Optimization of Storage Ring Optics

Elisa Pueschel
Physics Department, Binghamton University, Binghamton, NY, 13850
(Dated: August 14, 2003)

A goal of accelerator machine research is to determine operating parameters that yield high luminosity, small beam size, and long beam lifetime. In this project, computer simulations were used to determine promising machine tunes for Cornell's electron storage ring. Aspects of the beambeam interaction were studied via simulation, and applied towards this goal.

I. INTRODUCTION

The movement of the electron and positron beams used in CESR is controlled by a magnetic guide field. A series of dipole magnets bend the beams through a circular orbit. In the uniform field of the dipole magnets, particles displaced from the beam center will remain displaced, and will be lost if they receive a sufficiently large vertical or horizontal kick. In order to increase the density of the beam and the beam lifetime, quadrupole magnets are used to focus the beam. The field of a quadrupole increases linearly as distance from the center of the magnet increases. Particles displaced from the ideal trajectory therefore receive a kick towards the beam center. Due to the structure of the quadrupole, a magnet that focuses the beam horizontally will defocus vertically, and vice versa. To compensate for this effect, the quadrupole magnets are arranged around the storage ring at right angles to each other, alternately focusing and defocusing the beam horizontally and vertically. This causes the vertical and horizonal beam size to oscillate about the ideal trajectory. The number of oscillations the beam completes in one revolution around the storage ring is defined as the betatron tune. Independent values exist for the vertical and horizontal tunes.

Betatron tunes become important when resonance issues are considered. The beam orbits the ring with a set frequency, thus any imperfection in the guide field will apply a force to the beam at the revolution frequency. In other words, the system is driven at its natural frequency. If the beam is in the same phase of its betatron oscillation each time it receives this kick, a resonant condition is achieved and the amplitude of oscillation increases with each turn. Eventually, the oscillations become too large for the guide field to control. Beam size increases and particles are lost. In order to combat this effect, operating tunes must be chosen such that the beam is in a different phase of oscillation each time it passes a given point in the ring. Higher order resonances occur if the beam comes back to the same phase in its oscillation after two or three turns around the accelerator.

Determination of optimal tunes is complicated by interactions between the electron and positron beams. Both long range parasitic interactions and beambeam interactions at the collision point affect tune.

Long range parasitic interaction refers to the interaction of beams at points other than the collision point. Left in an undisturbed orbit, the beams would collide at over eighty points in the accelerator, due to the fact that there are multiple trains within each beam, and multiple bunches within each train. Multiple collisions would destroy the beam, so the orbits of the beams must be altered to prevent collisions at the parasitic collision points. This results in a complicated orbit path known as a pretzel. Although the beams do not collide at the parasitic collision points, they pass in close enough proximity at these points that each beam is affected by the other's electric field.

Attraction between the oppositely charged beams affects the focusing of the beams, and therefore the tunes. Thus, a single beam in the accelerator may be tuned to avoid problems with resonances, but interactions with the second beam may cause a change in tune sufficient to produce resonance. The phenomenon of tune shifting is further examined in a later section.

II. SIMULATION TOOLS

Using the accelerator to determine the optimal betratron tunes experimentally is impractical in light of the number of possible combinations of vertical and horizontal tunes. Computer simulations are an effective way of examining beam size, lifetime and luminosity for different betatron tunes, as well probing the factors affecting interaction between the beams.

A number of simulation tools were used. All programs assumed a constant distribution of positrons, Gaussian in the x, y, and z directions. The positron distribution, or strong beam, had a fixed trajectory and a fixed beam current, usually of 1.0 mA/bunch. A Gaussian distribution of 100-200 electons was randomly generated. The movemment of each electon through the accelerator ring and through interaction with the strong beam was tracked. The final particle distribution and luminosity was recorded for the surviving beam. All programs used a lattice file that gave in explicit detail the properties of the accelerator ring, including long range parasitic interactions, beambeam interactions, beam crossing angles, field non-linearities, sextupole fields, wiggler fields, and synchrotron radiation.

III. RESULTS

The first sequence of simulations studied the tune shifts caused by long range parasitic and beambeam interactions as a function of the strong beam current. The simulation was started with a set initial tunes. The tune was calculated after the addition of long range parasitic interactions, and again after the addition of beambeam interaction at the collision point. The strong beam current was varied from 0.1 to 1.0 mA/bunch, in increments of 0.1. Increasing the strong beam current increased the magnitude of the Coloumb force felt by the weak beam and changed the magnitude of the weak beam's tune shift.

