Characterization and Optimization of CESR-c Lattice Design

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The CESR-c lattice creates a pretzel orbit to keep positron and electron particle beams separated at the parasitic crossing points. A major parameter in the separation of the beams at the parasitic crossing points is the long range beam-beam interaction. In this project simulation software was used to analyze the effects of these interactions on the injected electron beam clearance of the stored positron beam at the parasitic crossing points for all bunches in the beam pipe. The analyses were performed for three different lattice designs including the current 1.9 GeV CESR-c lattice, the 2001 5.3 GeV lattice, and the 2006 1.9 GeV lattice.

I. INTRODUCTION

The Cornell Electron Storage Ring, CESR, was built in 1979. Since then it has been altered many times. In recent years the storage ring has been changed in order to study charm quarks as well as bottom quarks. The high energy lattice used previously was run at 5.3 GeV with a positron beam current of 6 mA/bunch. It was used to study the heavier bottom quark. This lattice was used for standard operations in June of 2001, just before the use of superconducting magnets in the interaction region began. During it’s run the 5.3 GeV lattice produced the highest luminosity ever attained at CESR.

In 2004 the storage ring was changed to incorporate 12 new wiggler magnets and to run at a lower energy and beam current. This lattice is currently in use. It is run at an energy of 1.9 GeV, a current 2 mA/bunch, and is used in the study of the lighter charm quark. Although the use of wiggler magnets has increased the efficiency of electron injection other problems remain, the most serious problem being a lack of luminosity produced. The solenoid magnet used by CLEO in the research of particle physics is blamed for the low luminosity because it causes a defocusing effect on the beam.

In order to correct this problem and increase luminosity a new lattice design will be implemented in January 2006. The 2006 lattice include anti-solenoid magnets which should compensate for the distortions caused by the solenoidal CLEO detector magnet. Currently, skew quadrupoles are used to correct distortions, but it is suspected that at lower energy these magnets cannot be as effective. The incorporation of the new anti-solenoid magnets may have unforeseen effects on other aspect of the stored beam. Part of this project was to begin analysis of the 2006 lattice design and look for potential changes and disruptions in the beam optics.

Since the use of CESR and the varying lattice designs began so has the analysis of its beams optics. These analyses have been made using software written primarily in FORTRAN with the use of the locally developed BMAD libraries. Throughout the analyses particular focus has been on increasing the luminosity of the particle beam collisions. Several different parameters were altered and tested to determine how to increase beam lifetime.
and, therefore, time-integrated luminosity. Often neglected are the problems caused by long range beam-beam interactions at the parasitic crossing points. Many physicists see these problems as being unavoidable and therefore having no solution. This project began a deeper analysis of the beam interactions at parasitic crossing points with the intention of further understanding of their characteristics and effects on particle beam behaviors. Through a better understanding physicists at CESR may be able to attain the long term goal of finding a solution to the distortions caused at the parasitic crossing points.

II. INJECTION OF MULTIPLE PARTICLE BEAMS

The injection of particle beams into CESR follows a very specific sequence. The particle beams are injected as trains with each train containing 5 bunches of particles. A bunch is the segment of the beam, about 1 cm long, which contains particles. Initially the positron beam is injected using kicker and septa magnets. The kicker magnet removes the beam from the synchroton and the septa magnets guide the beam into the Transfer Line. The beam then encounters a pulsed septum magnet which forces it into the storage ring. The beam is injected in bunches and the total process includes several injections of new particle bunches into bunches already stored and orbiting the ring. This use of bunch by bunch injection is what allows physicists at CESR to control the current in the ring, determined by the amount of positron particles orbiting the ring. In order to combine the injected bunch with the stored bunch a bumper magnet is used. The bumper magnet uses a wave pulsed orbit bump to bring the stored beam closer to the beam being injected on the injection turn. The injected beam then oscillates around the stored beam until, within 10 kilo-turns, it has damped to the stored beam orbit. [?]

