SLAC-PUB-9222
May 2002

MEASUREMENT OF TRANSVERSE BUNCH SIZE BLOW-UP DUE TO THE ELECTRON CLOUD INSTABILITY AT PEP-II

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Invited talk presented at the International Workshop on Two-Stream Instabilities in Particle Accelerator and Storage Rings, 9/11/2001—9/14/2001, Tsukuba, Japan

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Work supported by Department of Energy contract DE–AC03–76SF00515.

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Abstract

The electron cloud instability at PEP-II is responsible for enlargement of the transverse bunch size for positron bunches at high current. Presented in this paper are the measurements of transverse beam blow-up taken by a two nanosecond-gated camera. The measurements point out that a current-ramp, mini-gaps between trains, and arc solenoid windings help reduce the positron bunch size blow-up due to the electron cloud instability.

1 INTRODUCTION

The PEP-II B-Factory has two rings, a low energy ring (LER) for positrons, and a high-energy ring (HER) for electrons. Presently the peak current in the LER is 1.65A and when collided with 0.95A of electrons, a peak luminosity of 4.3×10^{33} cm^{-2} sec^{-1} is achieved. Some of the PEP-II parameters are listed in table 1.

This luminosity achievement has been hampered by the growth in the positron (LER) bunch size due to the electron cloud instability. Steps have been taken to reduce the bunch size blow up by: 1) installing solenoid windings around the vacuum chamber in the arc and straight sections of the LER storage ring. 2) Optimizing machine parameters such as bunch spacing, ramping the positron current after the ion-clearing gap, and inserting mini-gaps in the bunch pattern. These steps have reduced the effect of the electron cloud instability and are presented in the paper.

Table 1: Present parameters of the PEP-II storage rings

Parameter	LER	HER
Circumference [m]	2199.322	
RF Frequency [MHz]	476.00	
Harmonic Number	3492	
Max. Colliding Bunches	1658	
Crossing Angle [mrad]	<0.1	
Colliding Current [mA]	1650	950
Energy [GeV]	3.119	8.973
β^*_x, β^*_y [cm]	50,1.25	50,1.25
$\varepsilon^*_x, \varepsilon^*_y$ [Nm]	49,1.5	49,1.5
σ_x, σ_y [μm]	157,4.7	157,4.7
σ_z [μm]	12.3	11.5

2 PAST OBSERVATIONS OF THE ELECTRON CLOUD INSTABILITY

The first evidence of the electron cloud instability in the LER of PEP-II were made in the spring of 2000. While filling the LER the ion vacuum pumps in the straight sections behaved in a rather peculiar manner. It was noticed at low current, below the electron cloud threshold, the ion pump current grew slowly. As the total bunch current passed the electron cloud threshold (at approximately 800mA), the pump current, which is proportional to the vacuum pressure, would grow rapidly (see figure 1). It was also noted that when the bunches were aborted the pump current decays quickly to zero.

This rapid rise of vacuum pressure has been attributed to a multipactor process. Synchrotron radiation hitting walls of vacuum chamber pipe in the straight sections releases electrons. These electrons are drawn toward the positron bunches and subsequently hit the beam pipe and cascade to make an electron cloud. The straight sections, where the pump currents rise were measured, were subsequently outfitted with solenoid windings that help suppress this cascade of electrons (figure 1). An applied solenoid field above 25 gauss greatly reduced the generation of these unwanted electrons.

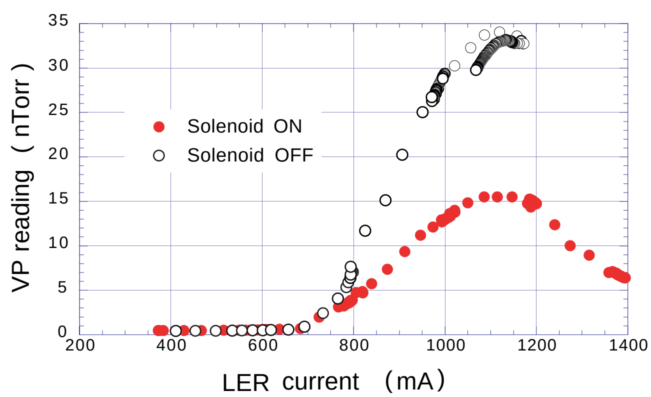


Figure 1 (color). A correlation between the LER total bunch current and a straight section vacuum pump with and without the solenoid windings turned on [1].