Figure 1 plots current versus change in tune. The horizontal tune shift caused by the parasitic interactions decreased with increasing current, whereas the vertical tune shift increased. Additionally, both the horizontal and vertical tunes increased with increasing current after adding the effect of beambeam interactions.

These results corresponded to theoretical predictions about the effect of long range parasitic and beambeam interactions on the tune. **Figure** 2 shows the Coloumb force on the weak beam during long range interaction with the strong beam. Increasing the horizontal distance from the strong beam decreases the force that the weak beam experiences in the x direction. Decreasing horizontal displacement increases the force experienced. Particles close to the strong beam will be drawn away from the center of the bunch, while particles far from the strong beam will only be weakly attracted, smearing the beam out. This is an example of a defocusing field. Decreasing focus is equivalent to removing a focusing

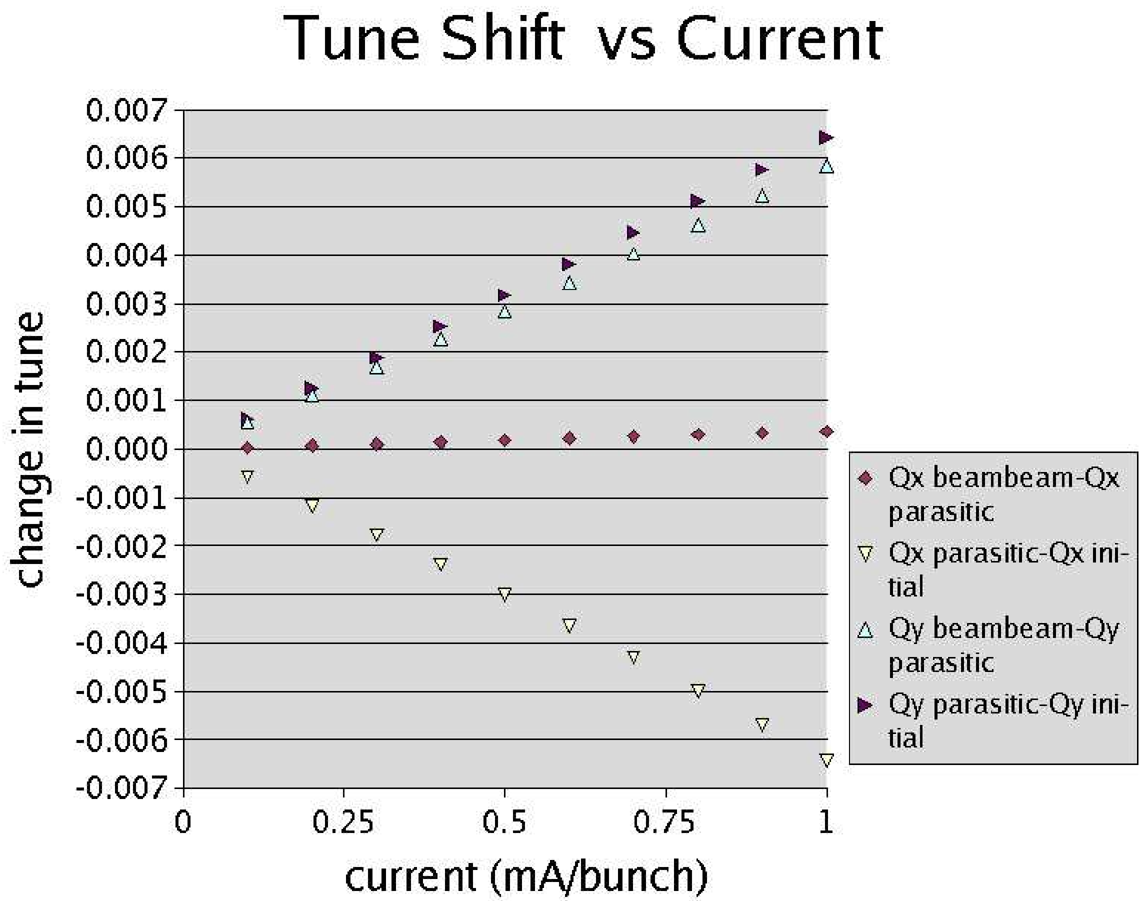

FIG. 1: The change in tune with the addition of parasitic and beambeam interaction is plotted as a function of current.

element such as a quadrupole. With fewer focusing elements, the beam goes through fewer oscillations and the tune decreases.

