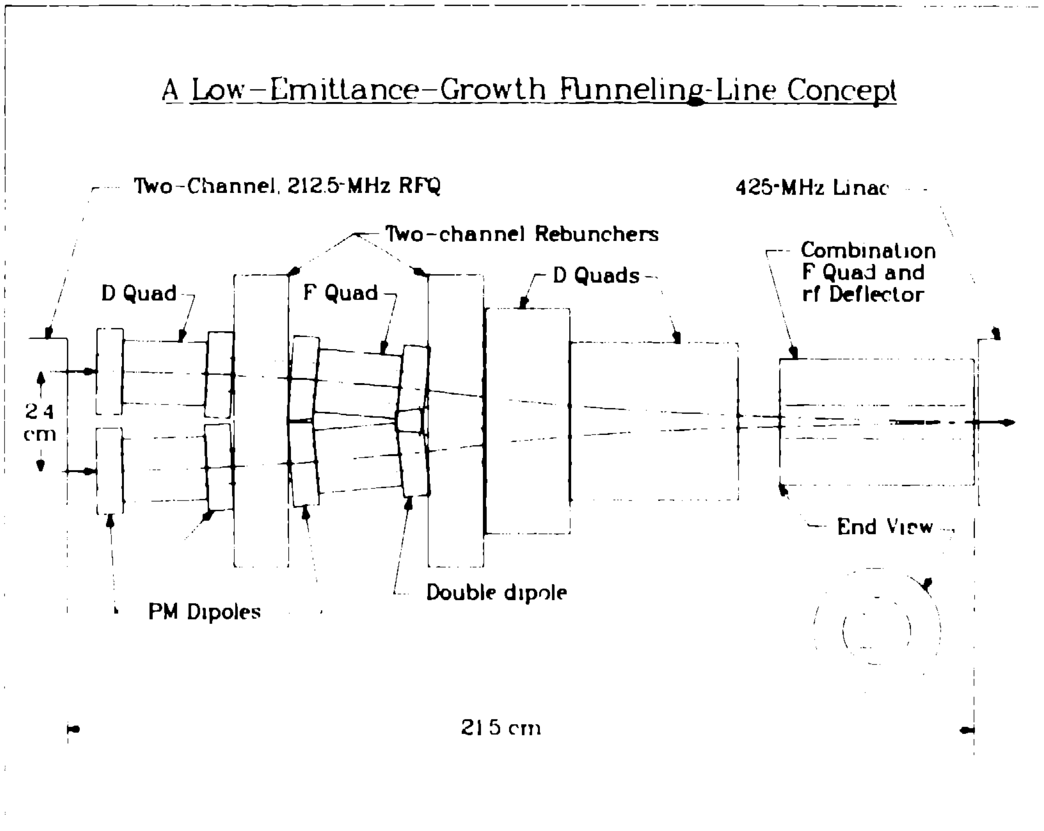

Fig. 1. Drawing of funneling line.

Table 1. Beamline elements

1.	Drift, 0.7 cm long
2.	Dipole, 0.6 cm long, -1.69° bend, 10 000 G
	(All dipoles and quadrupoles are permanent magnets)
3.	Defocusing quadrupole, 2.0 cm long, 20 000-G/cm field gradient
4.	Dipole, 0.6 cm long, -1.69° bend, 10 000 G
5.	Rebuncher, 1.4 cm long, 0.12-MV peak voltage, 425 MHz
6.	Dipole, 0.6 cm long, -1.69° bend, 10 000 G
7.	Focusing quadrupole, 2.0 cm long, 24 000-G/cm field gradient
8.	Dipole, 0.6 cm long, -1.69° bend, 10 000 G; a "double dipole"
9.	Rebuncher, 1.4 cm long, 0.04-MV peak voltage, 425 MHz
10.	Defocusing quadrupole, 2.0 cm long, 7 000-G/cm field gradient
11.	Defocusing quadrupole, 4.0 cm long, 10 000-G/cm field gradient
	(The preceding two quadrupoles bend the beam a total of +3.9°)
12.	Drift, 1.0 cm long
13.	Combination element, 4.6 cm long:
	a. Focusing quadrupole, 12 000-G/cm field gradient
	b. Rf deflector, 6.5-MV/M peak voltage, 212.5 MHz; +2.86° bend

Dimensions of the magnetic elements and of the beamline portions of the rf elements are shown to relative scale in Fig. 1. Inductive portions of the rf elements are not shown because their configurations have not been determined. All magnetic elements in the line are permanent magnets; dimensions of these elements are calculated from the formulae given by Halbach[4] subject to the conditions that (a) the material remanant field B_r = 12 kG, (b) the maximum pole tip field is 10 kG, and (c) the magnets are each composed of eight segments of permanent-magnet material.

