# CESR Transfer Line Optimization

Chad Morris

*Physics, Ohio State University, Columbus, Ohio, 43210*

## Abstract

The purpose of this study is to improve upon the existing magnetic optics of the transfer lines between the synchrotron and storage ring of the Cornell Electron Storage Ring facility. I looked into the possibilities of adding an additional quadrupole to the line as well as repositioning the quadrupoles of the current line. I, also, looked into the feasibility of going to higher magnetic field strengths of the quadrupoles. It will be shown that by employing these options definite improvements can be achieved in reduction of needed aperture on the beamline due to less than optimal injection parameters.

## Introduction

When electrons or positrons are to be injected into CESR, they must first be generated by an electron gun. The electrons then pass through the linear accelerator (linac), where the some initial energy is given to the particles and positrons can be produced if desired. The particles travel into the synchrotron where they are accelerated to their target energy. The beam must then be moved from the synchrotron into CESR via a transfer line. The transfer line is a special set of magnets whose purpose is to transport the beam from the synchrotron to CESR and prepare the beam for injection.

The task of injection is complicated by the fact that, with the exception of the first injection, there is already a beam being stored in CESR. It is not possible to inject the particles directly into the beam in CESR without disrupting the already-stored beam. However, we can inject the beam on a path that is very close to the CESR beam, as well as modify the path of the CESR beam slightly to facilitate this process. The consequence of this injection procedure is that the newly injected beam has a small horizontal displacement from the ideal beam path. As it progresses about the ring, the newly injected beam will oscillate in the horizontal plane about the ideal beam path. If these "betatron" oscillations are large enough the injected beam will come into contact with, or "scrape," the walls of the beam line. This would result in the loss of particles in the injected beam and an overall decrease of luminosity of the CESR beam. So it is to our advantage to try to match the parameters of the injected beam as closely as possible to the characteristics of the stored beam. This will minimize betatron oscillations and beam loss due to scraping.

## Methods and Programs

There are six parameters that will be matched in order to maximize injection effiency. They are $\beta_x$, $\alpha_x$, $\beta_y$, $\alpha_y$, $\eta$, $\eta'$. The variables in our system will be the field strength, $k$, of the five existing quadrupoles along with their placement along the longitudinal axis of the transfer line, $s$. There also exists the possibility of adding an additional quad to the transfer line. This would bring six quadrupole field strengths, $k$, to match six constraints, an appealing prospect.

There are three main computer programs that will be used during this project. This first, and most crucial, is the BMADZ optimizing program. This is a standard CESR routine for optimizing a given lattice subject to certain constraints. The program is given the placement of the quads along with the starting parameters, target parameters at the end of the line, constraints of the line itself and their weights. The program will then look for an optimal solution to the given requirements. As good as this program is, it does require the occasional assistance. It seems to get stuck in local minima and requires a nudge from time to time. A custom written program by Stuart D. Henderson, SDH, will simulate the transfer line optics of the lattice file produced by BMADZ. Finally, the IDL software package will be used along with some custom written macros by SDH to display the data generated by the transfer line simulation.

## Definitions and Calculations

### What is $\beta$?

The transfer line is made of a several types of magnets. Of particular interest to this project are the quadrupole magnets. A quadrupole magnet acts as a focusing lens for the charged particle beam. This magnetic lens has a focal length which is directly proportional to the strength, $k$, of the magnetic field of the quadrupole. A particle passing through the center of the quadrupole, the ideal path, will feel no force acting upon it. However, the further away the particle is from the center of the quad the greater the force that acts on the particle. It is a linear restoring force. This means that the system behaves somewhat like a simple harmonic oscillator. There are some differences. First, the quadrupole magnet can only focus one plane at a time. As the magnetic lens focuses on the horizontal plane it is actually defocusing on the vertical and vice versa. Also, the linear restoring force is only present while the beam is in the field of the quadrupole. These oscillations are the betatron oscillations and are given by the $\beta$ function. That is, the larger that $\beta$ is the larger the oscillations are. In fact, the maximum lateral displacement in these oscillations is directly proportional to the square root of $\beta$ [2].

$$X_{max}(s) = A * \sqrt{\beta(s)} \tag{1}$$

### Why match $\beta$?

The percent difference of $\beta$ at any given point on the ring can be calculated from the following equation, [1]

$$\frac{\Delta\beta_i}{\beta_i} = \frac{\Delta\beta_{34}}{\beta_{34}} * \cos 2\phi \tag{2}$$

