Measurement and Analysis of Injected Beam Loss in the Advanced Photon Source Storage Ring Using the Beam Loss Position Monitor and Simulation with Elegant

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1 Abstract

Measurement and Analysis of Injected Beam Loss in the Advanced Photon Source Storage Ring Using the Beam Loss Position Monitor and Simulation with Elegant. MATT BUCHOVECKY (Carnegie Mellon University, Pittsburgh, PA 15234) JEFF DOOLING (Argonne National Laboratory, Argonne, IL 60439).

The electron beams in the Advanced Photon Source (APS) are precisely aligned, and unavoidable imprecisions in the apparatus can cause electrons to be lost. Beam loss decreases the efficiency of the APS, and can also damage some components in the lattice, particularly undulator magnets. Our project focused on the injection process, which is the second most intense loss mechanism. We were able to utilize experimental data from the Beam Loss Position Monitor (BLPM) in Sector 33. By comparing the signal levels in the different channels, we could infer the position where more particles were being lost. We also simulated the injection process using the program elegant. Elegant allowed us to track electron beams through our model of the APS storage ring (SR) and provided information about the lost particles. We were able to conclude that the majority of particles were lost on the inside of the apparatus, while only a small portion were lost on the outside. This was observed in both simulation and experimental data. The elegant simulations also showed that the most beam loss occurred in Sectors 3 and 4, which contained the smallest apertures. Loss occurred in other sectors, including Sector 33, though it was much less intense. We were also able to determine that loss occurs in regions with high betatron functions.

Research Category: Beam Diagnostics

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2 Introduction

The Advanced Photon Source uses high-energy electrons to create high-energy x-rays. The electrons are first generated in an electron source, then are sent through various elements to accelerate them to higher energies. The final stage of acceleration occurs in the synchrotron booster, where the electrons reach their target energy of 7GeV. Once the electron beam has reached its final energy, it must be transported to the storage ring (SR) so it can produce high-energy photons. Prior to injection, the booster to storage (BTS) transport line transfers the beam to within close proximity of the SR, and places it in a parallel trajectory to the stored beam [1]. During injection, four kicker magnets, placed symmetrically about the injection point in the storage ring, are turned on. While the stored beam feels the kick from all four magnets, the injected beam will only feel the second two kicks. The strengths of these kicks are designed such that the stored beam will remain in the storage ring and the injected beam is bumped from its offset position into the storage ring. Though there are many types of injection, the most common type is called off-axis injection. In an off-axis injection, the injected beam will not be bumped directly onto the axis and stay there, but will oscillate about the axis of the storage ring. This must be done because the kicks will not allow for both beams to go directly on the axis. Typically, the oscillations are shared by both the stored and injected beam in what is called a mismatched injection, which lowers the injection loss. Though these oscillations do damp away very quickly, beam loss occurs before they damp completely.[1]

The injection process is not perfect and typically yields about 80 efficiency. This means that electrons are being lost during the injection process. Loss can occur when an electron is not within the acceptance of a beam, or it is not within the physical aperture of the lattice it is travelling through. "Injection efficiency is related to injection trajectory, injected beam emittance and matching" [2]. There are many places that electrons could be lost.

It is possible there is loss occurring in the BTS line before it reaches the SR. They could also be lost during the injection kicks themselves, but could also be lost at any point in the ring from disturbances caused by the injection kick.

Lost particles decrease the running efficiency of the APS, increasing running costs and requiring additional resources. In addition, stray electrons can cause physical problems for the apparatus. For example, they can cause damage to insertion device (ID) elements used to generate x-ray photons such as the undulator magnets. [2] They can also damage stepper motors and other electronics gear. Damaged components must be repaired, potentially causing down time for the beam and added expense. The lost particles can also cause problems by activating beamline components. In order to minimize the loss that occurs, we must understand how and where the particles are being lost. Though there are other means of particle loss, namely Touschek scattering and beam dumps, our project focused only on injection.

We employed both simulations and measurements to investigate the loss patterns of particles during injection. We made our measurements using a Beam Loss Position Monitor (BLPM) that was located in Sector 33 [3]. Because we could only get limited information from the BLPM, we simulated the the injection process using the program elegant. This allowed us to see the interactions in more detail, and also gave us the ability to change parameters of the beam and lattice and observe the effects. To strengthen our conclusions, we compared the simulation results with experimental data to see if they were consistent.

3 Methods and Materials

We began our investigation of injection loss by using the observational data available to us from the BLPM. The BLPM's layout is shown in Figure 1. It contains four bundles of fused silica fiber optic cables, three of which are placed above the beam and one below the beam in the center. The fiber-optic cables run parallel to the beam. They are resistant to low-energy radiation, and detect only fast electrons. When a fast electron is lost, it can enter into the aperture of the fiber-optic cable, which can activate both Cherenkov radiation (CR) and optical transition radiation (OTR). [3] These light signals propagate through the cable to a photomultiplier tube (PMT). The PMT converts photons into electrons which are then amplified in the tube up to an observable level. The PMT output current flows through a resistor generating a voltage read on an oscilloscope. The digitized waveform is then archived for subsequent post-processing analysis.

