Vertical Injection into CESR

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Abstract

Injection into CESR using vertical phase space rather then horizontal has a potential advantage in the reduction of beam-beam effects from parasitic crossings. I looked into the problems with designing a vertical injection line for the injection of particles into CESR. I also tried to find a simplified solution to tracking particles through nonlinear fringe fields of the Synchrotron magnets. I ended up with a design for a vertical transport line made by linear fields.

Introduction

The object of my project was to design a vertical transfer line for particles from the Synchrotron to CESR. There are many reasons for wanting to do this. CESR's injection scheme is presently configured for phase-space stacking in the horizontal plane. Because of the finite intensity per bunch available from the linac/synchrotron injector for CESR, the charge in each storage ring bunch must be built up over many hundred individual injection cycles. It is impossible to add the new particles directly to the already-stored particles since at some point in the process the bending of the injected particles onto the storage ring orbit will also affect the stored particles. This difficulty is overcome in CESR by bringing the injected particles close to, but not exactly on top of, the stored bunch. As a result, the newly injected particles oscillate in horizontal position about the particles in the stored bunch. These "betatron" oscillations are quite large and sometimes come close to the counter-rotating bunches, making adjustment of the many magnets increasingly critical as the intensity of the counter-rotating bunches increase (increasing the magnitude of their electro-magnetic field). An alternative is to inject the particles vertically, so they oscillate about the stored bunches in the vertical plane and do not wander into the path of the counter-rotating bunches (which are separated horizontally). Vertical injection differs from horizontal injection primarily because the bunches are usually very small in the vertical dimension compared to the horizontal, and the vacuum chamber is smaller vertically than horizontally. This injection scheme will allow us to avoid the parasitic beam-beam interactions with the counter-rotating beam. These beam-beam interactions cause a major problem and will only get worse when the currents in CESR are increased.

Programs

This summer I basically used 2 programs. I worked with Microsoft Excel to make linear approximations to fringe fields in magnets. I also used it to draw graphs of data. The other program I used was BAD 8 or Basic Accelerator Design. This is a program running on a PC that can be used to simulate almost any linear conditions in an accelerator design. It allows you to enter a great number of types of linear optics and parameters that affect those optics. The different types of linear optics available in the program are drifts, quadrupoles, dipoles, vertical dipoles, rectangular dipoles, sectordipoles, and kicks. The different parameters available for the linear optics are the gradient, radius of curvature, lengths, and pole face angles for general dipoles.

Partitioning of Magnets

Extracting a beam from a circular machine often requires transporting the beam through the fringe field of magnets. A fringe field is an unpleasant nonlinear field in a magnet. This makes the path of the particle very different when it has to go through one of these fields compared to going through the central field. To compensate for these fields in the program I partitioned the magnet into pieces and found out where the particle went through these fields to see if we could make an approximation for them linearly instead of taking a rigorous treatment of tracking the particle through the non-linear field.

This approximation was done by first graphing the two dimensional (transverse) magnetic or B field through the magnet. Then I found where the particle passed through the magnetic field by adding the specification data to the distance the track is off the isomagnetic line. The isomagnetic line is the design centerline of the magnet. The specification data is the distance from the isomagnetic line to the ideal path the particle would take through the magnet. Then I found out where the particle passed through the magnet by adding or subtracting this number, so that the path was on the outside of the centerline of the magnet. The effective parameters depend on whether it was a vertically or horizontally focusing magnet. After this I graphed the position of the isomagnetic line and where the particle path passed through the B field at each piece. The result is show in Fig. 1. I then used this information to extrapolate data to enter into the program using the following variables and equations:

$$\kappa_n = \kappa_o (m_n/m_o) \tag{1}$$
$$\rho_n = \rho_o (B_o/B_n) \tag{2}$$

B_o= B field at isomagnetic line (Tesla)
B_n= B field at the nth piece of the magnet at actual beam trajectory (Tesla)
κ_o= the gradient at isomagnetic line (Tesla/m)
κ_n= the extrapolated gradient for the nth piece at actual beam trajectory (Tesla/m)
ρ_o= the radius of curvature at the Isomagnetic line (m)
ρ_n= the extrapolated radius of curvature for the nth piece (m)
m_o= the B field slope at the isomagnetic line
m_n= the B field slope of the nth piece at actual beam trajectory

Figure 1. This chart is an illustration of the B_field graphed vs. the distance through the magnet. On this chart is the isomagnetic line and the beam trajectory displacement at ends of the 4 pieces this magnet was partitioned into. The isomagnetic line is the vertical line to the far left. The line to the right of that is the beginning of the pieces the magnets were cut into. The far right vertical line represents the end of the last piece.