Logically, a denser electron cloud should be observed in the arcs of the LER due to the increased presence of synchrotron radiation. To combat that possibility the arcs aluminum vacuum chambers were coated with titanium

*Work supported by Department of Energy contract DE–AC03–76SF00515

nitride (TiN), which lowers the secondary emission coefficient due to synchrotron radiation.

Unlike the straight sections vacuum chamber, the design of the arc vacuum chamber is such that a secondary electron cannot be detected in its vacuum pumps. The arc chambers have an antechamber that keeps the secondary electrons out of the main chamber and the vacuum pumps are attached to the antechamber. The lack of evidence of the electron cloud in the arc regions does not mean that electron cloud is not present; subsequently the arc chambers have also been wound with solenoids.

Another signature of the electron cloud instability is the growth in the positrons transverse bunch size as a function of current. The average bunch size was measured using a synchrotron light monitor (figure 2). The vertical and horizontal bunch size grows rapidly above the electron cloud threshold of approximately one ampere. The synchrotron light monitor is useful for measuring the average bunch size but for single bunch measurements, a faster camera that can resolve a single bunch, such as a gated camera, is needed.

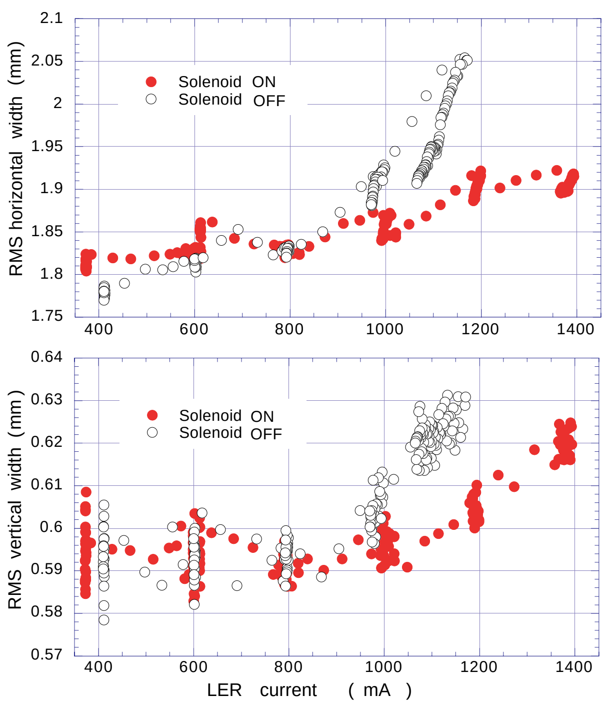


Figure 2 (color). The positron transverse bunch size as a function of current measured with a synchrotron light monitor with the straight section solenoid windings turned on and off [1].

3 LOW ENERGY RING OPERATIONAL PROCEDURES

Optimizing the PEP-II luminosity in the presence of the electron cloud instability is challenging and has resulted in varying certain machine parameters to maximize the luminosity for a given current[2]. The LER has 1660 available RF buckets, one every 4.2ns, for collisions and an ion-clearing gap of 86 RF buckets. The bunch spacing in PEP-II is varied to reduce the electron cloud and optimize luminosity. When the bunch spacing is 4.2ns, meaning every colliding bunch is filled, it is referred to as the "by 2 pattern". Presently this bunch pattern has a single bunch current which is too low to reach our peak luminosity, and as a result the by 2 pattern has not been explored. Table 2 lists different fill patterns, along with their limitations.

Pattern	Bunch Spacing	# of bunches	Limitations
2 pattern	4.2ns	1660	Have not yet explored
3 pattern	6.3ns	1106	HOM heating
4 pattern	8.4ns	830	No limitation
5 pattern	10.5ns	664	Beam-beam limited
6 pattern	12.6ns	553	Beam-beam limited

Table 2. Possible bunch fill patterns for the PEP-II storage rings.