The first period of the line is 1 $\beta\lambda$ (9.2 cm) long. It consists of a defocusing quadrupole, a focusing quadrupole, four dipoles distributed along the line to bend the beam towards the final axis, and two 425-MHz, two-channel rebunchers to compress the bunch longitudinally. It is necessary to operate the rebunchers at 425 MHz because bunches transit the rf gaps at this frequency, passing alternately through the two channels. The bunch length must be reduced about a factor of 2 along the length of the funneling line to match the beam to the following linac because the frequency of the linac is twice the frequency of the RFQs. The period ends at the center of the second rebuncher. The element axes, including the rebuncher channel axes, are centered on the individual beam paths. The first quadrupole of the funneling line is defocusing in the x-plane (the plane of the bends) and focusing in the y-plane to match the RFQ output. The beam is bent inward 1.69° at each dipole. There is not enough separation between the beams at the last dipole to permit implementation of conventional design procedures. Therefore, a combined dipole magnet (the "double dipole" in Fig. 1) similar to the "septumless septum magnet" suggested by Halbach* is used. The double dipole is shaped like a figure eight without a center bar rather than like the circle of the normal permanent-magnet dipole. The separation of the bending and focusing functions into distinct components is convenient for calculational purposes and may be the best way to construct the actual magnets. The bending function also could be done by offsetting the quadrupoles from the beam axes or by including a dipole component in the quadrupole when the magnetic segments are specified, manufactured, and assembled. Apertures along the first period are 0.4 cm, as shown by dotted lines in Fig. 1

The second-period component axes are centered on the final output beam axis. The first element in this period is a combination of permanent-magnet defocusing quadrupoles that provide as much focusing strength as possible while simultaneously deflecting the beam back toward the direction of the final axis. The beam exits this element with proper angular direction (x') and x-offset from the axis to intersect the axis in the center of the next element, which is a combined permanent-magnet focusing quadrupole and rf electric-field deflector. In the combined element, the beam is

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*This information was supplied by K. Halbach, University of California, Lawrence Berkeley Laboratory, Berkeley, CA 94720.

focused in the x-direction and deflected along the output z-axis. The deflector operates at 212.5 MHz to provide the proper alternating deflection angles for bunches coming alternately from the two input lines. Apertures in the second period vary to accommodate the changing offset of the beam from the beamline. Separation between the rf deflector plates is 0.8 cm; therefore, the final radial aperture is 0.4 cm. Ideally, this second period should be 9.2 cm long to maintain constant periodicity. However, the length of the rf deflector along the beamline is $\beta\lambda/2$ (4.6 cm) to maximize available deflection for a given peak electric field and to minimize the effect of fringe fields at the ends of the element. The defocusing quadrupole combination plus the following drift space is 7 cm long to obtain the proper beam trajectory. Half the length of the second rebuncher, 0.7 cm, is included in the second period. Therefore, the total length of the second period is 12.3 cm. The average focusing strength is less than in the first period, although focusing should really be stronger than in the first period to balance the higher space-charge forces resulting from longitudinal compression of the bunch. Better techniques for calculating the beam trajectory and designing the magnets may allow a reduction of the length of the period and an increase in focusing strength. It is important not to disturb the charge distribution of the beam; possibly the distribution can be kept constant by proper combinations of period length and focusing strength.

There are several elements in this design that have not been used before. A two-channel RFQ has not yet been demonstrated, but there seems to be no obvious reason as to why it should not perform as well as a conventional RFQ. The permanent-magnet dipoles and first-period quadrupoles are very small but should present no unexpected problems because the field requirements are not extreme. Higher order multipoles in the permanent magnets will probably be a few per cent at the radius of the aperture, and this should not have a large effect on emittance growth. The two-channel rebunchers may present a design challenge in that they must fit into a very small length of beamline and must accommodate two angled beams with the minimum possible field nonlinearity. The amount of field nonlinearity in the rebunchers has not been investigated.

The rf deflector surrounded by a focusing quadrupole is probably the highest risk component. The combination of deflecting and focusing functions was influenced by the desirability of a $\beta\lambda/2$ deflector and the simultaneous requirement of strong focusing. The final design of this element may not look like the conceptual sketch in Fig. 1. There have been only preliminary discussions and ideas concerning coupling the rf power, minimizing electric-field nonlinearities and edge effects, controlling sparking and multipactoring, and keeping heating to an acceptable level.