Before the signal levels can be compared directly, we needed to calibrate the PMTs for each channel, because PMTs do not all have the same level of sensitivity. To calibrate them, we directed amber LED light into the apertures of each bundle. We could then look at the different levels of PMT output signals that resulted from nearly constant input LED signals. The ratios of the peak input signals to the peak output signals for each channel gave us the relative calibration of the channels so we could compare them directly. By comparing the calibrated signals in the channels during injection, we could infer the average position of loss. More specifically, the x position could be found by comparing the signal levels in the top inside and top outside channels, and the y position could be found by comparing the top center and bottom center signal levels.

Among the other information available to us was the injection efficiency. The injection efficiency was the ratio of the change in current or charge in the beam to the amount of current or charge that was attempted to be injected. We wished to compare the efficiency to the total loss signal to look for a correlation. The total loss signal was found by using a script to integrate the area under the curve of the waveform. To avoid counting noise, a proper baseline had to be found that would exclude the noise without cutting out much of the real signal. We compared this total signal to the injection efficiency for multiple injections and looked for a correlation.

To run our simulations, we used the C-based program elegant, which stands for electron generation and tracking [4]. Elegant could track user-defined particle beams through customizable lattices. The simulation produced useful information that could be viewed and analyzed, such as lost particle coordinates and betatron functions. We began with a lattice that accurately modeled the APS storage ring provided by M. Borland. Starting from this point, we could make small adjustments to accurately simulate the injection process for both the stored and injected beam. We were able to optimize the kicker strengths so as to achieve matched and mismatched off-axis injection. Because it is the primary injection type, we mainly modeled the mismatched injection. Though it gave the minimal loss, it created disturbances in both beams, allowing us to analyze loss in the stored beam as well as the injected beam.

There were subtle differences between modeling the stored and the injected beams. The stored beam began at a normal, on-axis point and was tracked through Sectors 39 and 40, where the four kickers are located. After that, it was tracked for multiple passes through the SR with the kickers turned off. The injected beam, on the other hand, was tracked from the injection point, directly after Sector 39, with a -24 mm offset. It is then tracked through the second two kickers, which simulates the kick the injected beam experiences when being bumped from the BTS line into the SR. Again, the kickers are turned off for all subsequent passes. Particle-particle interactions were not very significant and were omitted for the purpose of running the simulations in reasonable times. The stored beam and injected beams were run separately and their results viewed independently. Elegant also allowed us to vary beam parameters. The parameters were mostly set to be as accurate as possible, using the real momentum present in the SR, and modeling the particles as electrons. The number of particles had to be kept low so as to keep the time required to run simulations reasonable. It was necessary to increase the emittance of the beam so we could effectively model the tails of the beam.

After running these simulations, we were able to look at various useful outputs from elegant. We were able to see the transverse coordinates of the lost particles, as well as in which sectors the losses occurred. In addition, we could see the betatron function at points of loss, and compare the number of particles that were lost during each pass through the SR.

4 Results

Using the calibration ratios, we were able to infer the average position of the loss. The calibration ratios we found and used can be seen in Table 1. The average x-coordinate of the loss was given by:

$$X = \frac{V(3) - V(1)}{V(3) + V(1)} \tag{1}$$

The average y-coordinate was given by:

$$X = \frac{V(2) - V(4)}{V(2) + V(4)} \tag{2}$$

where V represents the signals of each respective channel. Though the coordinates are unitless, as we can only observe the relative magnitudes of the loss signal, we still got useful information from them. A negative x-coordinate told us that particles were being lost on the inside, while a positive x-coordinate told us the particles were being lost on the outside. Similarly, a negative y-coordinate told us the particles were being lost mostly on the bottom, while a positive y-coordinate told us that loss was occurring on the top. Coordinates were found for multiple injections and plotted together. These results can be seen in Figure 2. All of the coordinates had negative x-values, indicating a much stronger loss on the inside. There was also a tendency of higher signal on the top, however this was not as strong.

Before integrating the total signals for the waveforms, we had to find an appropriate baseline. We found this by plotting the total integrated signal against the baseline value. At the point where the baseline falls below the noise level, there will be a sharp increase in the total signal. We determined from the plot in Figure 3 that a baseline of 0.2 V included most of the real signal without including any significant amount of noise. We used this baseline to integrate the total signal detected by the BLPM, and compared those totals to injection loss ($= (1 - \eta_{inj})$) where η_{inj} is injection efficiency. Figure 4 shows one such plot of data taken during a hybrid bunch mode. We added a trendline to it, which had a positive slope and a correlation coefficient of approximately 0.9. We also noticed that the points appeared to be in two distinct regions, which indicated the possibility of two different kinds of injection. Injection loss results of a 24 bunch fill pattern did not show as strong of a correlation.

