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# AN ISOCHRONOUS BEAM RECIRCULATION MAGNET SYSTEM

J. B. Flanz, S. Kowalski, C. P. Sargent
Massachusetts Institute of Technology, Cambridge, MA 02139

## Abstract

The beam energy capability of an electron linear accelerator can be extended by using a magnetic transport system to return the beam after passing once through the accelerator, to the injector end and then "recirculating" the beam through the accelerating structure several times. The most important property of the transport system is that it be a good achromat, since operability requirements and beam loading transients usually require at least a few percent energy bandwidth over which the beam will successfully traverse the accelerator during recirculation. The system must also be nearly isochronous, with linear phase-energy correlation corresponding to not more than a fraction of an RF wavelength over a few percent bandwidth and with a small second-order phase-energy correlation coefficient. Such a system to be described in this paper has been designed and is currently under construction for the purpose of recirculating the beam of the 400 MeV Bates Linear Electron Accelerator.

## Introduction

The injected beam at the 400 MeV/c Bates Linear Accelerator is contained within a normalized ($\beta\gamma=1$) emittance of 7 $\pi$ mm-mrad and an energy spread of 0.3%.[1] Typically peak currents are near 10 mA, with a beam loading coefficient of 3 MeV/mA. The excellent emittance lends the beam easily to recirculation. However, due to the pulsed nature of the beam, the resulting energy shifts during the transient period caused by recirculating the beam are appreciable. Much of this beam energy shift can be controlled by fast digital phase shifters or controlled attenuation of klystron power, although operability requirements dictate that the recirculation system be able to accommodate a ±3% range in energy. Thus the most important criteria of the transport system is that it be a good achromat with an appropriate energy bandpass. Given the accelerator focussing system, chromatic aberrations must be sufficiently small that focal lengths greater than 100 meters and effective drift lengths less than 50 meters develop over this range in energy. Centroid shifts must be less than 1 mm and 0.1 mrad. Geometric aberrations must produce not more than 10% increase in emittance. The system must be sufficiently isochronous that the first and higher order phase-energy correlations do not correspond to more than a few percent of an RF wavelength (10.5 cm in our S-band machine) over the range of the required energy bandpass.

These criteria are met by an achromatic and isochronous magnetic deflection system whose higher order aberrations are controlled by the symmetry of the first-order orbits and weak sextupole fields. Although several magneto-optical systems were investigated, practical considerations particular to the Bates environment dictated the choice of the system to be described in this paper.

## Theory

The phase space of the beam is preserved through the recirculation system to first order by requiring a unity transfer matrix from the input of the recirculator to its output. One way to fulfill this requirement is to produce first-order orbits with symmetry about the center of the system. Thus the horizontal (bend plane) transfer matrix at the end of the system in terms of the matrix elements at the symmetry point indicated by the subscripts is given by [2].

$$M = \begin{pmatrix} 2(X/X)_s(\theta/\theta)_s-1 & 2(X/\theta)_s(\theta/\theta)_s & 2(X/\theta)_s(\theta/\delta)_s \\ 2(X/X)_s(\theta/X)_s & 2(X/X)_s(\theta/\theta)_s-1 & 2(X/X)_s(\theta/\delta)_s \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

and we require this matrix to be diagonal with either positive or negative diagonal elements.

In addition to the first-order considerations, this choice of symmetrical orbits has effect on the second-order aberrations. The transfer matrix and aberrations q(L) at position L in the magnet system are related to the first-order orbits in general by [3].

$$q(L) = s(L)\int_0^L f(\ell)c(\ell)d\ell - c(L)\int_0^L f(\ell)s(\ell)d\ell \quad (2)$$

where $s(\ell)$ and $c(\ell)$ are the sinelike and cosine-like trajectories and $f(\ell)$ is the driving function[3] for the aberration q(L). Thus by the correct choice of symmetry, any aberration can be made to vanish.