When the weak beam is on the same horizontal plane as the strong beam, it experiences no electric force in the y direction. Changing the vertical displacement introduces a vertical component to the Coloumb force that moves the beam towards its initial position, where force is zero. Refer again to **Figure** 2. Thus, long range parasitic interactions are vertically focusing and tend to increase tune.

Figure 3 models the forces on the weak beam as it passes through the strong beam during beambeam interaction at the collision point. When the weak beam passes directly through the center of the strong beam, the charges surrounding the weak beam are balanced, and the beam experiences neither a vertical nor a horizontal force. If the beam is moved away from center, the amounts of charge on either side of it will no longer cancel out, and the beam will be attracted to the side with the larger net charge, towards the origin. Hence, the beambeam interactions focus the weak beam and increase its tune.

Next, the nature of beambeam interaction at the collision point was studied. Simulations tracked the spatial coordinates of the electron beam through a series of skew quadrupoles and collision with the positron beam. Initial coordinates were varied and compared the resultant final spatial coordinates. The center of the positron beam was taken as the origin

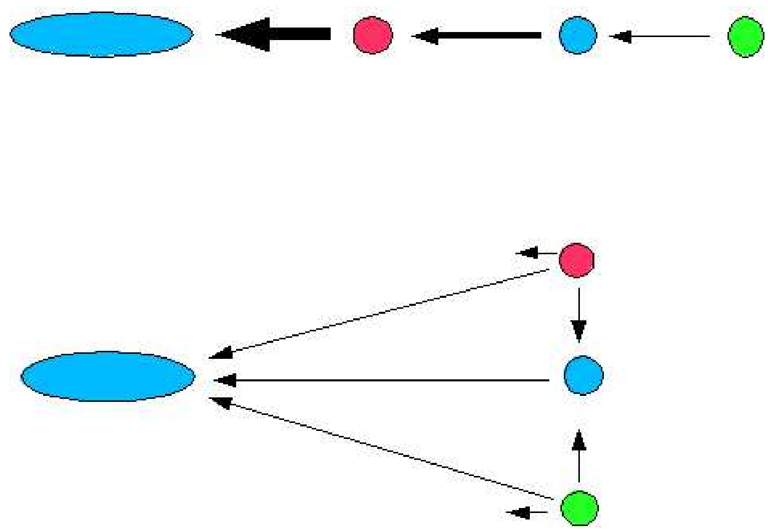

FIG. 2: The broad oval represents the strong beam, the circle represents the weak beam. A head-on view of the beams is shown. In the top scenario, the horizontal force on the weak beam increases with increasing distance. In the bottom scenario, changing the weak beam's vertical position introduces a component to the force experienced by the beam, which focuses in the direction opposite its displacement.

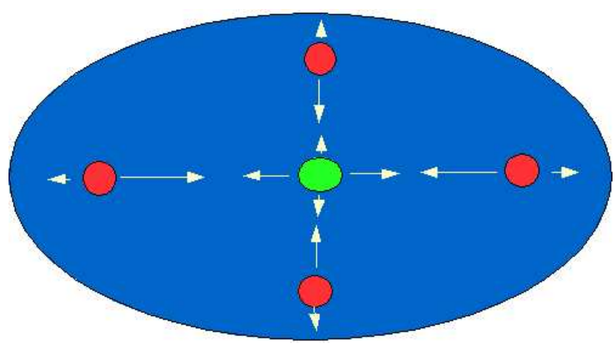

FIG. 3: A head-on view of the weak beam in collision with the strong beam is given. The weak beam experiences no force when it passes directly through the strong beam's center, but experiences a focusing force when it is displaced from center.

of the six-dimensional coordinate system, which was composed of x, x', y, y', z, and z'. Refer to Figure 4 for standard results. Incoming spatial coordinates were all set at zero.

The simulations show that x'_{out}, the horizontal kick, is dependent on x_{in}, and y'_{out}, the vertical kick, is dependent on y_{in}. A beam entering the skew quads and collision point with a positive x displacement received a negative horizontal kick, whereas a beam entering with a negative x displacement received a positive horizontal kick. The same behavior was observed for y and y'.

This behavior can be explained in terms of electical interaction between the electron beam and the positron beam. For example, if the electron beam starts with a negative vertical displacement, it passes below the positron beam. Its attraction to the oppositely changed positron beam will result in an upward kick. Passing above the positron beam results in an attractive downward kick.