For our simulation runs, we used the kicker strengths we found from optimization. These kicker strengths (as specified in elegant) can be seen in Table 2. The final results were obtained by modeling mismatched off-axis injection. In order to get significant amounts of loss, the simulations of both the stored and injected beams were run at emittance values of 100 nm to 300 nm. This is significantly higher than 65 nm, the approximate actual emittance of the injected beam, and much higher than 2nm, the approximate emittance of the actual stored beam. We also found that for the same emittance values, there was a higher percentage loss in the injected beam than in the stored beam. Despite this difference in percentage loss, we found that the stored and injected beams shared the same loss position and location characteristics; therefore, we did not distinguish between beams in our results.

Figure 5 is an example plot that shows the longitudinal position at which the particles were lost. A high resolution was achieved by using a very large number of particles in the simulation. The grid lines divide the plot into the sectors of the APS, so it is easy to see which sectors had the most loss. From the plot, we were able to see that the majority of losses were occurring in Sectors 3 and 4, which contain the smallest apertures in SR. There was also considerable loss occurring in Sectors 13, 18, 19, 20, 33, and 34, as well as small amounts of loss in other sectors. Figure 6 shows an example plot of the transverse coordinates of lost particles. These coordinates are cumulative across the entire ring, meaning the coordinates are not specific to loss at any longitudinal position. With high resolution, the shape of the apertures is apparent. The majority of the particles lie along the shape of the smaller aperture, which is located in Sectors 3 and 4. Other loss particle patterns show the shape of the larger aperture located in other sectors. Though there were a few particles lost on the outside, the majority of particles tended to be lost on the inside. However, there seemed to be no real preference between the top and bottom.

We also wished to investigate the relationship between the betatron function and loss. Figure 7 shows a partial plot of the betatron values as a function of longitudinal position. The red dots represent areas where loss occurs, with a higher position representing more lost particles. We found that loss always occurred in the regions with high betatron functions. Though the entire plot is too large to view at once, this held true for all regions.

Finally we looked at how the loss evolved over time. Figure 8 shows the number of particles remaining after each pass. We saw that loss occurred very quickly in the passes soon after injection, and then the number of circulating particles leveled off, approaching an asymptotic value.

5 Conclusions

From the results of our experiment, we were able to gain much information about where particles were being lost. Our experimental data showed a large preference for particles to be lost on the inside of the apparatus as opposed to the outside. This was strongly confirmed by the results of our simulation, which showed a strong tendency for particles to be lost on the inside. However, the tendency for particles to be lost on the top according to BLPM data was not supported by our simulations. This tendency, though, was not as strong, and was possibly due to an error in calibration. We also found that the majority of loss was occurring in Sectors 3 and 4. This made sense, as these sectors had the smallest apertures of the SR. There was loss in other sectors, though not as much as in Sectors 3 and 4. Among the sectors with small amounts of loss was sector 33, where the BLPM is located. It is possible that the reason the linear correlation between signal and efficiency was not always strong was because the losses causing inefficiency occurred mainly in other sectors. We also determined that loss occurred where betatron functions were high. Additionally, we found that the stored beam required a much greater factor by which the emittance had to be increased to lose a similar amount of particles as compared to the injected beam. The stored beam required its emittance be increased by approximately a factor of 100 before significant loss occurred, while the injected beam required an increase of about a factor of 2. This indicated to us that a much higher percentage of the injected beam is being lost during injection, though some stored beam could be lost as well.

In the future, it might be useful to place BLPMs in the sectors where more loss is occurring to get better data. In addition, through more empirical data and simulations, we hope to provide an absolute calibration that would indicate the actual number of lost electrons. The simulations could also be improved. Elegant has a halo function that allows is to simulate the tails of particle beams. This could potentially remove the need to increase the emittance to unrealistic values. More simulations could be run, and a better comparison between the stored and injected beams could be made.

References

[1] L. Emery, “Description of Injection in the APS Storage Ring,” APS internal report.

[2] M. Borland and L. Emery, “Touschek Lifetime and Undulator Damage in the Advanced Photon Source,” Proc. PAC 2005, 3835 (2005).

[3] J. Dooling, et al, “Development of a Fiber-Optic Beam Loss Position Monitor for the Advanced Photon Source Storage Ring,” to be published, Proc. PAC 2009.

[4] M. Borland, “User’s Manual for Elegant”, Advanced Photon Source, Program Version 21.0, February 27, 2009.