## Transport System

The recirculation transport system consists of three main components. First the input loop bends the beam exiting the accelerator through 180°, second the return path transports the beam parallel to the accelerator to the injector end, and third the output loop bends the beam 180° back into the accelerator for recirculation.

For the above reasons of symmetry, the input loop is the mirror image of the output loop and the return path is mechanically symmetric about its center. In this way the bending radius function is even.

The loop itself is also mechanically symmetric for reasons to be discussed below. The loop consists of five dipoles bending the beam through angles of $\theta$, $-\theta$, 180°, $-\theta$, and $\theta$. The negative bend angles reduce the linear phase-energy correlation $(Z/\delta)$ through that element and allow the total $(Z/\delta)$ though the loop be zero, or small.

The first-order conditions placed on the loop are chosen on the basis of both first- and second-order considerations. It is required to be isochronous and non-focussing, although a drift length of the order of its physical length is allowed to develop. The horizontal cosine function $c_x(\ell)$ is odd and the dispersion function $d(\ell)$ is even as shown in Figure 1. By virtue of these symmetries, $(\theta/\delta^2)$ vanishes via Equation 2. In this way $(X/\delta^2)$ is restrained from propagating through the return path.

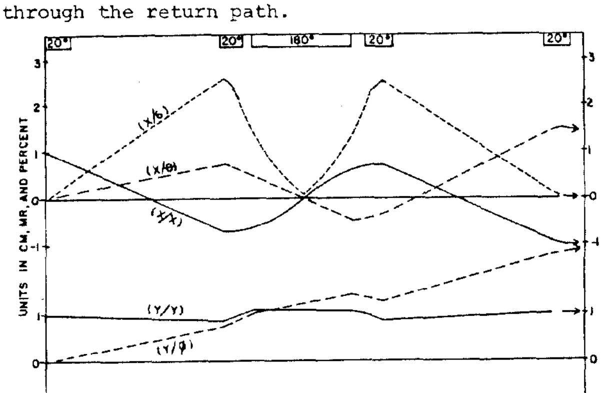


Figure 1. First Order Orbits In Loop

The first-order conditions placed on the return path are chosen so as to reduce a maximum number of second-order chromatic aberrations as well as to control the beam size through the beam path. As can be seen from Figure 2, the cosine function is even and the sine function is odd through the return path and thus throughout the entire system. In this way $(X/\delta^2)$, $(X/X\delta)$, $(\theta/\theta\delta)$, $(Y/\phi\delta)$, and $(\phi/\phi\delta)$ vanish by symmetry at the output of the recirculation optics. The centroid angular aberration $(\theta/\delta^2)$ remains small due to its small value halfway through the system. Thus the centroid position and angle shifts which can be chromatic aberrations are controlled as well as the chromatic magnifications. It remains to treat the other chromatic aberrations including $(X/\theta\delta)$, $(\theta/X\delta)$, $(Y/\phi\delta)$, $(\phi/Y\delta)$ and $(Z/\delta^2)$.