The second part of injection, the injection of the electron beam, is far more complicated than the first. This is due to the existence of the stored positron beam in the storage ring. The stored positron beam causes problems because it limits space available for electron beam injection and because it creates a current inside the ring. Two methods are used to decrease the severity of these problems. First, a pretzel orbit is established for the positron beam with four symmetrically placed electrostatic separators. The injection of the electron beam then follows the same sequence of magnet types and movements as the positron beam with the exception that upon entering the storage ring the electron beam enters into a pretzel orbit. The second change made for injecting electron beams is the use of a one-turn kicker magnet. This magnet is referred to as the pinger magnet and it provides a kick to the combination stored and injected electron beam in order to reduce injected beam oscillations. The pretzel orbit of the electron beam and the one turn kick are shown Figure ?? . The top plot shows the trajectory of the pretzel orbit followed by the electron beam, produced by separators continuously throughout the storage of the beam in the ring. The bottom plot shows only the displacement caused by the one-turn kick from the bumper magnets which is applied only once per injected bunch on the injection turn. [?]

The process of multiple beam injection requires analysis and optimization of the lattice design. In particular the long range beam-beam interactions can cause negative effects on the separation and general optics of the beams. This is due, in most part, to the current created by both beams as they orbit the ring. It is ideal to have more particles in the ring because that means more collisions at the interaction point and therefore a high luminosity. The more particle in the ring, however, correspond directly to the current of the long range beam-beam interactions. Higher interaction current disrupts the beam more and effects the
optics and clearances of the injected beams. It is these current values that were simulated to show the effects of long range beam-beam interactions at the injected electron beam parasitic crossing points.

III. IMPORTANT BEAM PROPERTIES

Several properties of the beam are critical to the understanding and explanation of the resultant data. The property of luminosity is of great importance. Luminosity is a measure of the concentration of particles colliding at the interaction point. It is optimized when the beams are highly focused. The lifetime of a beam is determined in most part by the rate at which particles are lost from the beam during a run. Loss of particles can be due to collisions with the beam pipe wall as well as with the other particle beam. The long range beam-beam interactions at parasitic crossing points become important here because if the interaction produces small beam clearance at crossing points beams could physically interact and particles will be lost from the beam. Loss of particles shortens lifetime and decreases time-integrated luminosity. The long range beam-beam interactions are proportional to bunch current. The current measured is that created by the stored positron beam which is directly correlated to the number of particles in the beam. This is a property that has been previously optimized at CESR to incorporate as many particles as possible, indicated by high current, while keeping negative effects due to high current and space limitations in check. Optimization has produced the values of 2mA/bunch for the current lattice and 6mA/bunch for the high energy lattice.

There are two other key properties of the beam which vary with the different lattice
energies. The Energy effects the beam-beam interactions because, although the they are
the same for a particular positron bunch current at different energies, at lower energies
the relative momentum kick due to the positron current is larger. For this reason higher
energy positron bunches are less likely to lose particles than at lower energy. The bunch
configuration of the beam in a high energy lattice is altered not only in number of particles
per bunch but total bunches injected. This change is made consciously at CESR. At higher
ergies 9 trains of 5 bunches are injected, referred to as 9x5 injection, and stored in the ring.
At the current lower energy only 8 trains are stored even though the lattice was designed
for a 9x5 bunch injection. The reason for these differences is an effect called ion trapping.
All these properties were incorporated into the analysis of the 5.3 GeV lattice performed in
this project.[?] 

IV. ION TRAPPING

A problem encountered throughout the study of particle physics at CESR has been the
interaction of the electron particle beam with free ions within the storage ring, referred to
as ion trapping. As the electron beam orbits the ring, collisions with other particles may
occur and create ions. Once these positive ions are created they accelerate away from the
beam with a positive net charge. The passing of electron bunches, however, creates a pulsing
attractive force which bring the ions back toward the center of the beam pipe. This is of
particular concern when atoms of high atomic number are involved because the mass to
charge ratio will cause a stronger effect on the electron particle beam. The positive ions
cause a deflection of the particles which enlarges the cross sectional size, the envelope, of
the beam. In high energy lattice designs ion trapping is less of a problem. In the current
lattice the problem is being resolved by injecting 8 trains instead of 9, which the lattice was
designed for. This allows more room between the first and last train in order to that the
ions will have room to accelerate towards the center of the beam pipe and pass completely
though it before the next bunch arrives at that point. The variance train number in the
storage ring for lower energy lattice designs will be considered in this paper.