The injection occurs at quadrupole 34 in CESR. So $\beta_{34}$ refers to the beta value of the stored beam at quadrupole 34 and $\beta_i$ denotes the beta value at any other point on the ring. In Eq. (2), $\Delta\beta_{34}$ is the absolute value of the difference between the $\beta$ at quad 34 in CESR and the $\beta$ of the injected beam and $\phi$ is a phase angle along the path of the beam. Since

CESR has a non-integer tune, the phase angle will change on any given turn [1]. Therefore, we can assume that after many turns $\phi$ has approached $\pi$ or zero and $cos(2\phi) = 1$. So we now have,

$$\frac{\Delta\beta_i}{\beta_i} = \frac{\Delta\beta_{34}}{\beta_{34}} \tag{3}$$

Thus, if given a 10% increase of $\beta$ at the injection point we can assume that a 10% increase will occur at all other points of the ring at some time. By using Eq. (1), we can find the percent increase in aperture required by this increase of $\beta$,

$$\frac{\Delta X_{max}}{X_{max}} = \frac{X'_{max} - X_{max}}{X_{max}} = \sqrt{1.1} - 1 = 0.0488 \tag{4}$$

In other words, a 10% increase of $\beta$ would mean an approximate 5% increase of required aperture in the beam line due to betatron oscillations.

## What is $\alpha$?

Alpha is merely the change in $\beta$ along the beam line, or $\frac{\partial\beta}{\partial s}$. We would like to match $\alpha$ to ensure that the injected $\beta$, $\beta_{inj}$, does not drastically diverge from the stored beam $\beta$, $\beta_{stored}$, down the beam path. For example, if $\beta_{inj}$ is increasing while $\beta_{stored}$ is decreasing then the injected beam will diverge from the path of the stored beam and increases the needed aperture to contain the beams.

## What are $\eta$ and $\eta'$?

The different particles in the beam do not all possess the same energy. Some have energies that are above the ideal energy. As such, the particles have closed orbits that are larger than that of the ideal path. The converse is true about particles with energies that are lower than the ideal energy. This characteristic is described as dispersion and is denoted as $\eta$. Similar to the $\beta$ functions, we can describe the difference in $\eta$ from the stored beam at any point on CESR with an equation [1].

$$\Delta\eta_i = \sqrt{\frac{\beta_i}{\Delta\beta_{34}}}\Delta\eta_{34} \times \cos\phi \tag{5}$$

And with a similar argument, we can treat $\cos\phi = 1$.

As with $\beta$, $\eta$ is a function of the beams longitudinal position, $s$, and we must try to match the injected beam to the change of $\eta$, as well. This is the last constraint that we will trying to match, $\eta'$. $\eta'$ is defined as the change in $\eta$ relative to the longitudinal position,$s$, of the beam. That is, $\eta'$ is $\frac{\partial\eta}{\partial s}$.

# Results

The west transfer line transports the positrons from the synchrotron to the storage ring. I have made the following adjustments to the west transfer line.

- Moved Quad 1 as close as physically possible to the synchrotron. I will refer to SB15 of the synchrotron as $s = 0$ of the transfer line. Quad 1, WXFR_QT1, now lies at $s = 0.5129$
- Shifted Quad 2 same distance as Quad 1 to maintain seperation between them.
- Added a sixth quadrupole positioned at $s = 6.0154$
- Removed constriction on field strength, $k$, of quadrupoles.

After setting up the new layout, I ran BMADZ to find a new set of k values for the 6 quadrupoles. Initially, I was trying to match the original six constraints at quad 34 on the west line, or Q34W. With six quadrupoles, we now have six variables, $k$, constrained to match six values. I expected to quickly find an ideal match. This was not the case. Eventually, I began to include constraining values of not just Q34W but Q35W and Q36W as well. The best match I found was done by using the original six constraints, the corresponding six constraints at Q35W, along with $\eta$ and $\eta\prime$ of Q36W. This set of $k$ values is shown in Table 1. The corresponding $\beta$ and $\eta$ values are shown in Table 2, listed as W MORRIS. Table 2, also, contains the current injection characteristics, W002, and the values of the stored beam, CESRQ34W.

