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ELECTRON CLOUD MEASUREMENTS IN FERMILAB BOOSTER*

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Abstract

Fermilab Booster synchrotron requires an intensity upgrade from 4.5×10^{12} to 6.5×10^{12} protons per pulse as a part of Fermilab's Proton Improvement Plan-II (PIP-II). One of the factors which may limit the high-intensity performance is the fast transverse instabilities caused by electron cloud effects. According to the experience in the Recycler, the electron cloud gradually builds up over multiple turns in the combined function magnets and can reach final intensities orders of magnitude greater than in a pure dipole. Since the Booster synchrotron also incorporates combined function magnets, it is important to discover any existence of an electron cloud. And if it does, its effects on the PIP-II era Booster and whether mitigating techniques are required. As the first step, the presence or absence of the electron cloud was investigated using a gap technique. This paper presents experimental details and observations of the bunch-by-bunch tune shifts of beams with various bunch train structures at low and high intensities and simulation results conducted using PyECLOUD software.

INTRODUCTION

In particle accelerators, free electrons are always present inside the vacuum chambers due to many reasons such as ionization of residual gas molecules, stray beam particles striking the chamber walls, etc. These electrons can be accelerated by the electromagnetic fields of the beam to the energies of several hundreds of eV to a few keV, depending on the beam intensity. When such electrons impact vacuum chamber walls, secondary electrons can be generated according to their impact energy and the Secondary Electron Yield (SEY) of the surface. Repeating this process, especially with a proton beam with closely spaced bunches can lead to an avalanche creating the so-called electron cloud (EC) [1-4].

These ECs can severely limit the performance of high-intensity proton accelerators due to transverse instabilities, transverse emittance growth, particle losses, vacuum degradation, heating of the chamber's surface, etc. The Super Proton Synchrotron (SPS), Proton Synchrotron (PS), and Large Hadron Collider (LHC) at CERN [5-6], Relativistic Heavy Ion Collider (RHIC) at Brookhaven national laboratory (BNL) [7], Proton Storage Ring (PSR) at the Los Alamos National Laboratory (LANL) [8] are few of the high-intensity accelerator facilities that encountered operational challenges due to EC effects.

In 2014, The Recycler at Fermilab also experienced fast transverse instabilities. Early studies by J. Eldred *et al.* [4] hypothesized that the instabilities might be due to the EC build-up in the Recycler. Further investigations by S. A. Antipov *et al.* [3] confirmed EC build-up in the Recycler, concentrated in the combined function magnets. The field gradient of the combined function magnets can create a magnetic mirror effect which facilitates electron trapping. According to his simulations, EC accumulates over many revolutions inside a combined function magnet and can reach final intensities orders of magnitudes higher than inside a pure dipole.

The Fermilab Booster [9] is a 474.2 m circumference rapid-cycling (15 Hz) synchrotron containing 96 combined function magnets. It accelerates the beam from 0.4 GeV at injection to 8.0 GeV at extraction over 33.3 ms (the rising portion of the sinusoidal current waveform) in about 20000 turns, where each turn contains 84 buckets filled with 81 bunches during High Energy Physics (HEP) cycle. The proposed Fermilab's Proton Improvement Plan-II (PIP-II) requires the Fermilab Booster to deliver a high-intensity beam of 6.5×10^{12} protons per pulse which is a 44% increase in the current intensity [10]. Thus, it is important to discover any existence of an EC in the PIP-II era Booster, and if it does, whether it poses any limitations to the desired performance and whether any mitigating techniques are required.

As the first step, the presence or absence of the EC was investigated using a gap technique. Further, corresponding simulations were carried out with PyECLOUD [11]. This paper presents the experimental details and observations of the bunch-by-bunch tune shifts of beams with various bunch train structures at low and high intensities and simulation results.

EXPERIMENTAL TECHNIQUE

According to past observations, a train of closely spaced bunches is required for the electrons to trap in the magnetic field. In the absence of a following bunch, the existing secondary electrons can go through a few elastic reflections and get absorbed by the vacuum chamber. Hence, if a trapped EC is present in the machine, a single bunch following the main batch can be used to clear the EC as it kicks the electrons into the vacuum chamber.

Since an EC act as a lens providing additional focusing or defocusing to the beam, this clearing of the EC can be observed in shifting the betatron tune. According to S. A. Antipov's analysis, a positive tune shift in the horizontal direction indicates the presence of an EC at the beam center, and a negative tune shift in the vertical direction indicates the maximum density of the EC near the walls of the vacuum chamber [3]. Adding a clearing bunch can reduce these tune shifts.