Along with changing the bucket spacing, the current for each bunch and gaps in the bunch pattern (called mini-gaps) have been used to optimize the luminosity. The bunch pattern, current ramp, and use of mini-gaps are partially responsible for the PEP-II luminosity achievement. Here is a more detailed description of these operational parameters:

1) Current ramp. The electron cloud dissipates due to the ion-clearing gap; therefore, the trains just after the ion gap do not interact with a high-density electron cloud and their transverse dimensions are not blown-up. As a result, the first few LER trains have better focused bunches which force the HER bunches to lose current. By reducing the LER current for the first few trains with a current ramp the HER bunches are not lost. Typically, the current ramp is linear starting at 70% to 100% of the average bunch current over the first 35 bunches after the ion gap.

2) Mini-Gaps. The electron cloud has a fast rise and decay time which makes it advantageous to have small gaps, called mini-gaps, to help partially clear the electron cloud. The length of the train (the number of bunches in succession) and mini-gaps are varied to optimize the luminosity.

3) Bunch pattern. To maximize the luminosity for each fill pattern the number of bunches should be minimized and the current per bunch maximized until the beam-beam limit is reduced. When the current is raised the bunch pattern is changed to avoid the luminosity limitation by the beam-beam effect.

Presently, with a LER current of 1.65A the by 4 pattern is used with 21 bunches per train with a mini-gap of 3 buckets for a total of 728 bunches, for a current per bunch of 2.27mA. A schematic of the fill pattern that includes the current ramp and mini gaps in the LER ring is shown in figure 3.

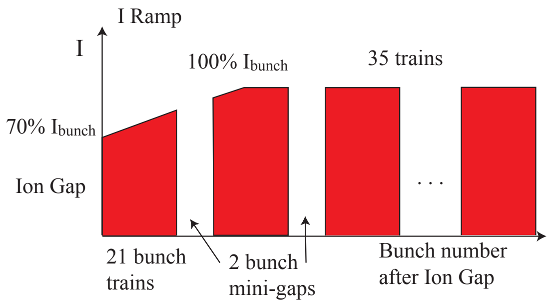


Figure 3 (color). The LER fill pattern under present conditions. Each train consists of 21 bunches with a 3 bunch mini-gap. The first bunch in the train has 70% of the average current and subsequently bunches are increased in current linearly to 100% of the average current by bunch 35.

3 DETAILED MEASUREMENTS OF BUNCH TRAINS WITH A GATED CAMERA

3.1 Gated Camera Images

Past transverse bunch size measurements were made with synchrotron light monitors, that are useful for determining the averaged bunch size but they cannot resolve the individual bunch size. To characterize the details of individual bunch size blow up due to the electron cloud a gated camera, with a two-nanosecond gate, is used[3]. The gated camera images synchrotron radiation from a dipole magnet in the LER. The synchrotron radiation is transported to a radiation safe area where the measurement can be performed. A sample image of a LER bunch is shown in figure 4. The camera's trigger is synchronized with the revolution frequency of the ring and can be delayed to measure any bunch in the ring.

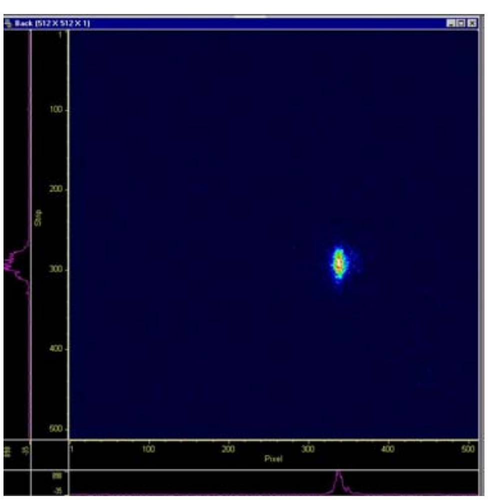


Figure 4 (color). A transverse image of an individual LER bunch provided by the gated camera. The bunch image shown here is rotated by 90 degrees (the vertical plane shown is the bunches horizontal plane).