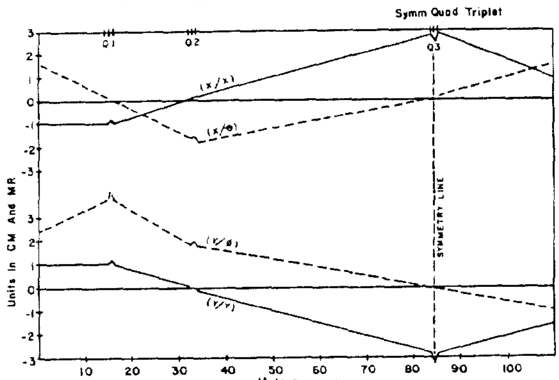


Figure 2. First Order Orbits In Return Path

In Figure 3, the choice for $\theta$ is made on the basis of the required focal strengths and sextupole strengths necessary to meet the above conditions. The sextupole corrections are greatly reduced for $\theta$ less than 25°, while the pole face rotations become large for $\theta$ less than 16°. Therefore the optimum angle is chosen to be 20°. The physical parameters of the system and uncorrected aberrations are listed in Table I. Due to the size of the dispersion, it is impractical to use physical sextupoles for all the second-order focussing. Therefore, pole face curvatures are to be used on the -20° bend and the 180° bend. In addition, a sextupole is needed in the drift space between the 20° and -20° bends. The sextupole strengths and corrected aberrations are listed in Table II. These aberrations produce effects comparable to our limiting constraints when the energy shifts in the accelerator reach +5% to -3%. The asymmetry is due to the higher order aberrations. Thus the system exceeds the design specifications.

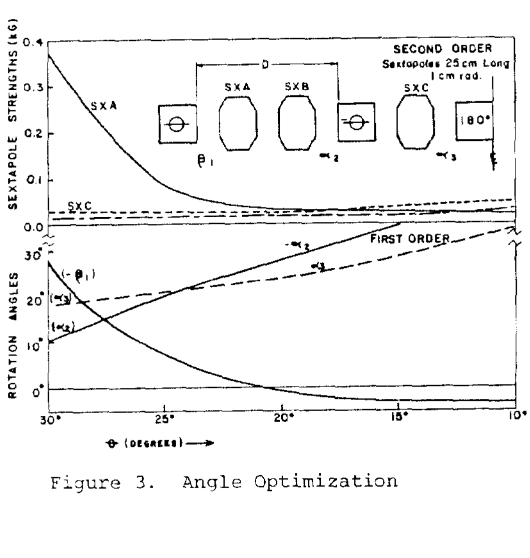


Figure 3. Angle Optimization

Table I: Uncorrected Aberrations (Units in cm and mr)

| | |
|---|---|
| $\rho$ | 1.33M |
| D | 720.329cm |
| $\beta_1$ | 2.0540° |
| $\alpha_2$ | -14.798° |
| $\alpha_3$ | 13.156° |
| $1/R_2$ | 0 |
| $1/R_3$ | 0 |
| SEXT. | 0 |

| | LOOP | WHOLE SYSTEM |
|---|---|---|
| $(X/X\delta)$ | 5.66(-2) | - |
| $(\theta/\theta\delta)$ | -6.93(-4) | -2.23(-1) |
| $(\theta/X\delta)$ | -7.64(-2) | 2.25(-1) |
| $(\theta/\theta\delta)$ | 5.65(-2) | - |
| $(Y/Y\delta)$ | 5.74(-1) | - |
| $(Y/\phi\delta)$ | 5.74(-1) | -1.92(0) |
| $(\phi/Y\delta)$ | 5.05(-1) | 9.28(-1) |
| $(\phi/\phi\delta)$ | 5.72(-1) | - |
| $(X/\delta^2)$ | 3.47(-2) | - |
| $(\theta/\delta^2)$ | - | - |
| $(Z/\delta^2)$ | 8.57(-2) | 1.71(-1) |
| $(X/\delta^3)$ | -2.14(-3) | -9.32(-5) |
| $(X/\delta^4)$ | 8.01(-5) | 5.16(-4) |
| $(\theta/\delta^3)$ | 1.03(-3) | -4.34(-3) |
| $(\theta/\delta^4)$ | -8.96(-5) | -3.81(-5) |
| $(Z/\delta^3)$ | -2.52(-3) | -5.03(-3) |
| $(Z/\delta^4)$ | 8.43(-5) | 2.04(-4) |

