 ELECTRON CLOUD MEASUREMENTS IN FERMILAB BOOSTER

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NAPAC 2022, Albuquerque, New Mexico
August 10th, 2022

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
Motivation

- Proton Improvement Plan–II (PIP-II) requires an intensity upgrade from $4.5 \times 10^{12}$ to $6.5 \times 10^{12}$ protons per pulse in Fermilab Booster

- High-intensity performance may be limited by fast transverse instabilities caused by electron cloud effects
  - Is there electron cloud present in the Fermilab Booster?
  - Will it pose a challenge in PIP-II era Booster?

Acknowledgment

I would like to thank:
J.S. Eldred, C.Y. Tan, E. Pozdeyev, and the Fermilab Booster group
R. Ainsworth and A. Schreckenberger
Booster layout

- Fermilab Booster is a synchrotron that accelerates protons from 400 MeV to 8 GeV

| Parameter                  | Value         |
|----------------------------|---------------|
| Circumference [m]          | 474.20        |
| Injection energy [MeV]     | 400           |
| Extraction energy [8 GeV]  | 8             |
| Cycle time [s]             | 1/15          |
| Harmonic number            | 84            |
| Transition energy [GeV]    | 4.2           |
| Total intensity, $N_p$     | $4.5 \times 10^{12}$ |

- Booster contains 96 combined function magnets

Fig. 1: Schematics of the Fermilab Booster synchrotron.

Fig. 2: Schematics of the Fermilab Booster synchrotron.
In a combined function magnet, the electron cloud accumulates over many revolutions, reaching a much higher density, than in a pure dipole. A clearing bunch destroys the trapped cloud, preventing the accumulation.

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 20, 044401 (2017).

- Antipov et al. found that trapping in combined function magnets of the Fermi Recycler causes an amplification of electron cloud, which leads to a 2014 instability

- The Booster also has combined function magnets; a similar effect can cause instabilities
Experimental technique

- Following the clearing bunch technique, different gaps were introduced in the bunch structure to study the electron cloud effect.

- In the Booster, we have the laser notcher and the notch kicker, which we can misalign to create two different gaps instead of one.

- Studied the tune shift in high-intensity and low-intensity data with these three different notches and with horizontal and vertical pings.

- High intensity: $4.5 \times 10^{12}$ ppp
  Low intensity: $1.9 \times 10^{12}$ ppp

- Each data set was aligned per turn with these bunch structures.
Experimental Set up

Fig. 6: Scope signal includes horizontal sum and difference, vertical sum and difference.
Tune comparison near injection

**Horizontal data**

- The single notch, double-notch, and opposite-notch look almost the same despite the beam intensity.

- Change in horizontal tune in the first few bunches is not due to electron cloud (too large, present in both high and low-intensity data), but due to the notch kicker.

- There’s no visible impact to the bunches next to the notch created by the laser notcher.

- High intensity: $4.5 \times 10^{12}$ ppp
  Low intensity: $1.9 \times 10^{12}$ ppp

For single notch both Notcher kicker and laser notcher are placed on top of each other.
Tune comparison near injection

Vertical data

• There is a tune shift from the laser notcher in both low and high-intensity data.

• There is a possibility of impedance tune depression effect in the vertical data, as the lower intensity bunches (near the laser notcher) show less of it. Don’t have enough data to verify.

• The tune shift towards the end of the bunch train in low-intensity data is likely due to notcher kicker.

• High intensity: $4.5 \times 10^{12}$ ppp
  Low intensity: $1.9 \times 10^{12}$ ppp

For single notch both notcher kicker and laser notcher are placed on top of each other.
Background

- Recycler data shows electron cloud-induced tune-shift along the length of the batch

Positive horizontal tune shift indicates the presence of a negative charge at the beam center.

Negative vertical tune shift indicates that the maximum density of the cloud is outside the beam.