The transverse bunch size is determined from the image (figure 4) by summing up the horizontal and vertical pixels, to form the transverse profiles. The profiles are fit to a Gaussian function and the sigma from the fit quantifies the bunch size. Figure 5 is a representative distribution fit to a Gaussian function.

Presently the camera is not calibrated so the absolute bunch size has little meaning. The results presented in this paper are normalized to allow easy recognition of the relative changes in the bunch size.

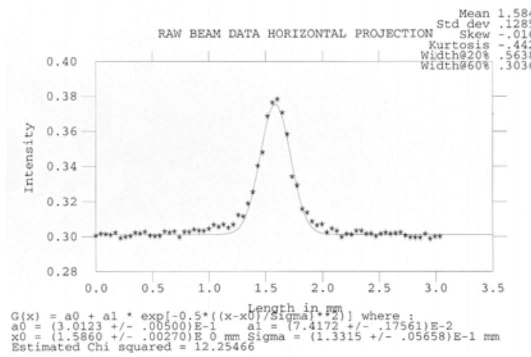
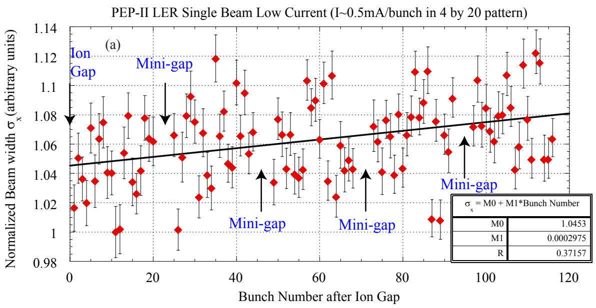


Figure 5. A typical vertical profile for a single bunch in the LER. The distribution is fit to Gaussian function to determine the vertical bunch size.

For the measurements presented in the following sections several points should be made. 1) To reduce the pulse-to-pulse bunch size variation each data point consists of an average of five-gated camera measurements. 2) All the measurements were made in the by 4 bunch pattern but with different size mini-gaps. 3) Due to the scarcity of machine studies time on PEP-II, most of the experiments were made parasitically during colliding beams physics running when there is no opportunity to vary collider parameters. 4) The trains just after the 361ns ion clearing gap exhibit the interesting dynamics due to the electron cloud, therefore, most of the measurements were made just after the ion-clearing gap.

3.2 Non-Colliding and Colliding Bunch Size Measurements

Past measurements have shown that the average bunch size grows as a function of current. After the ion-clearing gap, it is presumed that bunch size growth within a train due to the electron cloud is minimal at low current, and significant at high current. This statement is verified by comparing low and high current measurements of the bunch size. Figure 6 (a) and (b) are the transverse bunch size measured for the LER at low current of 0.5mA/bunch (I_{total}=350mA) with a single beam (not during collisions) present in PEP-II. For this measurement there were 20 bunches in each train and the first five trains after the ion gap are displayed. A slight bunch size growth after the ion gap is evident by the linear fit to the data.



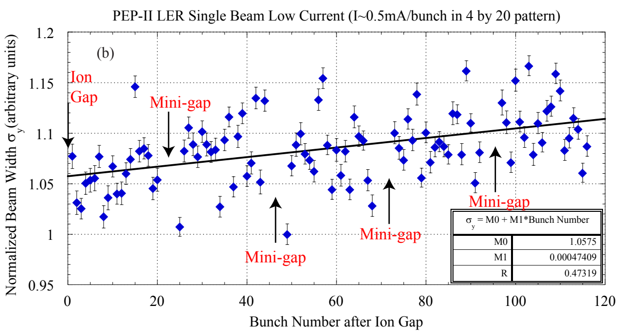
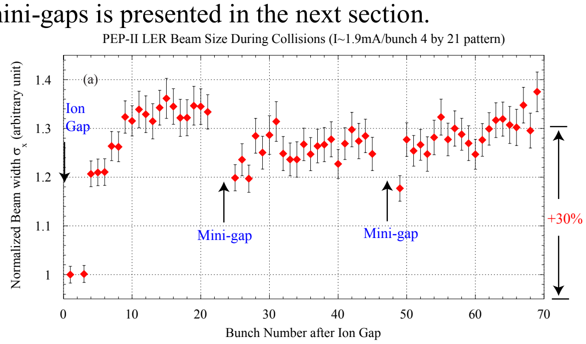