Table 1: Calibration Ratios

Channel	Ratio	Error
1	0.71	.13
2	1.03	.04
3	1.32	.02
4	1.62	.05

Table 2: Optimized Kicker Strengths

Kicker	Strength (angle)
IK1	0.0009844
IK2	-0.0007542
IK3	-0.0007779
IK4	0.0012207

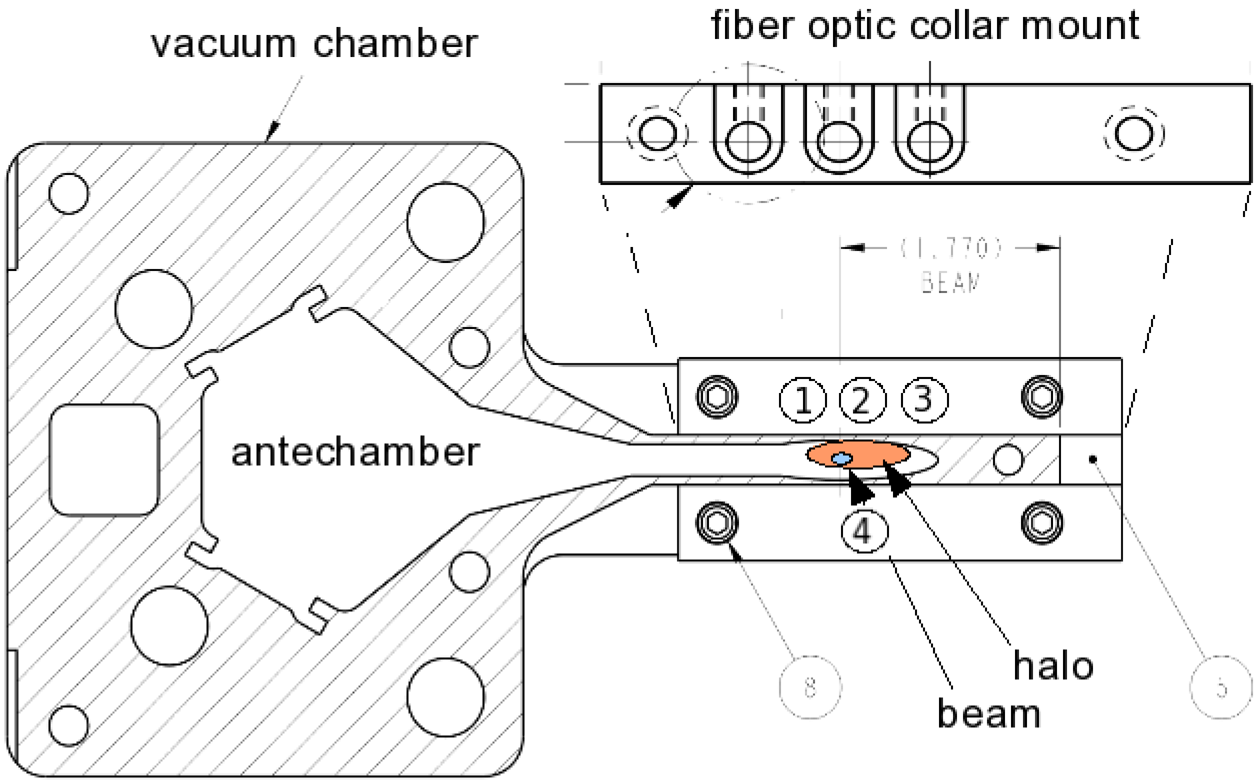