The presence of the clearing bunch reduces the tune shift between the head and the tail of the high-intensity bunch train.

Electron cloud clearing pushes horizontal tune downward and vertical tune upward.

Fig. 7: Betatron tune shift within the 80-bunch train with respect to the first bunch, measured over 600 revolutions with a stripline detector in the Recycler.

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 20, 044401 (2017).
Tune comparison near transition

Horizontal data

- Both single notch vs double notch and single notch vs opposite notch show a fall near the transition in high-intensity data, consistent with Antipov’s analysis.

- Low-intensity data shows no significant difference near the transition between single notch vs double notch and single notch vs opposite notch.

- Cannot identify the tune shift in between 200-1000 turns.

By considering the bunches with tunes unaffected by the notcher kicker or laser notcher:

For single notch vs double notch: $\Delta Q_x = \text{Mean}(Q_x)_{\text{double notch}} - \text{Mean}(Q_x)_{\text{single notch}}$

For single notch vs opposite notch: $\Delta Q_x = \text{Mean}(Q_x)_{\text{opposite notch}} - \text{Mean}(Q_x)_{\text{single notch}}$
Tune comparison near transition

Vertical data

By considering the bunches with tunes unaffected by the notcher kicker or laser notcher

For single notch vs double notch: \( \Delta Q_y = \text{Mean}(Q_y)_{\text{double notch}} - \text{Mean}(Q_y)_{\text{single notch}} \)

For single notch vs opposite notch: \( \Delta Q_y = \text{Mean}(Q_y)_{\text{opposite notch}} - \text{Mean}(Q_y)_{\text{single notch}} \)

• Too noisy to conclude; seems both single notch vs double notch and single notch vs opposite notch show a rise near the transition, consistent with Antipov’s analysis

• Low-intensity data shows no significant difference near the transition between single notch vs double notch and single notch vs opposite notch

• Cannot identify the tune shift in between 200-2000 turns
**PyECLoud simulations**

- Electron cloud buildup inside a combined function magnetic located in the Booster synchrotron was simulated
- The cross-section of the combine function magnet was considered as a rectangle with dipole and quadrupole magnetic fields.
- Simulated 3 turns near transition for both low and high-intensity beams

| Simulation parameters | Value |
|-----------------------|-------|
| Beam energy [GeV]     | 4.2   |
| Bunch spacing [ns]    | 19.2  |
| Bunch length, $\sigma$ [m] | 0.253 |
| SEY, $\delta$        | 1.8   |
| initial number of electrons | $10^4$ |

- There is electron cloud present in the Booster
- Both low and high-intensity beam shows almost the same electron cloud saturation in spite of their bunch structure
- All three bunch structures show electron cloud reduction inside the gap
- High-intensity data shows larger electron cloud reduction inside the gap compared to low-intensity data resulting in possible larger tune shift in high-intensity data compared to low-intensity data
Summary

From bunch-by-bunch tunes near the injection

- Change in horizontal tune is not due to electron cloud (too large, present in both high and low-intensity data. Bunches at gap created by laser notcher not impacted) and likely due to the notch kicker. The vertical show something similar towards the end of the bunch train.

- There is a possibility of impedance tune depression effect in the vertical data, as the lower intensity bunches (near the laser notch) show less of it. Don’t have enough data to clarify. Will try to figure out if it is electron cloud or impedance.

- There are a lot of peaks in frequency spectrum we haven’t identified and features we don’t fully understand.

From average tune comparison near the transition

- High-intensity horizontal data shows a clear indication of the electron cloud.
- High-intensity vertical data is too noisy to make a conclusion.
- Low-intensity data also shows features that are consistent with the presence of electron cloud.

From simulations

- There is electron cloud present in the booster.
- The accumulated electron cloud density reduces with the gap resulting in possible tune shifts that have been seen in the experimental data.

We are going to continue this work to understand the data.

Still, we do not know whether this will affect PIP-II.
Thank you!