In addition to the dependence of x'_{out} on x_{in} and y'_{out} on y_{in}, coupling occurs between x and y. Although varying x_{in} has neglible effect on y out, varying x_{in} has an appreciable effect on y'_{out}, as seen in **Figure** 4. The cause of this coupling was determined by turning off various functions in the simulation until the effect was no longer seen.

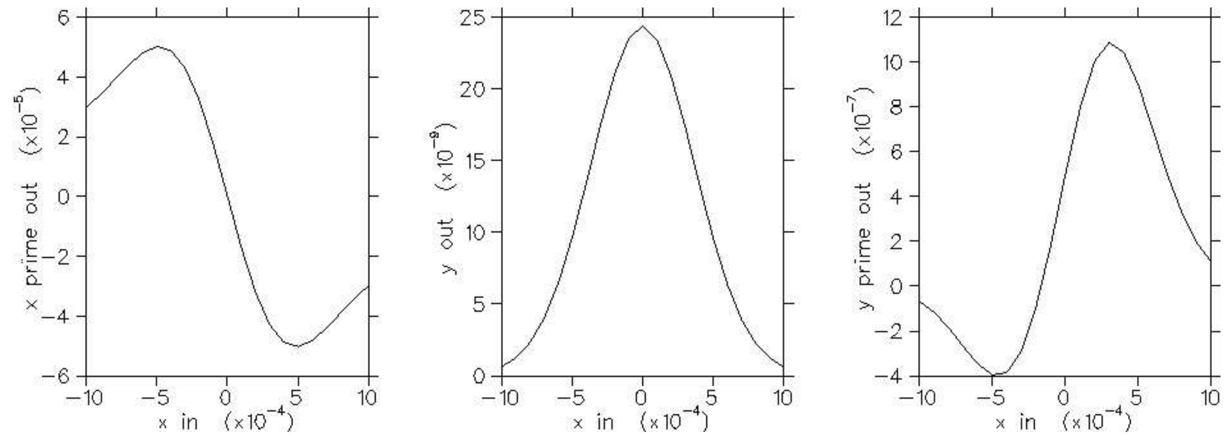

FIG. 4: Outgoing spatial coordinates are plotted as a function of ingoing coordinates. Left plot shows x'_{out} versus x_{in}, middle plot shows y out versus x_{in}, right plot shows y'_{out} versus x_{in}.

The asymmetry in the plot of y' versus x shown in Figure 4 can be removed by setting a different vertical displacement. Refer to **Figure** 5 for plots of simulations done with different displacements. It is possible to change the displacement such that the vertical kick is entirely negative or entirely positive. In this case, the weak beam must have stopped colliding head-on with the weak beam, and instead passed entirely above or below it. A vertical displacement was found that made the plot symmetric about the origin, indicating a head-on collision.

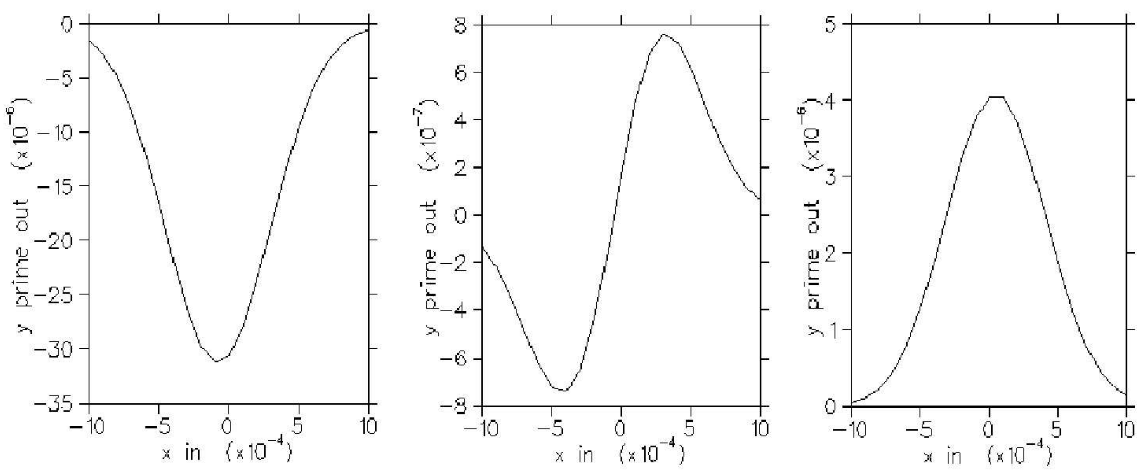

FIG. 5: All plots show y'_{out} versus x_{in}. Coupling between y' and x is sensitive to vertical displacement. The plot can be made symmetric by altering the vertical displacement.