Figure 1: Diagram of Beam Loss Position Monitor

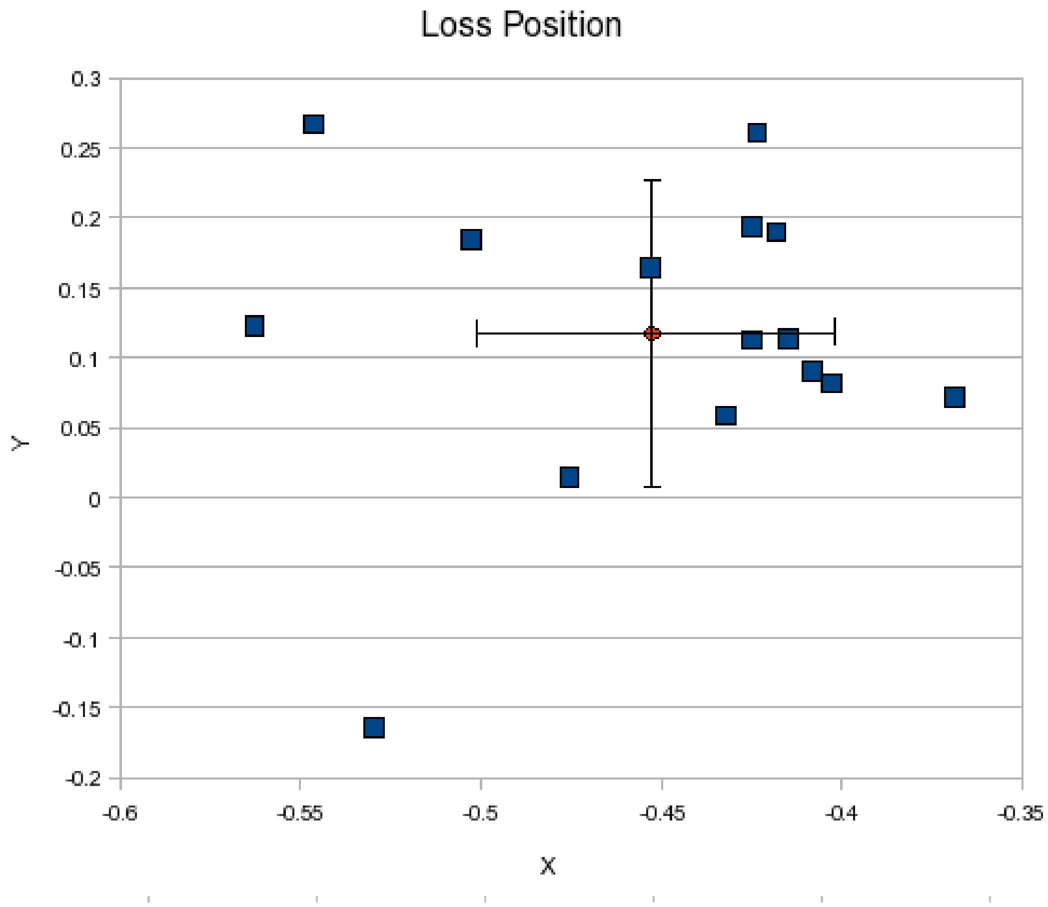

Figure 2: Lost Particle Coordinates from BLPM Data

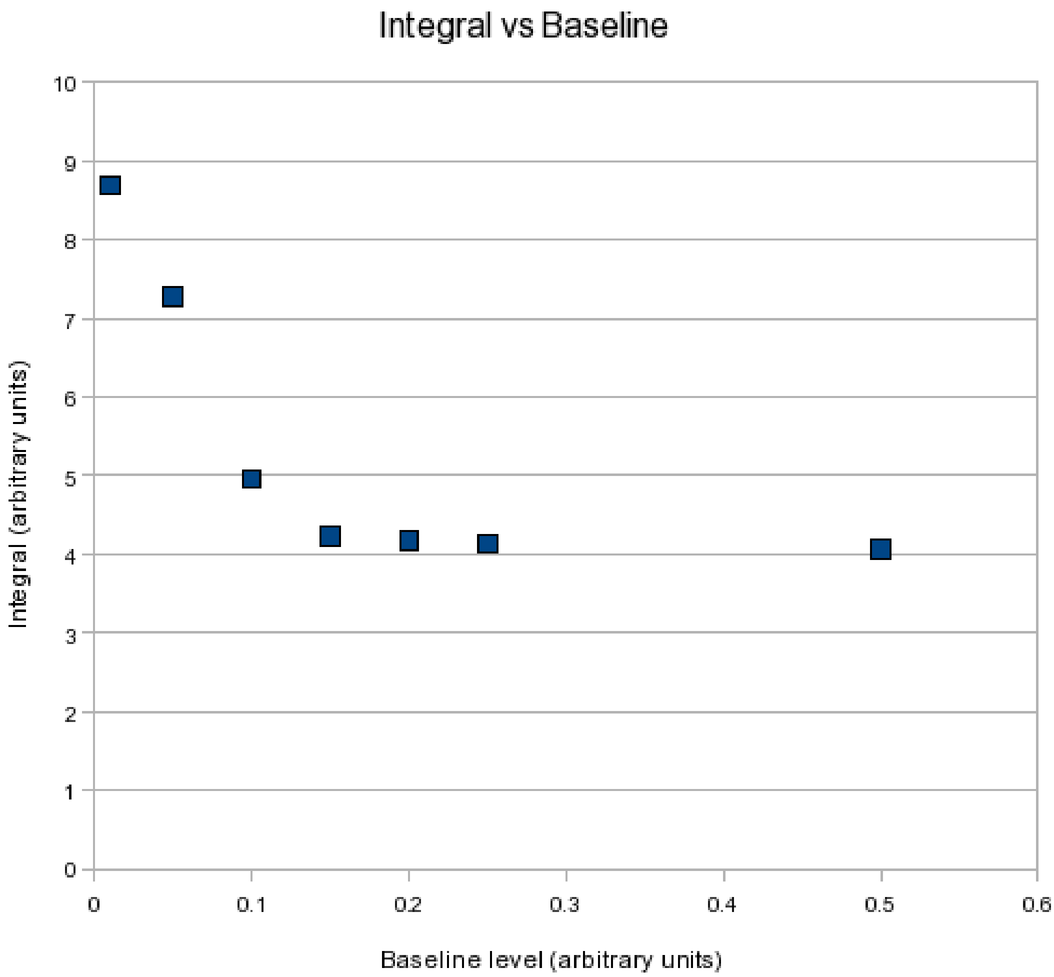

Figure 3: Determination of Noise Floor

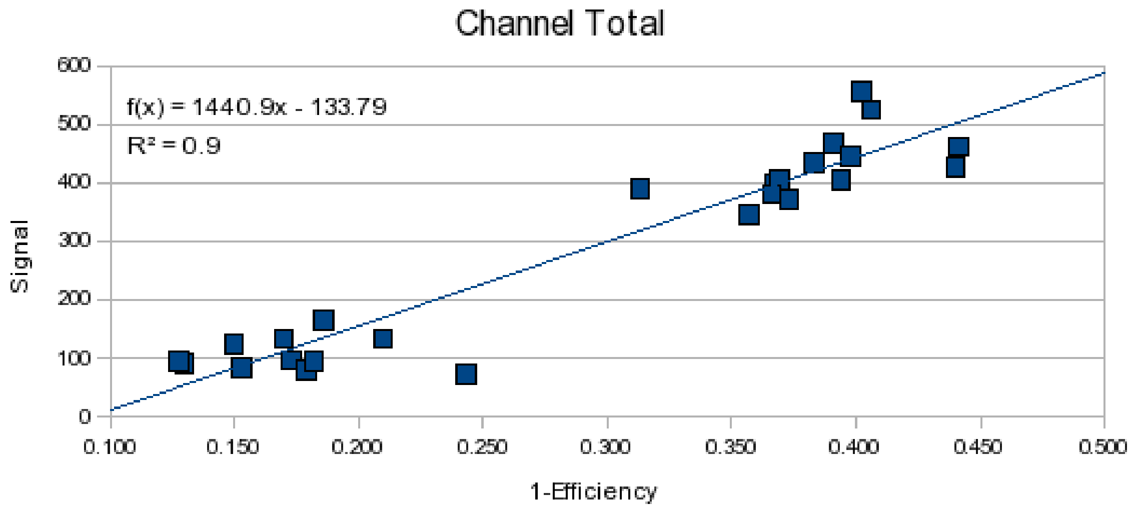

Figure 4: Signal vs (1-efficiency)