Figure 6 (color). The (a) horizontal and (b) vertical bunch size in the LER at low current (0.5mA/bunch). The locations of the mini-gaps are denoted on the figure.

Comparing the low current non-colliding bunch sizes with high current colliding bunch sizes points out the bunch size blow-up due to the electron cloud. Figure 7 is the transverse bunch size measured at a bunch current of 1.9mA/bunch (I_{total}=1375mA) during high-energy physics collisions. It should be noted that the straight section solenoids were turned on and the arc solenoids were turned off during the measurements. Comparing the two results several conclusions can be made: 1) the bunch size after the ion gap shows dramatic growth in both planes (σ_x~10% and σ_y~30% increase). 2) The bunch size growth rate is τ~40ns. 3) For the high current case the bunches are in collisions so the beam-beam effect needs to be accounted for. Because the bunches have similar currents, the beam-beam effect is the same for all bunches, hence the blow-up observed here is due to the electron cloud. 4) The bunches at the front of the train have smaller transverse bunch sizes when compared to the bunches at the end of each train. The mini-gaps between trains, which are used to clear out the electron cloud, reduce the bunch size blow up due to the electron cloud. A more detailed measurement that exhibits the benefits of mini-gaps is presented in the next section.



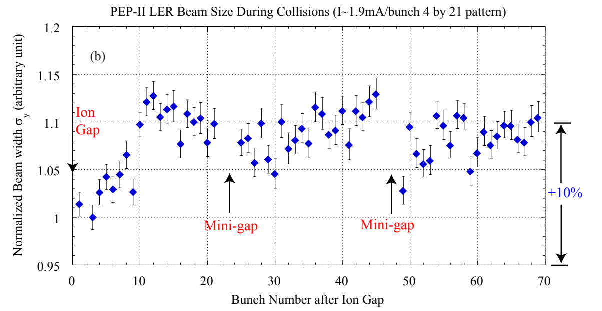
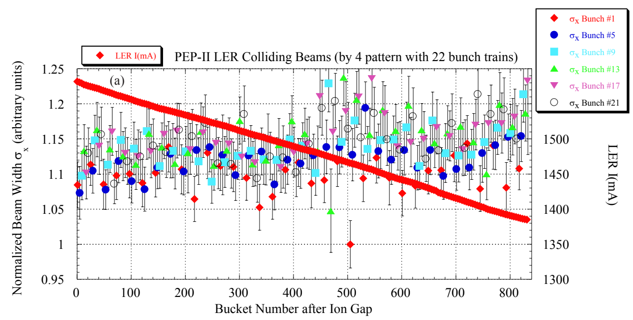


Figure 7 (color). The (a) horizontal and (b) vertical bunch size at high current (1.9mA/bunch).

3.3 Affect of Mini-Gaps on Bunch Size

To quantify the benefit of mini-gaps, the following experiment was devised. The transverse bunch size was measured for every 4th bunch in a train with 22 bunches per train (starting after the ion gap) present in the LER. The measured bunch size and current result are displayed in figure 8.



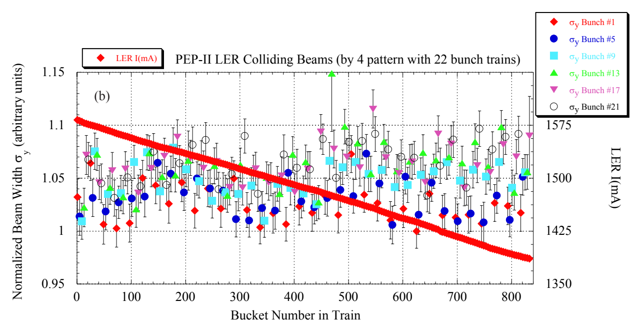


Figure 8 (color). The (a) horizontal and (b) vertical bunch size for every fourth bunch starting at the ion-clearing gap through the whole ring. The total bunch current in the LER is also plotted.