TABLE 1. $k$ strengths of west transfer line.

| QUAD | $k$ |
|---|---|
| 1 | 0.897704 |
| 2 | -0.914949 |
| 3 | 0.915309 |
| 4 | 0.338521 |
| 5 | -0.462387 |
| 6 | 0.401509 |

TABLE 2. $\beta$ and $\eta$ values at west injection point (Quad 34W)

| | W002 | W MORRIS | CESRQ34W |
|---|---|---|---|
| $\beta_x$ | 34.6792 | 43.0364 | 39.1508 |
| $\beta_y$ | 12.8999 | 11.9740 | 15.1411 |
| $\eta$ | 0.6517 | 1.6397 | 1.8382 |

The east transfer line, which transports the electrons, is approximately 8m longer than the west. For this reason, the solution to the east line differs from that of the west. Suprisingly, I did not find it necessary to insert a sixth quadrupole into this line. The entire line, from the first quad EXFR_QT1 up through EXFR_QT5, has been shifted 0.5m closer to the synchrotron. Other than this shift, the layout of the line remains unchanged.

TABLE 3. New $k$ strengths of east transfer line quadrupoles.

| QUAD | $k$ |
|---|---|
| 1 | 0.578046 |
| 2 | -0.548095 |
| 3 | 0.115852 |
| 4 | 0.0822198 |
| 5 | -0.0188114 |

TABLE 4. $\beta$ and $\eta$ values at east injection point (Quad 34E)

| | E002 | E MORRIS | CESR Q34E |
|---|---|---|---|
| $\beta_x$ | 43.6752 | 39.4982 | 39.3409 |
| $\beta_y$ | 11.2512 | 14.3874 | 14.8685 |
| $\eta$ | 2.3640 | 1.8760 | 1.8244 |

Since an increase in either $\beta$ or $\eta$ during injection directly translates into an increase elsewhere on the ring, I feel this is a good method of quantifying my results. I will be using Eq. (6) to calculate the beam width in terms of $\beta$ and $\eta$ [1].

$$\sigma_i = \sqrt{\epsilon\beta_i + \eta_i^2\delta^2} \tag{6}$$

I can use Eq. (6) to find a percent difference in beam widths between the injected beam characterics and the stored beam characteristics.

$$\frac{\Delta\sigma_i}{\sigma_i} = \frac{\sqrt{\epsilon(\beta_i + \Delta\beta_i) + (\eta_i + \Delta\eta_i)^2\delta^2} - \sqrt{\epsilon\beta_i + \eta_i^2\delta^2}}{\sqrt{\epsilon\beta_i + \eta_i^2\delta^2}} \tag{7}$$

Note that Eq. (6) is only valid for beam width in the horizontal, or $x$-plane. $\eta$ does not affect the beam size in the $y$-plane so it dropped from the equation and the equation becomes:

$$\sigma_i = \sqrt{\epsilon\beta_i} \tag{8}$$

A corresponding percent difference can be calculated similar to Eq. (7).

Using the $\beta$ and $\eta$ values shown in Table 2 and Table 4 along with Eq. (7), I derived the values shown in Table 5.

TABLE 5. Percent difference of injected beamwdith from stored beamline

| | W002 | W MORRIS | E002 | E MORRIS |
|---|---|---|---|---|
| $\frac{\Delta\sigma_x}{\sigma_x}$ | 50.2% | 10.2% | 23.2% | 9.98% |
| $\frac{\Delta\sigma_y}{\sigma_y}$ | 7.14% | 9.96% | 11.5% | 1.61% |

## Conclusions

A significant reduction in beam width can be attained by making some changes to the transfer lines of CESR. The greatest reduction occurs in the horizontal plane of the west line. The addition of the sixth quadrupole and the shifting of the magnets closer to the synchrotron have shown the expected results. The unusually high $k$ values needed for this configuration were not previously attainable due to the physical restrictions of the magnets themselves. The $k$ strength for the magnets are linearly related to the energy of the beam itself. So with the CLEO III upgrade and the new lower energy of the beam, this configuration might be possible as the $k$'s will scale accordingly. The failure to attain reduction in the $y$-plane of the west line corresponds to the fact that the dispersion function, $\eta$, is only present in the horizontal plane. The calculated beam width in $y$ only depends upon $\beta$ so the improvements to $\eta$ are lost in this plane.

## Acknowledgments

I would like to thank David L. Rubin for his patience and guidance in this project. I would also like to thank the organizers and Co-principal Investigators of the program: Rich Galik and Gerry Dugan. This program has been funded by the NSF under the REU grant PHY-9731882 and research grant PHY-9809799.

## Footnotes and References

1. David L. Rubin, email correspondence with author, June-Aug (2002).
2. Matthew Sands, SLAC-121, 'The Physics of Electron Storage Rings - An Introduction' (1970).