BEAM-DYNAMICS CALCULATIONS AND RESULTS

The beam-dynamics calculation was performed on the particle-tracking code PARMILA. A 3-D space-charge subroutine was used so that the off-axis beam (which is not expected to be round) could be calculated properly. No beam-beam or bunch-bunch interactions were included; these effects are expected to be small and can be easily included later, if desired. No image-charge effects were included. Also, no spatial nonlinearities were included in the magnetic or electric fields because these were unknown. Included in the calculation were the temporal nonlinearity in the rebuncher voltages and phase-angle-dependent and energy-dependent dispersion in the rf deflector. The effect of the rf deflector would actually occur over the entire length of the element; but in the calculations, the effect was applied as an angle impulse to each particle at the center of the element. This caused a small error that can be corrected by a more sophisticated combination deflector-quadrupole subroutine.

The funneling-line input beam was obtained by taking individual output particle coordinates from the RFQ calculation. The RFQ emitted 329 macroparticles and none were lost in the funneling-line calculation. In the first period, 100% of the macroparticles remained within a radius of 0.28 cm and 90% remained within 0.2 cm; in the entire line, 100% of the macroparticles remained within 70% of the aperture radius and 90% remained within 50% of the aperture radius. A run using the RFQ beam-ellipse parameters with an initially spatially uniform bunch of 500 macroparticles gave practically the same results for the beam envelope and emittance growth.

Beam envelopes and emittances are shown in Figs. 2 and 3. A line diagram is shown at the bottom of these figures. The quadrupoles are divided into short sections for calculational purposes. The transverse envelopes are fairly constant in the first period but vary in the second; the transverse emittances show little change in the first period and then increase in the second. If the envelope variations in the second period could be reduced, perhaps this increase could be controlled, as discussed previously. There is a small jump in the x-emittance at the position of the rf deflector that is correct in magnitude but should be distributed over the length of the deflector. The longitudinal or z-emittance shows jumps at the rebunchers (caused by the nonlinear longitudinal fields) and variations in the bending elements. These variations have not yet been fully analyzed but are believed to be caused by the mixing that bending elements introduce between longitudinal and transverse phase space. Z-emittances are shown in units of π·cm·mrad for direct comparison with transverse emittances.

The bunch length is reduced by less than a factor of 2 by the time the bunch enters the rf deflector. Bunching causes longitudinal emittance growth because the bunch is twice as long in phase angle in the 425-MHz rebunchers as in the 212.5-MHz RFQ. In future RFQ designs, if the bunch compression could be initiated in the last part of the RFQ, then the bunch could be shorter in the rebunchers,

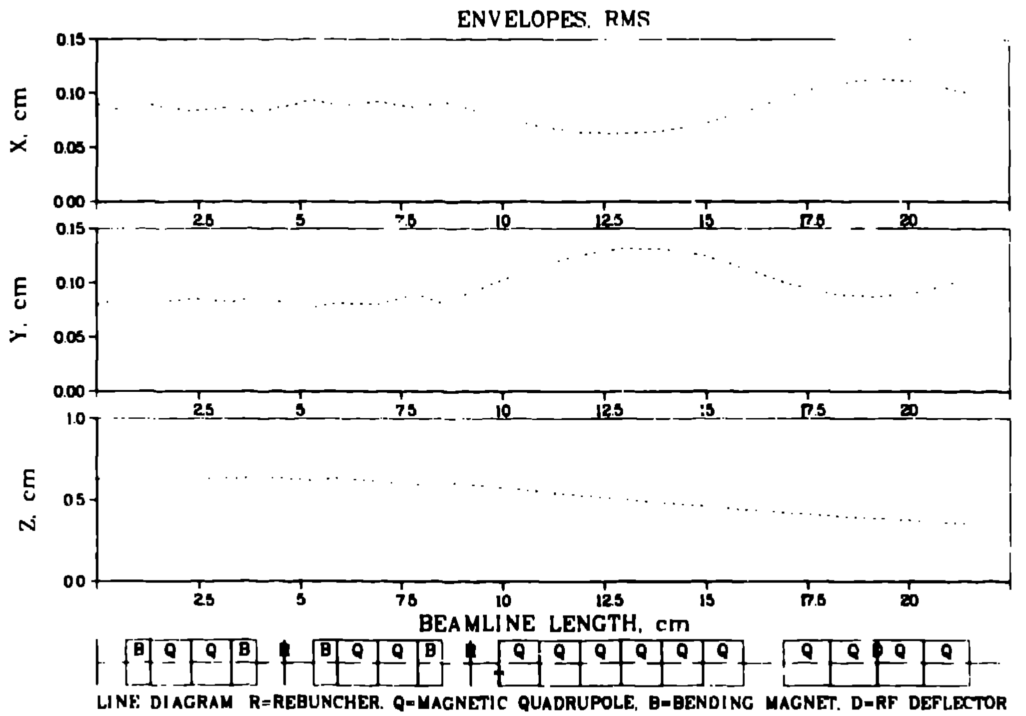

Fig. 2. Beam envelopes.