Superimposing the bunch size for each bunch in a train and computing its average, as shown in figure 9, the beam size growth rate with the train is determined. It can be concluded that mini-gaps provide a higher luminosity for bunches in the front of each train by reducing their bunch size. On average there is approximately 5% growth in the train.

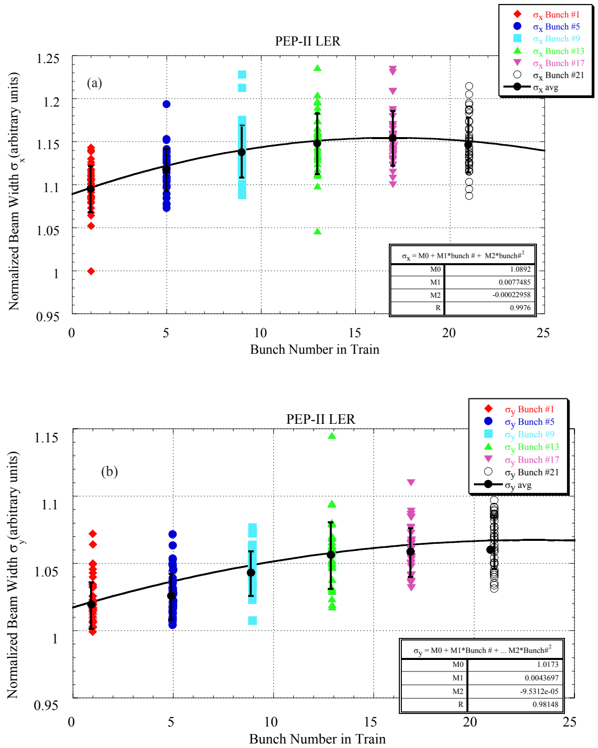
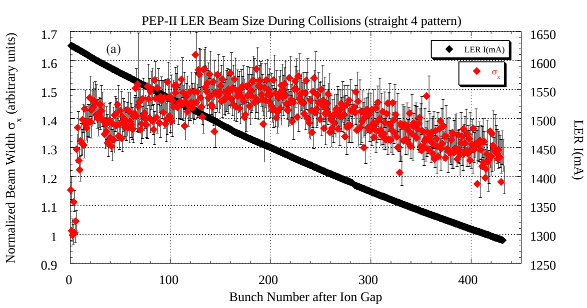


Figure 9 (color). The (a) horizontal and (b) vertical bunch size for every fourth bunch in every train in the LER. The average bunch size (in black) for each bunch is plotted as well as the fit to the average bunch size.

3.4 Advantages of a Current Ramp

It was determined experimentally that a current ramp eliminated current losses for the first few HER trains after the ion clearing gap. Gated camera measurements were made independently to verify the benefit of a current ramp. This verification was made during a short period of time when PEP-II was run with a straight by 4 pattern (no mini-gaps). During this time of no mini-gaps the bunch size in the LER was measured. Figure 10 is the bunch size for the first 440 bunches in the LER during collisions. After the initial rapid bunch size growth, the bunch size continues to grow until I_{bunch}~1.75mA/bunch (I_{total}=1450mA), after which it reduces in size.



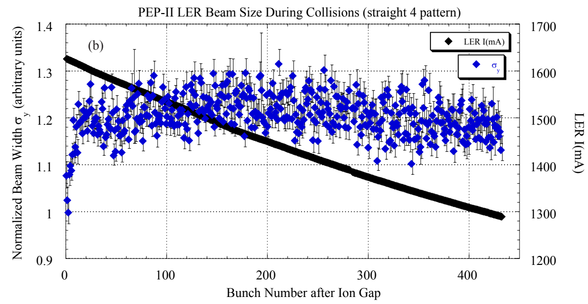


Figure 10 (color). The (a) horizontal and (b) vertical bunch size in the LER with a straight 4 pattern without a current ramp. The total LER current is also plotted.