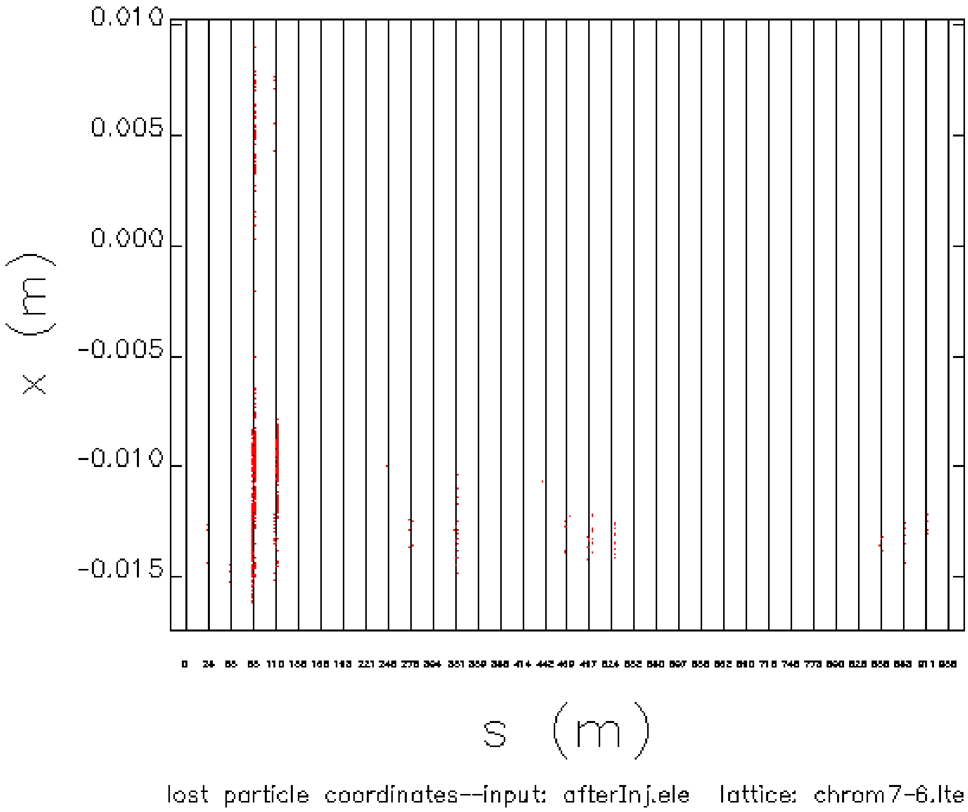

Figure 5: Longitudinal Position of Loss

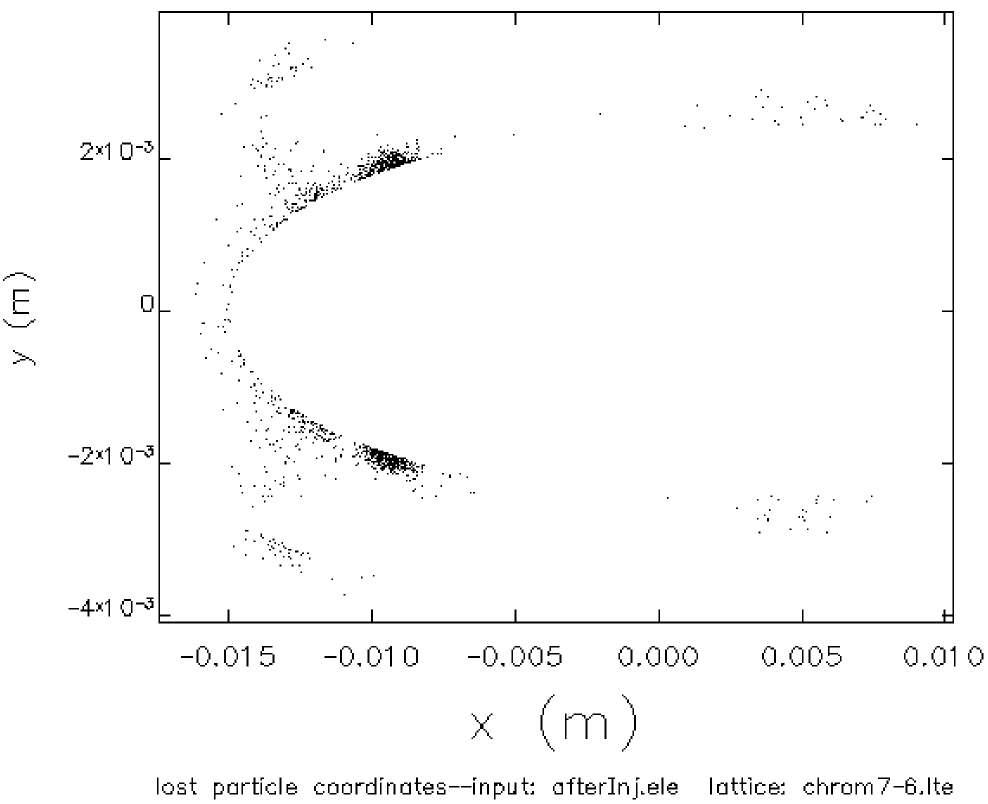