V. PROCEDURE

Several Programs have been written to characterize and optimize the current and past
lattice designs at CESR. The program used primarily throughout the course of this study
was envelope which was developed by S.Henderson and J. Crittenden. Envelope is written
in FORTRAN 90 and uses BMAD modules created at Cornell University. The purpose
envelope is to show the optics and physical behaviors of an electron bunch which contribute
to its overall envelope. The envelope of a beam is defined as the physical space occupied by
the beam's centroid over many turns.[?] The calculations made by envelope are specific to
the second bunch injected into the ring after a stored electron bunch already exists. Several
parameters are included in the program and can be altered to observe different effects on
the beam. In this case the electron train and bunch number as well as the current from long
range beam-beam interactions (lrbbi) were the key parameters being adjusted. The use of
different train and bunch numbers allowed the observation of the parasitic crossing points for
bunches besides the first bunch of the first train, while the alteration of the current allowed
for observation of the effect of beam-beam interactions on the parasitic crossing points for all
bunches. *Envelope* includes calculations which alter the beta functions and pretzel orbit as a function of the long range beam-beam current strength determined by the positron beam current. The program assumes the Weak-Strong Approximation in its calculations, which means it assumes that the electron beam is effected by the positron beam while the positron beam is unaffected by the electron beam. From these calculations and the known pretzel orbit the clearance of the beam pipe wall and the other particle beam was then determined. [? ] The program was run several times using combinations of lrbbi current and bunch numbers for three lattice designs. During the program run time data was stored in ntuple files.

In order to view the ntuple files created with *envelope* a second program was used. The second program was also written in FORTRAN 90 and run in Physics Analysis Workstation (PAW). When the program ran it created graphs of the data previously stored as ntuples. Several plots were created from the data calculated by *envelope*, but of particular interest were the plots which showed the movement of the injected electron beam around the stored positron beam. The plots use the zero line to represent the stored positron beam position and plot the trajectory of the injected electron beam with respect to the stored beam as well as the ratio of the distance from the positron beam to the electron beam size, referred to as sigma. The distance between the two beams is called the clearance. Each parasitic crossing point is indicated by a red dot on the plots. These plots were used to determine how the lrbbi parameter effects the clearance of the positron beam by the electron beam at the parasitic crossing points. The plots were also looked over for bunches which showed parasitic crossing points where the beams were or could be physically interacting. This was done for each of the three lattice files and the data was used to observe the differing effects on lattices of different energy and different bunch configuration.

**VI. ANALYSIS**

A. Analysis of Current Lattice Design

The plot of the stored positron bunch clearance by the injected electron bunch was used to analyze all bunches of all trains that pass through the storage ring. The data from this plot had been previously analyzed for train 1, bunch 1, shown in figure ?? . The plots on the left show the injected beam clearance with the lrbbi turned on and the two on the right show the injected beam movement with the lrbbi turned off. From these plots it looks a though, and until recently has been assumed, that the lrbbi parameter does not make a different in the clearance of the parasitic crossing points. Upon running the remaining bunches through *envelope* it became apparent that the beam-beam interaction current can cause large differences in clearance and sigma values. Figure ?? shows the plots produced for bunch 2 of train 3 with the lrbbi current set to on and off. As is clear from the plots the lrbbi setting can have a large effect on the injected beam. Plots created for the other bunches also indicated a strong effect of lrbbi on the clearance of the electron beam. From this data it is apparent that train 1, bunch 1 cannot be used as a reliable indication of the behavior of the electron particle beam as a whole. It was also shown that on a bunch by bunch basis the lrbbi may have extensive and detrimental effects on the clearance of the beam, possibly resulting in physical beam-beam interactions at the parasitic crossing points.