Superimposing the transverse bunch size measured for the first three trains with and without a current ramp present points out that (figure 11): for similar currents per bunch the bunch growth rate is approximately 20% larger without a current ramp; the straight 4 pattern does not benefit from a bunch size reduction from mini-gaps.

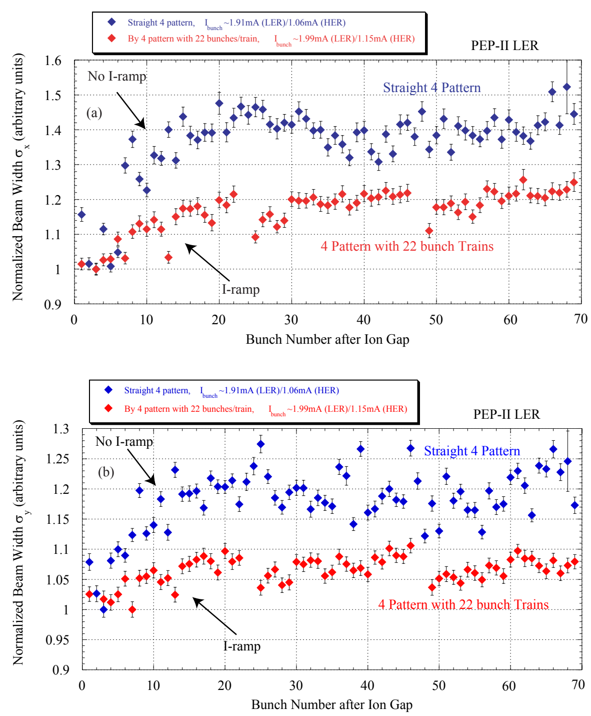


Figure 11 (color). The (a) horizontal and (b) vertical bunch size in the LER under two different operational conditions. The red data is the by 4 pattern with 22 bunches per train and a current ramp. The blue data is the straight 4 pattern without the current ramp.

By plotting the transverse bunch size for every fourth bunch in the straight by 4 pattern it is evident that the bunch size remains constant throughout the train (figure 12).

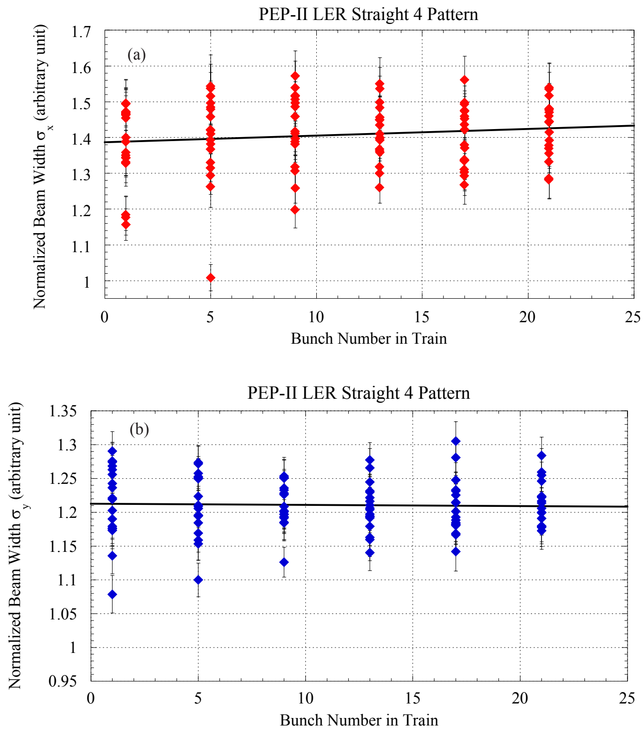


Figure 12 (color). The (a) horizontal and (b) vertical bunch size for every fourth bunch in every train for the first 440 bunches in the LER when the straight 4 pattern without a current ramp was collided in PEP-II.