Figure 6: Transverse Coordinates of Lost Particles

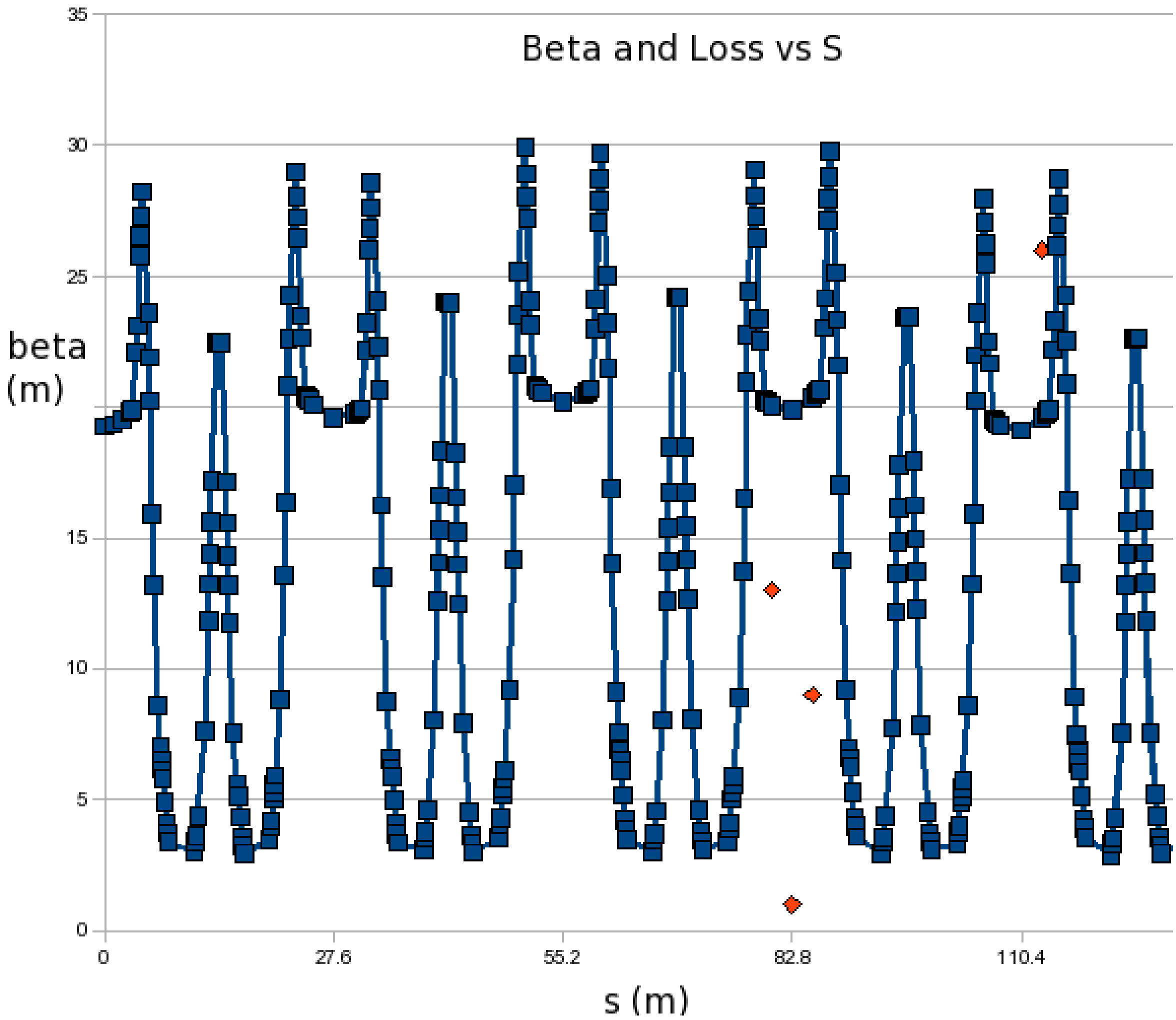