Although the asymmetry of the graphs can be attributed to the beams not colliding head-on, this does not explain the coupling between x and y'. The coupling was traced back to the changes in beam orientation introduced by the skew quadrupole magnets. The skew quadrupoles are placed near the interaction point in order to compensate for the effects of the solenoid surrounding that area. The purpose of the solenoid is to produce a uniform magnetic field near the collision point. The curved trajectories of charged particles produced in a collision are used to determine the momentum of the particles and thereby identify them. The solenoid has the negative effect of tilting the beam along its axis such that it no longer collides perfectly head-on with the other beam. The skew quadrupoles are set to alter the magnetic field such that the beams, although tilted in the interaction region, collide head-on at the interaction point.

Even though the tilt of the beam at the interaction point is compensated, the beam has some finite length. Collisions of particles in the head and tail of the are displaced from the IP, where the compensation of the tilt of the strong beam is incomplete. The tilt causes part of the electron beam to extend above the positron beam and part to extend below. Hence, there is a vertical force proportional to horizontal displacement. When the centers of the beams collide head-on, half of the electon beam is above the positron beam and half is below, resulting in the same characteristic curve seen earlier in plots of x'_{out} versus x_{in}.

Simulations were run verifying that the tilts cause coupling between x_{in} and y'_{out}. Turning the tilts off in the simulation decreased the magnitude of the effect. Increasing the value of the tilts by a factor of ten increased the magnitude of the vertical kick by a factor of ten. Setting a negative tilt caused the plot of x'_{out} versus x_{in} to flip. This occurred because the part of the beam that was previously below the positron beam was rotated until it extended above the beam.

The last set of simulations, tune scans, were used to identify favorable pairs of horizontal and vertical tunes. A grid of horizontal and vertical tunes, running from Qx=0.505-0.57 and Qy=0.58-0.64, was created. The synchrotron tune was fixed. For each pair of coordinates on the grid, a weak beam with the given tunes was tracked through 10000 turns in the accelerator. The weak beam's final luminosity and beam size were recorded, as was the number of surviving particles. Luminosity, particle loss and beam size were plotted as functions of tune. See **Figure** 6 for a tune scan example. Resonance lines are easily identified by the large beam size and low luminosity. Points with high luminosity, small beam size and low particles losses were given further study.

A program that outputs the final weak beam particle distribution was used to examine high luminosity operating points. A number of favorable operating points were identified, for example Qx,Qy = (0.551, 0.612) and Qx,Qy = (0.566,0.639). Final beam distributions for these tunes as well as the distribution for a low luminosity point on a resonance line (Qx,Qy = 0.553,0.648), are shown in **Figure** 7. In the initial distribution $\sigma_y \sim 0.076\mu m$. Clearly, the beam distribution for a set of high luminosity tunes is narrower than that of a set of tunes that correspond to a resonance line. This serves to reinforce the data collected on particle loss and final beam size.

In the past, CESR has operated near Qx = 0.536 and Qy = 0.59. Based on the generated tune scans, it is recommended that tunes within the region Qx = 0.552-0.566 and Qy = 0.605-0.645 be tested. This appears to be a region of high luminosity and low beam size for many sets of tunes.

Further tune scans were run in order to study the dependence of luminosity on other parameters. A scan with strong beam current of 0.5mA/bunch, rather than the nominal