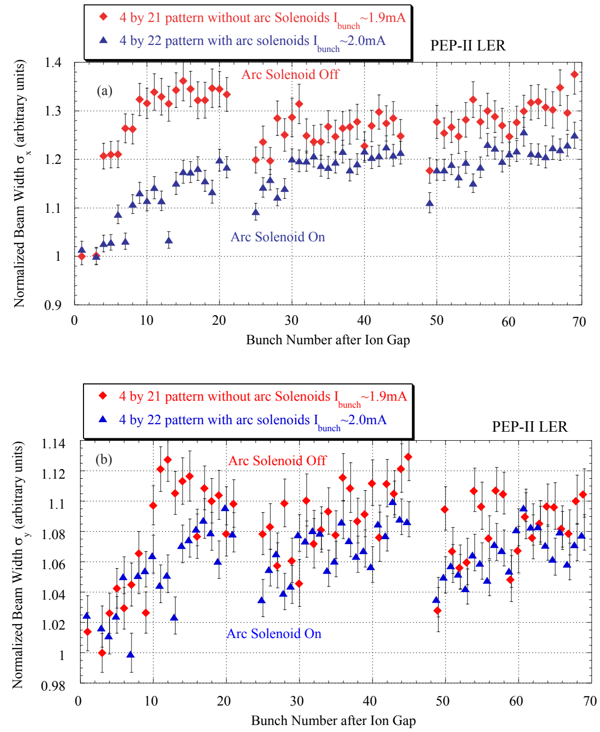


Figure 13 (color). The (a) horizontal and (b) vertical bunch size in the LER under two different operational conditions. The red data is the by 4 pattern with 21 bunches per train with the arc solenoids turned off. The blue data is the straight 4 pattern with 22 bunches per train with the arc solenoids turned on.

3.5 Reduction of Bunch Size Due to Arc Solenoids

There has been no direct observation of the electron cloud in the LER arc regions, nonetheless, at the time of these measurements solenoid windings have been installed in three and one-half of the six arc regions. When the arc solenoid windings were turned on the luminosity and lifetime initially decreased due to the steering of the bunch from the solenoid windings. After the orbits and coupling were corrected the lifetime and specific luminosity were enhanced by the addition of the solenoid field. In addition, the transverse bunch size was measured before and after the arc solenoids were turned on. The bunch pattern for the two measurements were different but at approximately the same bunch current.

Figure 13 is a superposition of the bunch size measurements with and without the three and one-half arc solenoids turned on. It is evident, from figure 13, that the growth rate with the new arc solenoids windings on is τ~80ns (~20 bunches), and the overall bunch size is smaller.

4 SUMMARY

The gated camera has provided interesting insight and verification of some operational parameters of the PEP-II collider used to maximize the luminosity at PEP-II in the presence of the electron cloud instability. Measurements have shown that:

1) Transverse bunch size blow up has been measured above the electron cloud instability threshold both in the horizontal and vertical planes.

2) The electron cloud builds up quickly and decays quickly so mini-gaps in the fill pattern reduce the transverse bunch blow-up for the next train.

3) The current ramp reduces the rapid bunch size growth after the ion gap and helps eliminate the HER bunches from dropping out.

4) The arc solenoids reduce the bunch size blow-up associated with the electron cloud and increases the bunch size growth rate time. Plans to complete the arc solenoid windings for the remaining two and one-half arcs are underway.

In the near future higher currents will be needed at which point the by two pattern will be implemented and these measurements will be repeated with the new bunch pattern.

5 ACKNOWLEDGMENTS

I would like to thank the accelerator operations group for providing me with stable colliding beams for these measurements. I would also like to thank Alan Fisher, Artem Kulikov, and John Seeman for providing the equipment and incentive for these measurements.

5 REFERENCES

[1] Kulikov, A., et al., "The Electron Cloud Instability at PEP-II", SLAC, June 2001. Presented at the Particle Accelerator Conference, Chicago, IL, June 2001.

[2] Decker, F.-J., et al., “Complicated Bunch Pattern in PEP-II”, SLAC, June 2001. Presented at the Particle Accelerator Conference, Chicago, IL, June 2001.

[3] The gated camera is made by Princeton Instruments.