Figure 7: Betatron Function

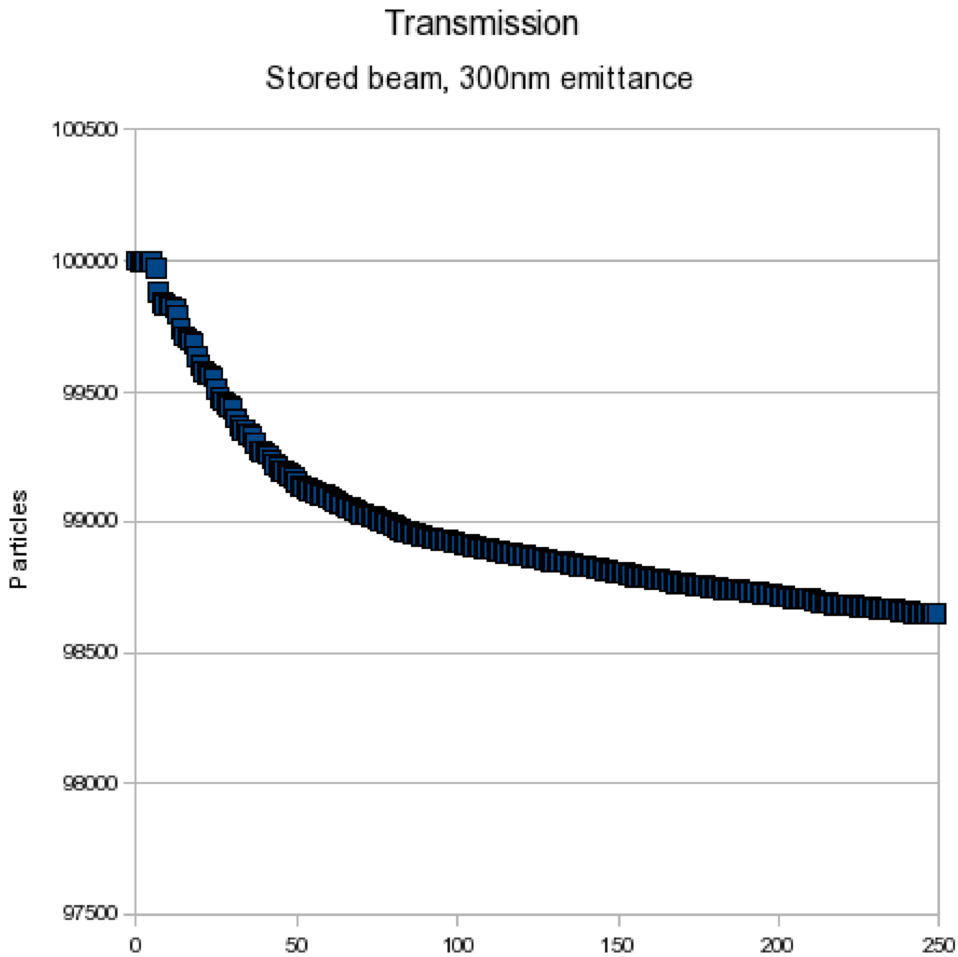

Figure 8: Number of Particles Present After Each Pass