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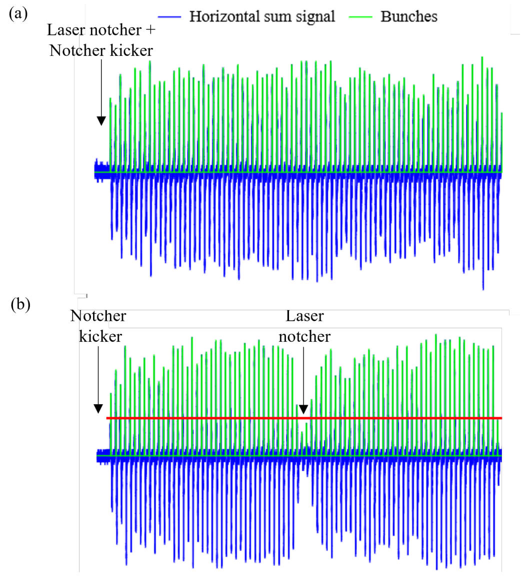

Figure 1: Bunch structures (a) nominal (b) opposite notch. The red line shows the threshold value above which the signal was considered a bunch.

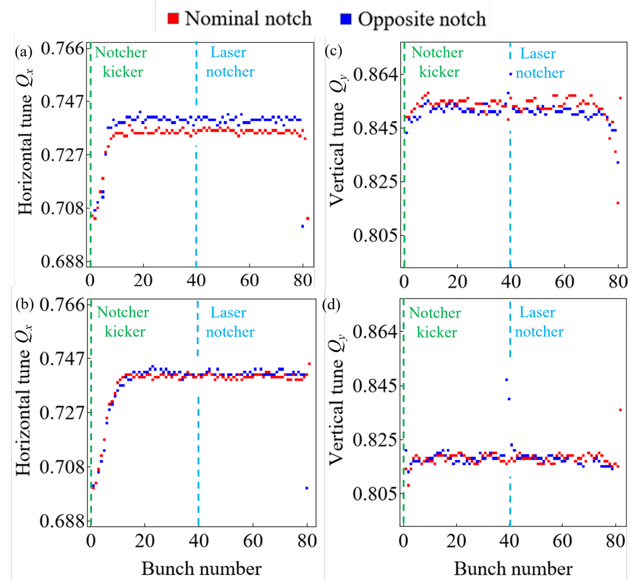

Figure 2: Bunch tune variation in turn 1 for nominal and opposite notches (a) low intensity, horizontal ping, (b) high intensity, horizontal ping, (c) low intensity, vertical ping, and (d) high intensity, vertical ping. The dashed line indicates the location of the notcher kicker (green) and laser notcher (light blue). The notches formed by the notcher kicker only and (notcher kicker + laser notcher) are at bunch number 1.

The existence of the EC in the Booster was investigated by introducing different gaps in the bunch structure with varying beam intensities and horizontal and vertical pings. Then the corresponding tune shifts were analyzed. This paper presents measurements taken for two different beam intensities 4.5×10^{12} and 1.9×10^{12} protons per pulse. The bunch structure was varied by misaligning the laser notcher and the notcher kicker [12], as shown in Fig. 1. The Booster employs the laser notcher to remove 3 bunches from 84 bunch turn to reduce the losses at the extraction. Since the laser notcher is not capable of completely clearing these bunches, a notcher kicker is also implemented. In the nominal case, the laser notcher and notcher kicker are placed on top of each other, resulting in 3 empty buckets and, thus, 81 bunch turns. For this study, we misaligned them to create a bunch structure with two notches on opposite sides of the train. In this structure, there are about 79 bunch turns. Early studies indicate that this variation in bunch structure may have a small effect on extracted beam emittance [13].

In order to take the measurements, a damper pickup located in the Booster ring at Long 10 was used with a high bandwidth scope. The damper pickup provides the sum and the difference signals for horizontal and vertical planes. Before extracting the beam positions from the data, it is essential to ensure each turn of a particular data set follows the same bunch structures corresponding to its notcher pattern. After aligning all the turns, the betatron tune of each bunch was determined by performing a Fourier analysis considering every 1024 turns.

RESULTS ANALYSIS

Figure 2 shows each bunch's horizontal and vertical tune variation in turn 1 (after injection and capture) for both bunch structures and for both intensities.