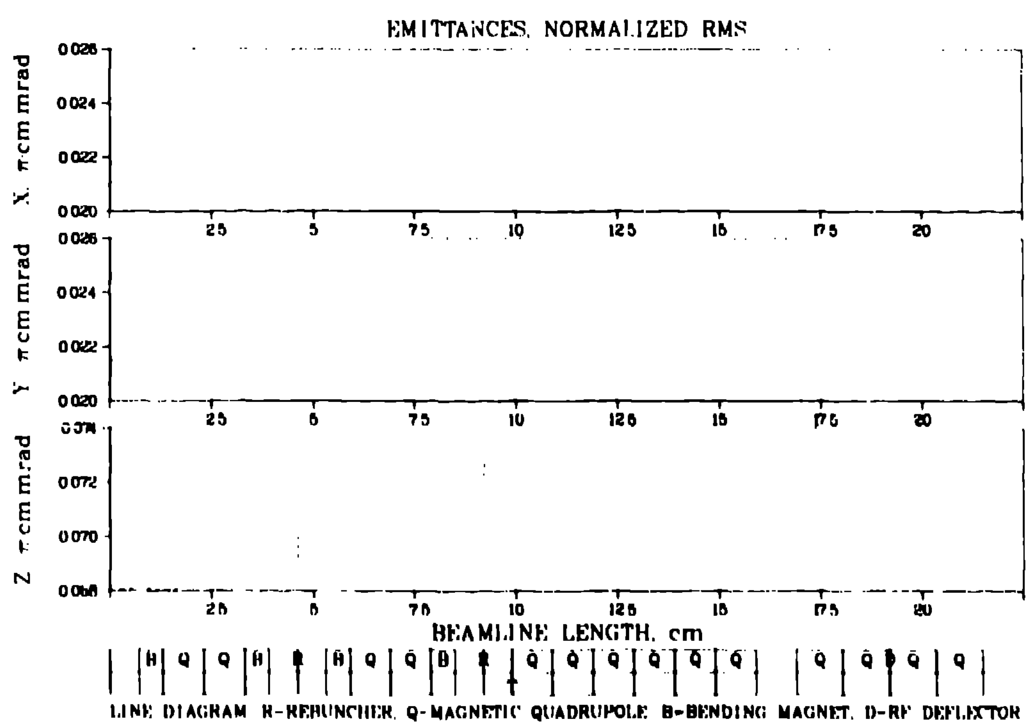

Fig. 3. Beam emittances.

thereby reducing the z-emittance growth in these elements. A shorter bunch in the rf deflector would reduce the x-emittance growth there.

The transverse emittance increase averaged over the two transverse planes in this calculation was 15%, and the final longitudinal increase was 4%. Part of this increase may have been because of the small number (329) of macroparticles in the 3-D space-charge calculation. Too few macroparticles causes unphysical small-scale lumpiness in the charge distribution that results in artificial increases in the transverse particle velocities. There is another way of looking at this effect: If two macroparticles happen to approach each other closely, they will repel each other violently, causing large velocity changes and emittance growth; whereas, the actual particles would be subjected to a more gentle repulsion as they drift into regions of higher charge density and would therefore not change velocity as much. Haber[5] has called this effect "collisional emittance growth." Using a larger number of macroparticles in both the RFQ and the funneling-line calculations will help to quantify this effect as well as to reduce the (probably fairly large) statistical uncertainty.

CONCLUSIONS

The funneling line presented in this paper gives an encouragingly low emittance growth based on beam-dynamics calculations. The study is preliminary, with the following shortcomings:

- Some of its elements may be difficult or impractical to construct exactly as they are envisioned here.
- The beam-dynamics calculations are not as complete or extensive as they should be.
- There are certain effects (such as the relation between focusing strengths, periodicity, beam radius and charge distribution) that should be better quantified.

Nevertheless, these results have confirmed some ideas about how emittance growth can be controlled. Energy dispersion in bending elements and phase-difference-induced dispersion in rf deflectors can be minimized by making the bends as small as possible. Phase-difference-induced dispersion in rf deflectors can also be reduced by compressing the bunch longitudinally (this compression is necessary for matching the bunch to a following linac in which the frequency has been doubled). The radius of the beam should be kept small by high focusing strength so that it will remain in the linear portion of the focusing, bending, and rebuncher fields. Most important of all, space-charge-induced emittance growth (which usually dominates in high-current beams) can be minimized by maintaining, as nearly as possible, constant focusing and bending strength and periodicity. The success of these ideas, at least in this simulation study, has improved our understanding of the causes of emittance growth and has allowed us to design a low-emittance-growth funneling line.

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