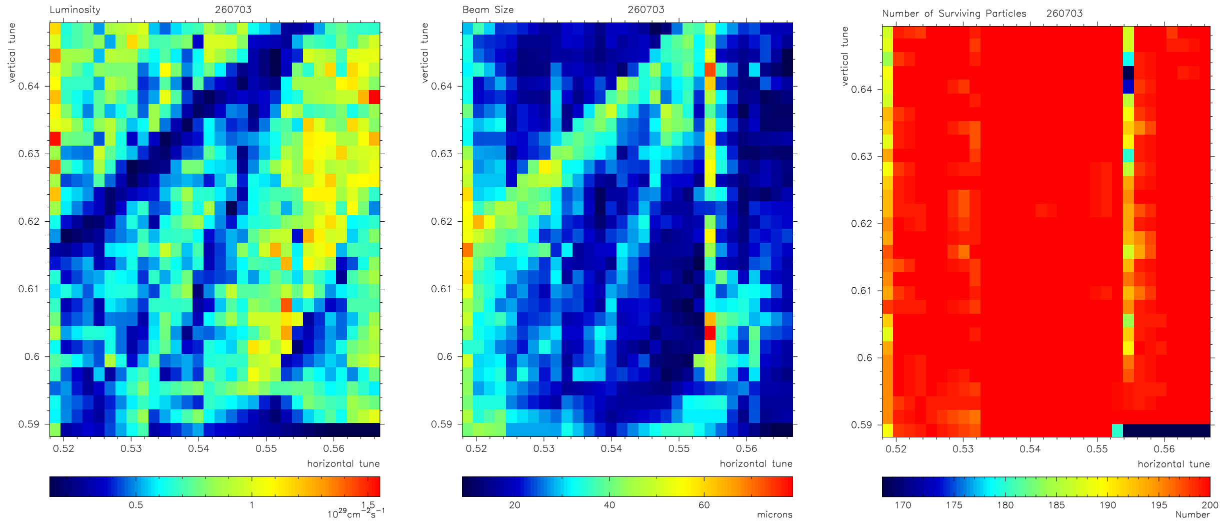

FIG. 6: Tune scan shows final weak beam luminosity, beam size, and particle loss. Tunes from Qx = 0.552-0.566 and Qy = 0.605-0.645 appear to be favorable, based on the high luminosity in this region.

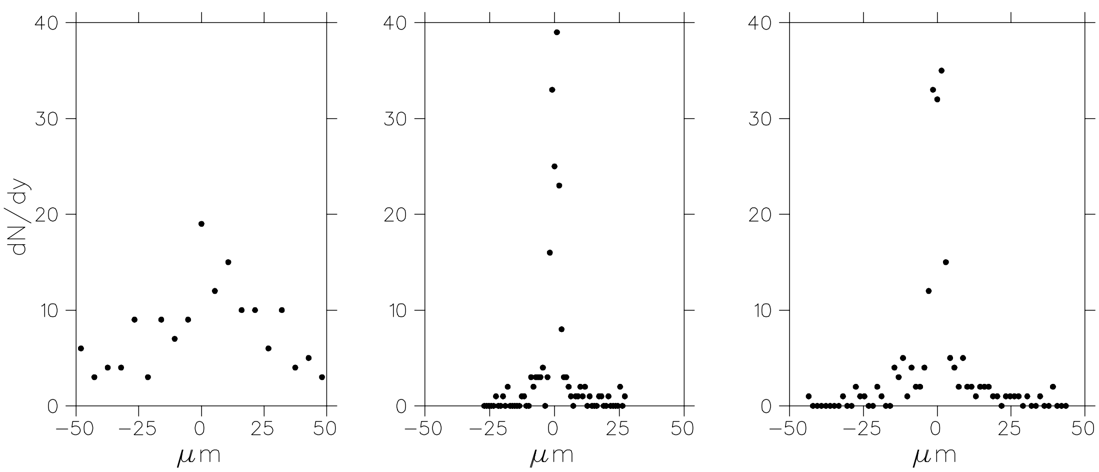

FIG. 7: Final vertical weak beam distribution. Left plot corresponds to tunes on a resonance line Qx,Qy = (0.553,0.648) where the luminosity is poor. The middle and right distributions are for the relatively high luminosity points, Qx,Qy = (0.551,0.612), and Qx,Qy = (0.566,0.639).

1mA/bunch, indicates that the increase in beam size is dominated by the beam beam interaction rather than nonlinearities of the guide field. We also began to explore the dependence of the luminosity on the location of the weak beam bunch within the train. Because the bunches are localized in trains, their spacing is not uniform and each bunch within the train experiences a different set of parasitic interactions with the opposing beam. We find that luminosity does depend on bunch number and further study of this effect is in progress.

IV. CONCLUSIONS

Betratron tunes that correspond to high beam luminosities were identified using simulation tools. Final beam size and particle loss were studied for high luminosity tunes by examining final beam distributions. Tunes within the region Qx = 0.552-0.566 and Qy = 0.605-0.645 were revealed to be favorable operating points. Additionally, the tunes shifts due to long range parasitic interaction and beambeam interaction were studied, and the mechanics of the beambeam interaction at the collision point were characterized.

V. ACKNOWLEDGEMENTS

I would like to thank David Rubin of Cornell University for his careful guidance in this project, and Richard Galik for facilitating the REU program. This work was supported by the National Science Foundation REU grant PHY-0243687 and research cooperative agreement PHY-9809799.