I then inserted the extrapolated data from equations (1) and (2) into the BAD 8 program. I repeated the procedure if the tracks and angles changed by a small amount, until the change was negligible.

The resulting data the BAD 8 program gave me back was wrong. The reason for this procedure being wrong is because I had available only two control parameters. These were the radius of curvature and the gradient. Both of these were corrected for the distance from the isomagnetic line. This gave the program 2 dependent B field parameters. B_x, which is the magnetic field where that piece of the path goes through the magnet. This parameter gives us x and x' or the change in x. The other parameter it gave us was κ_x or the gradient at that piece of the magnet. This tells the program what the Beta and Alpha for that piece will look like. The problem was that we needed a third B field parameter called B_o. B_o would be the magnetic field of the design orbit. The reason we needed this was so the program had a basis for the calculation of x and x'. When I changed the radius of curvature I also changed the design orbit through the magnet. The new radius of curvature I was getting was smaller then the design orbits. Therefore this made the numbers I was getting all too large for x and x'. While it is possible to take account of this change by additional calculation, the simplicity of the linear approximation is lost.

The result of this approximation led to a few changes in my program. With no way to linearly approximate the path of the particle through the synchrotron magnets I had to start my layout for the injection line at the beginning of the injection line. The path of the particle beam trajectory up until that point was calculated as follows in a program called BMAD. In this program the beam is first stepped through the magnet in small longitudinal increments. At each step, the local radius of curvature is calculated from the field profile. the angle x' is adjusted: x' = x' + ds/rho, and a step is taken: x = x + ds*x'. The twiss parameters are evolved from the fundamental differential equations for the beta function and dispersion. These equations depend on the local radius of curvature and the magnetic field gradient. Both these quantities are calculated at each step, and the beta functions and dispersion are incremented accordingly. This gave me a starting point for my injection line.

Designing the Vertical Injection Line

The design of the injection line was done in the Bad Program aforementioned. I took the present injection line and proceeded to alter it for vertical injection. There were a few alterations required to make the vertical injection line. The beam pipe had to be raised 30 mm in a certain distance depending on the vertical bend placement. It also had to be brought parallel and aligned horizontally over the CESR beam pipe. Finally it had to avoid the fixed CESR magnets.

First I figured out what was needed to change the line, what magnets from the present line could be reused, and what would have to be changed, added, or subtracted from the line. I then did a bunch of measurements to find out how much the line would have to be moved over to bring the beam pipe over top of the line for vertical injection. I then designed the final bending magnet or septum to bring the line into the right spot over the CESR beam pipe. I figured this out by choosing a length of 1.5 m for the magnet and using the idea that the septum magnet was a special magnet that could have a field of about 0.5 tesla. I then made a calculation for the radius curvature using the following formula and variables:

$$\rho = E_o / (e\, c\, B) \tag{3}$$

ρ = radius of curvature (m)
E_o= the energy of the machine (eV)
B = the magnetic field (Tesla)
c = the speed of light $2.9979*10^8$ (m/s)
e = electron (positron) charge

After that I removed a few magnets and moved a few others around. There are many reasons why I moved magnets around and removed others. The magnets were either removed or moved to make space for new magnets, to change optics, to alter the path of the particle, or because they were not needed. With the magnets in their new positions I had to figure out the changes to the radius of curvature of the some magnets. I did this with the following equations and variables:

$$\theta = l_m / \rho_{old} \tag{4}$$
$$\rho_{new} = l_m/(\theta+\phi) \tag{5}$$

ρ_{old} = the old radius of curvature for that magnet (m)
ρ_{new} = the new radius of curvature for that magnet (m)
l_m = the length of the magnet (m)
θ = the original angle change of the particle path (rad)
ϕ = the change in the angle of the particle path (rad)

After this was done I figured out the placement of the two vertical bends to raise the line 30mm. I then measured the distance between the two magnets and figured out the radius of curvature it would take to move the particle path 30 mm up in that distance by the following formulas:

$$\tan(\theta_v) = (h/d) \tag{6}$$
$$\rho_v = l_m/\theta_v \tag{7}$$

ρ_v = the radius of curvature for the vertical bends (m)
θ_v = the angle needed for the bend (rad)
d = the horizontal distance the change must take place in (m)
h = the vertical distance the path of the particle must move (m)
l_m = the length of the magnet (m)

The radius of the first vertical bend magnet would be positive to raise it vertically and the second one would be negative to level it off, so that it is parallel with the CESR ring.