Table II: Corrected Aberrations (Units in cm and mr)

| | |
|---|---|
| $\rho$ | 1.33M |
| D | 720.329cm |
| $\beta_1$ | 2.054° |
| $\alpha_2$ | -14.798° |
| $\alpha_3$ | 13.156° |
| $1/R_2$ | $.0142M^{-1}$ |
| $1/R_3$ | $.0257M^{-1}$ |
| SEXT. | -3.908 Gauss/cm (500 MeV/c) |

| | LOOP | WHOLE SYSTEM |
|---|---|---|
| $(X/X\delta)$ | -5.38(-3) | - |
| $(X/\theta\delta)$ | 7.81(-2) | -1.95(-1) |
| $(\theta/X\delta)$ | 6.56(-3) | 4.84(-2) |
| $(\theta/\theta\delta)$ | -5.37(-3) | - |
| $(Y/Y\delta)$ | -6.34(-2) | - |
| $(Y/\phi\delta)$ | -5.96(-2) | -1.71(-1) |
| $(\phi/Y\delta)$ | -5.60(-2) | -7.60(-3) |
| $(\phi/\phi\delta)$ | -6.33(-2) | - |
| $(X/\delta^2)$ | 1.99(-2) | - |
| $(\theta/\delta^2)$ | - | - |
| $(Z/\delta^2)$ | -3.61(-3) | -4.81(-3) |
| $(X/\delta^3)$ | 8.12(-5) | -6.15(-4) |
| $(X/\delta^4)$ | 1.75(-4) | 2.10(-4) |
| $(\theta/\delta^3)$ | -1.16(-4) | -1.56(-3) |
| $(\theta/\delta^4)$ | -1.75(-3) | 4.79(-4) |
| $(Z/\delta^3)$ | -4.17(-3) | -8.70(-3) |
| $(Z/\delta^4)$ | -8.82(-5) | -1.67(-4) |

## Instrumentation

The layout of the recirculation system and its instrumentation is shown in Figure 4. The slits are used to prevent energy shifts greater than the band-pass from entering the recirculator. The synchrotron monitor will be used primarily to monitor the energy at a point where the dispersion is large. The vertical steering coils are used to compensate tilts of the 180° dipole as detected by the traveling wave monitors after each loop. Dynamic loads will be used on all dipoles. These serve not only to match the fields but as horizontal trim. The -20° and 180° dipoles will be wired in series so as to provide a self-compensating unit as protection against magnet excitation fluctuations since most of the effects of fluctuations in the 180° dipole are canceled by those in the -20° bends. Traveling wave position monitors and wire lutes are to be used in the return path and accelerator for general steering and focussing. A microcomputer is to be used in monitoring the magnetics and beam position. It may be possible to program in the betatron oscillation function and thereby control the steering by the computer. However, in its initial operation it will serve only as a monitor. Phasing the recirculator can be accomplished either by moving the 180° dipoles or by trimming the field in them.

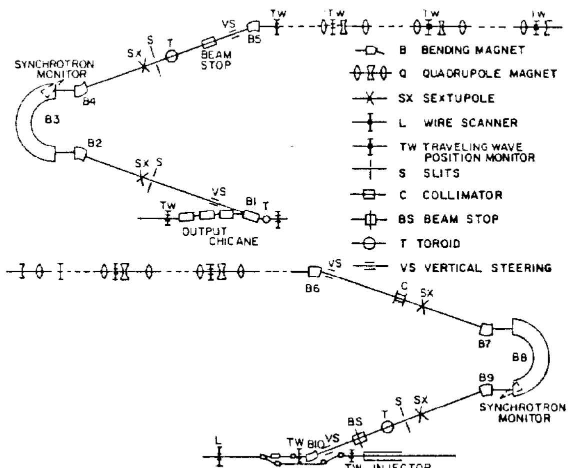

Figure 4. INSTRUMENTATION FOR TWO-PASS RECIRCULATOR

## Conclusion

An achromatic, isochronous magnet transport system capable of recirculating the beam of the Bates linac has been designed. With the help of weak sextupole corrections it should be possible to recirculate an energy bandpass of +5% to -3%. With higher order multipole corrections, it may be possible to extend this range. The system uses negative bends to achieve isochronism. The system is scheduled to be completed by the end of 1981, and will increase the maximum energy of the accelerator to about 725 MeV.

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## References

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