B. Comparing High and Low Energy Lattice Designs
The next analysis performed was on the high energy lattice used in June 2006. For this lattice when envelope was run with the lrbbi turned on it was set to 6 mA/bunch. The plots produced showed much smaller clearance values as well as sigma values. There was also a larger difference in the effect of the long range beam-beam interaction parameter setting on these values than in the current lattice plots seen by a greater increase in clearance and sigma values when the setting was turned off. Figure ?? shows the plots for train 1, bunch 1 for the lrbbi turned on and then off. From the figure it is observed that with the lrbbi on several parasitic crossing points are below two sigma. When the lrbbi was turned off the number of parasitic crossing points below two sigma decreased significantly. The remaining bunches were all run through envelope. The resulting plots showed a consistently lower clearance and greater effect of the lrbbi parameter at high energy. From this data along with the known high luminosity produced by the 5.3 GeV lattice the conclusions can be made that the higher momentum allows for smaller clearance at the parasitic crossing points with less negative effect felt by either beam. Also, it is the high energy that allows the use of all nine trains with smaller effects due to ion trapping.

C. Analyzing the Lattice Design to be Implemented in January 2001

The final part of the project was to analyze the effect of long range beam-beam interactions on the parasitic crossing point for the injected electron beam. As with the current lattice, only the first bunch had previously been used to optimize the lattice design. The
remaining bunches were run through *envelope* and the plots created through PAW were analyzed. The plots for train one bunch one differ from the plots for the current lattice in that they show a noticeable increase in clearance when the long range beam-beam interactions are turned off. This can be seen in the plots in Figure ?? . When the remaining bunches were analyzed they showed a combination of bunches with small clearance with high long range beam-beam interaction dependence and larger clearance with low long range beam-beam interaction dependence. An example of the latter can be seen in Figure ?? , which shows the plots created bunch two of train three. From the overall analysis of bunches no new concerns were raised as to the effects of the long range beam-beam interactions on the future lattice. It was also concluded that the first bunch better represented the overall beam behavior with respect to beam beam interactions for this lattice design than for the current lattice design.

VII. CONCLUSION

The results of this project indicate that the long range beam-beam interactions at the parasitic crossing points have a substantial effect on the particle beams. The effect is particularly important during the injection of the electron beam in the presence of the stored positron beam. Running analysis on all injected bunches also showed that using the first bunch of the first train is not sufficient for creation and optimization of a lattice design. In the future more than just one bunch should be used to observe the effect of different lattice designs on the entire particle beam. Further more, it was noted that the lattice to
be implemented in January 2006 shows no major difference in the overall effect of the lrbbi parameter for the injected electron beam from the current lattice. These observations reinforce the expectation that no new problems due to long range beam-beam interactions at the parasitic crossing points should arise with the use of the new lattice design.

From the analysis of the 5.3 GeV lattice design it can also be noted that at a higher energy the beam clearance at the parasitic crossing points is reduced at the operating current. From the understanding of beam rigidity along with the previous knowledge of the higher luminosity values, however, it can be determined that at higher energies the beams can sustain lower clearances without losing particles. This data may be advantageous in the creation of future lattices.

VIII. ACKNOWLEDGEMENTS

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FIG. 5: Plots showing the clearance and sigma values at the parasitic crossing points of the January 2006 lattice for train 1, bunch 1. The left two plots show the values with the lrbbi current set to 2mA/bunch and the two plots on the left show the lrbbi current set to 0mA/bunch.

IX. REFERENCES

FIG. 6: Plots showing the clearance and sigma values at the parasitic crossing points and of the January 2006 lattice for train 3, bunch 2. The left two plots show the values with the lrbbi current set to 2mA/bunch and the two plots on the left show the lrbbi current set to 0mA/bunch.