Results and Conclusions

In conclusion, by the end of the summer I ended up with a preliminary vertical injection line illustrated in Fig. 2. I also found out that there is no easy way to do linear approximations for fringe fields in magnets.

Acknowledgements

I would like to acknowledge David Rice, of Cornell University, for proposing this Research Experience for Undergraduates project, guiding my efforts, and having patience with me. I would also like to thank Stuart Henderson for his help with tracking the particle path through the fringe fields, helping in the location of my problem with the tracking procedure, and in the procurement of the magnet specifications. Finally I would like to thank Prof. Giovanni Bonvicini, of Wayne State University, for his efforts in preparing me for this program. This work was supported be National Science Foundation REU grant PHY-9820306, PHY-9731882, and research grant PHY-9809799.

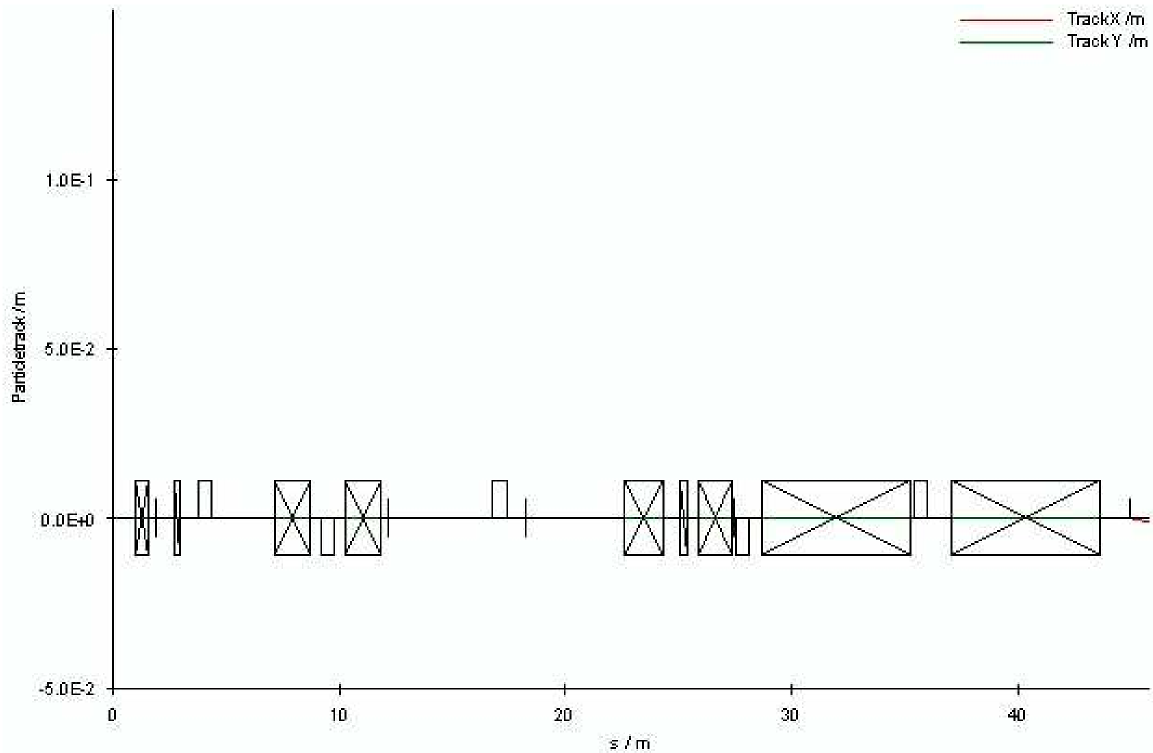

Figure 2. This figure is a representation from the BAD program of the final layout that I came up with for the Vertical Injection Line . It starts right as the injection line leaves the synchrotron and ends with a few of the bending magnets in the CESR ring.

References

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