The above plots show the horizontal tunes in both high and low-intensity beams were not affected by the laser notcher. Conversely, the vertical tunes show a positive shift in both high and low-intensity beams due to the laser notcher. However, this may be due to the impedance tune depression, as the low-intensity beam shows a smaller shift than the high-intensity beam. The more significant horizontal tune shift in the first few bunches cannot be recognized as an effect from the EC as it is too large compared to the Recycler observations and also can be seen in both high and low-intensity beams. According to the observation, this is likely due to the orbital distortion caused by the notcher kicker as it kicks the beam 10 mm in the horizontal direction.

Figures 3 and 4 depict the horizontal and vertical tune shifts of opposite notch bunch structure with respect to the nominal notch bunch structure, from injection up to the transition (~8500 turns), respectively. Note that the tune difference of each turn was calculated by considering the bunches with typical tunes (unaffected by the nearby notches) and taking the average of them. The negative horizontal tune shift near the transition in the high-intensity beam (Fig. 3(a) indicated by the red dotted circle) reveals that the introduced gap helped to reduce the tune shift, which is a clear indication of the reduction in EC density [3]. Further, the slight positive vertical tune shift near the transition in the high-intensity beam (Fig. 4(a) indicated by the blue dotted circle) also indicates that the introduced gap reduces the tune shift, hence a reduction in EC density. Low-intensity beam does not show a considerable horizontal or vertical tune shift near the

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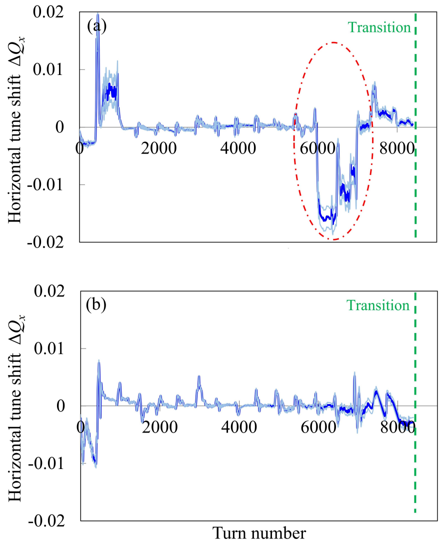

Figure 3: Horizontal tune shift due to the gap from injection to transition (a) high-intensity, (b) low-intensity. The error envelopes (light blue) were calculated by taking the standard errors of the mean. The spikes are the pings.

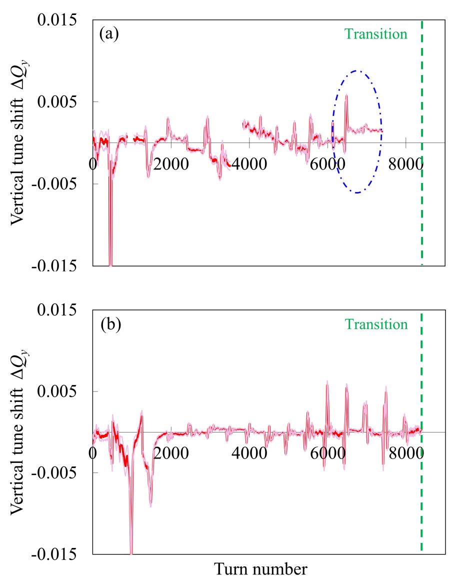

Figure 4: Vertical tune shift due to the gap from injection to transition (a) high-intensity, (b) low-intensity. The error envelopes (light red) were calculated by taking the standard errors of the mean. The discontinuity in the high-intensity plot is due to the distorted tune bands. The spikes are the pings.

transition, which is also consistent with the presence of the EC. The origin of the tune shift between 0 to 2000 turns in all the plots could not able to be identified.

SIMULATIONS

In order to simulate the EC build-up inside a combined function magnetic located in the Booster synchrotron, PyECLOUD code was employed [11]. Table 1 lists the main input parameters used in the simulations.

Table 1: Input Parameters in PyECLOUD Simulations

Parameter	**Value**
Beam energy [GeV]	4.2
Bunch spacing [ns]	19.2
Bunch length, σ [m]	0.25
SEY, δ	1.8

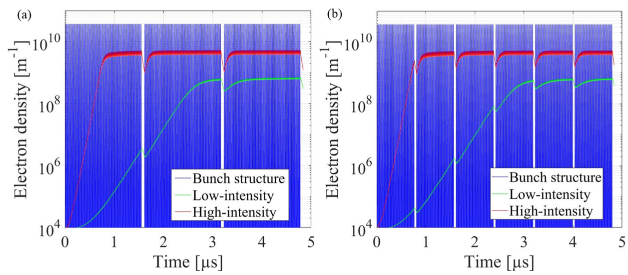

Figure 5: EC build-up for low and high-intensity beams (a) nominal notch, (b) opposite notch.

The combined function magnet cross-section was considered a rectangle with dipole and quadrupole magnetic fields. The initial number of electrons was taken as 10^4. The beam filling pattern was included as 81 bunches and 3 empty bunches for the nominal notch and twice 40 bunches and 2 empty bunches for the opposite notch. The simulation was conducted for 3 turns near transition for both low and high-intensity beams. Figure 5 shows the early simulation results.

According to the above plots, EC is present inside the Booster. The EC build-up for low-intensity beams in opposite notch bunch structures is slow compared to the nominal bunch structure. However, both low and high-intensity beams show almost the same EC saturation despite their bunch structure. Further, both notch structures show EC reduction in the gap, and high-intensity plots show larger EC reduction compared to low-intensity, resulting in possible larger tune shifts in high-intensity data that have been seen in measurements compared to low-intensity data.

CONCLUSION

The presence or absence of the EC in the PIP-II era Booster was investigated by changing the bunch structure. An analysis of tune variation by bunch number was not able to provide any pattern consistent with the presence of EC. Apparent tune variation as a result of bunch structure was measured, consistent with the presence of EC, and is supported by PyECLOUD simulations near transition. However, there are a lot of features in the data that we are still identifying. We will continue to further investigate the EC effect in the Booster with more measurements, including microwave measurements and simulations.

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REFERENCES

[1] M. Furman, S. Henderson, and F. Zimmermann, eds., *Electron-cloud effects. Proceedings, 31st ICFA Advanced Beam Dynamics Workshop, ECLOUD'04*, Napa, USA, 2004, CERN Yellow Reports: Conference Proceedings, 2005. doi:10.5170/CERN-2005-001

[2] G. Rumolo *et al.*, "Electron cloud effects on beam evolution in a circular accelerator," *Phys. Rev. ST Accel. Beams*, vol. 6, p. 081002, 2003. doi:10.1103/PhysRevSTAB.6.081002

[3] S. A. Antipov, P. Adamson, A. Burov, S. Nagaitsev, and M. J. Yang, "Fast instability caused by electron cloud in combined function magnets," *Phys. Rev. Accel. Beams*, vol. 20, p. 044401, 2017. 10.1103/PhysRevAccelBeams.20.044401

[4] J. S. Eldred *et al.*, "Fast Transverse Instability and Electron Cloud Measurements in Fermilab Recycler", in *Proc. HB'14*, East Lansing, MI, USA, Nov. 2014, paper THO4LR04, pp. 419–427.

[5] G. Arduini, T. Bohl, K. Cornelis, W. Hofle, E. Métral, and F. Zimmermann, "Beam observations with electron cloud in the CERN PS & SPS complex," in *Proceedings of ECLOUD'04*, 2004. doi:10.5170/CERN-2005-001.31

[6] G. Iadarola *et al.*, "Analysis of the electron cloud observations with 25ns bunch spacing at the LHC," in *Proceedings of IPAC'14*, Dresden, Germany, 2014. doi:10.18429/JACoW-IPAC2014-TUPME027

[7] W. Fischer *et al.*, "Electron cloud observations and cures in the Relativistic Heavy Ion Collider," *Phys. Rev. ST Accel. Beams*, vol. 11, p. 041002, 2008. doi:10.1103/PhysRevSTAB.11.041002

[8] R. J. Macek, A. Browman, M. Borden, D. Fitzgerald, T. S. Wang, and T. Zaugg, "Electron cloud diagnostics in use at the Los Alamos PSR," in *Proceedings of PAC'03*, Portland, OR, 2003, paper ROAB003.

[9] Booster rookie book: https://operations.fnal.gov/rookie_books/Booster_V4.1.pdf.

[10] E. Prebys *et al.*, "Long Term Plans to Increase Fermilab's Proton Intensity to Meet the Needs of the Long Baseline Neutrino Program", in it Proc. IPAC'16, Busan, Korea, May 2016, pp. 1010-1013. doi:10.18429/JACoW-IPAC2016-TUOAA03

[11] G. Iadarola, PyECLOUD Version 8.6.0, CERN, 2021.

[12] D. Johnson *et al.*, "MEBT Laser Notcher (Chopper) for Booster Loss Reduction," in *Proc. HB'18*, Daejeon, Korea, 2018. doi:10.18429/JACoW-HB2018-THP1WC01

[13] J. Eldred, R. Ainsworth, V. Lebedev, K. Seiya, and V. Shiltsev, "Impact of Double-Notch on Extracted Booster Emittance", Fermilab, Batavia, IL, USA, Rep. Beams-doc-8910-v3.