ELECTRON CLOUD MEASUREMENTS IN FERMILAB BOOSTER

Sajini Wijethunga
PIP-II
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Motivation

- Proton Improvement Plan-II (PIP-II) requires an intensity upgrade from 4.5×10^{12} to 6.5×10^{12} protons per pulse in the Fermilab Booster
- High-intensity performance may be limited by fast transverse instabilities caused by electron cloud effects

  - Is there an electron cloud present in the Fermilab Booster?
  - Will it pose a challenge in PIP-II era Booster?

Booster layout

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

Parameter	Value
Circumference [m]	474.20
Cycle time [s]	1/15
Harmonic number	84
Number of cells	24
Transition energy [GeV]	4.2
Total intensity, N_p	4.5×10^{12}
Number of turns	20000

- Booster contains 96 combined function magnets

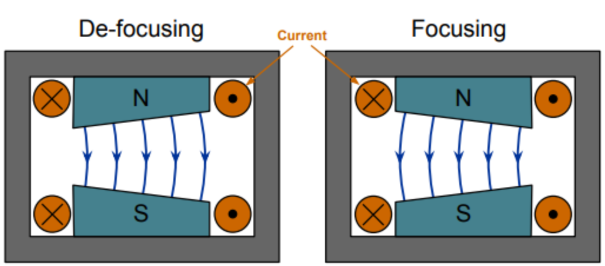


Fig. 1: Schematic of the combined function magnets.

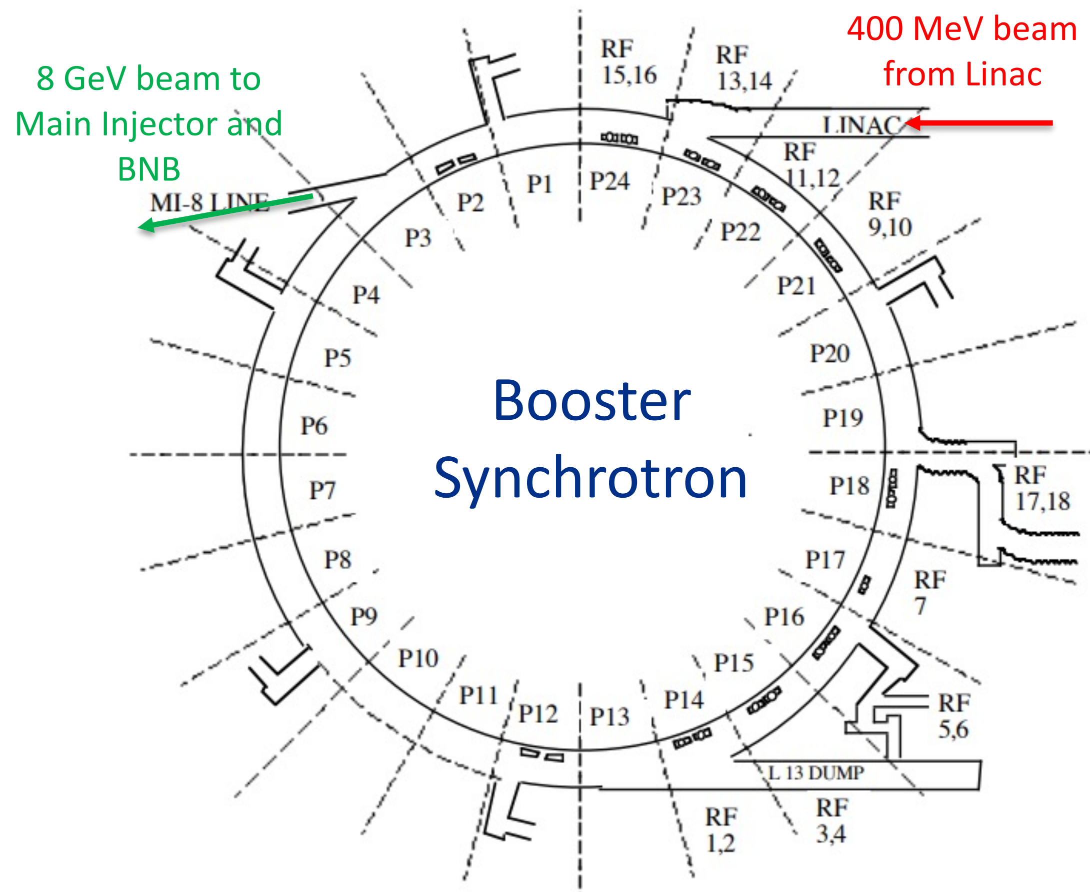


Fig. 2: Schematic of the Fermilab Booster synchrotron.

Background – Electron cloud trapping

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

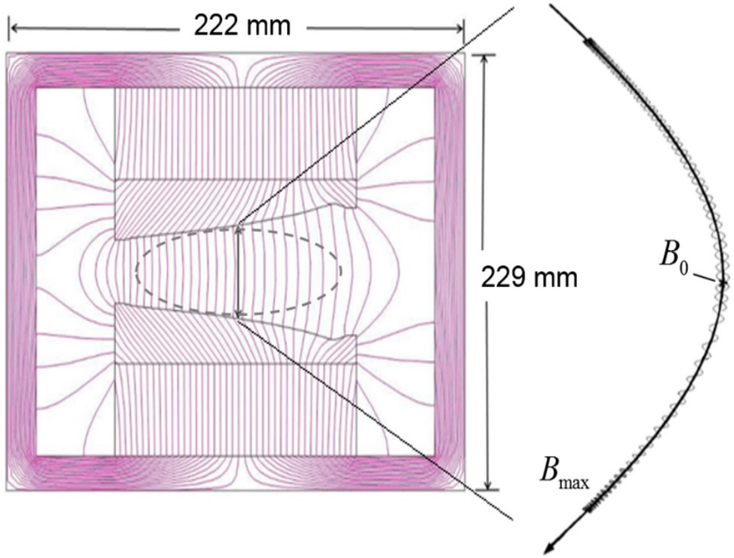


Fig. 3: Field lines inside a combined function magnet.

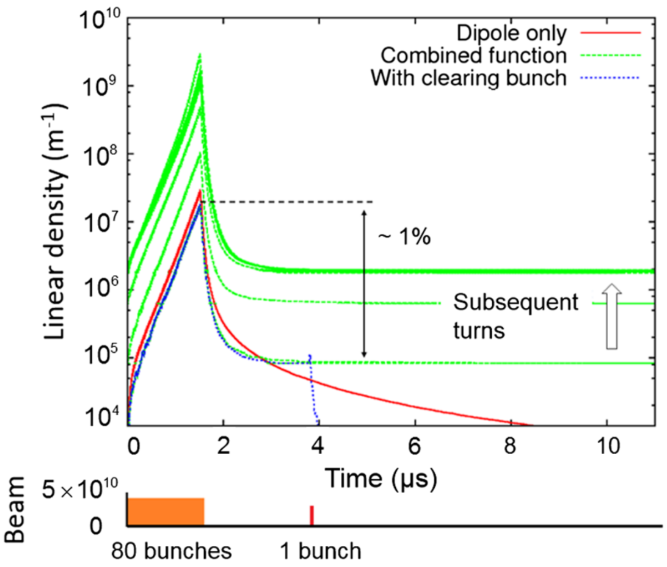


Fig. 4: Electron cloud accumulates over many revolutions in Recycler. PEI code simulations.

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).

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

Experimental technique

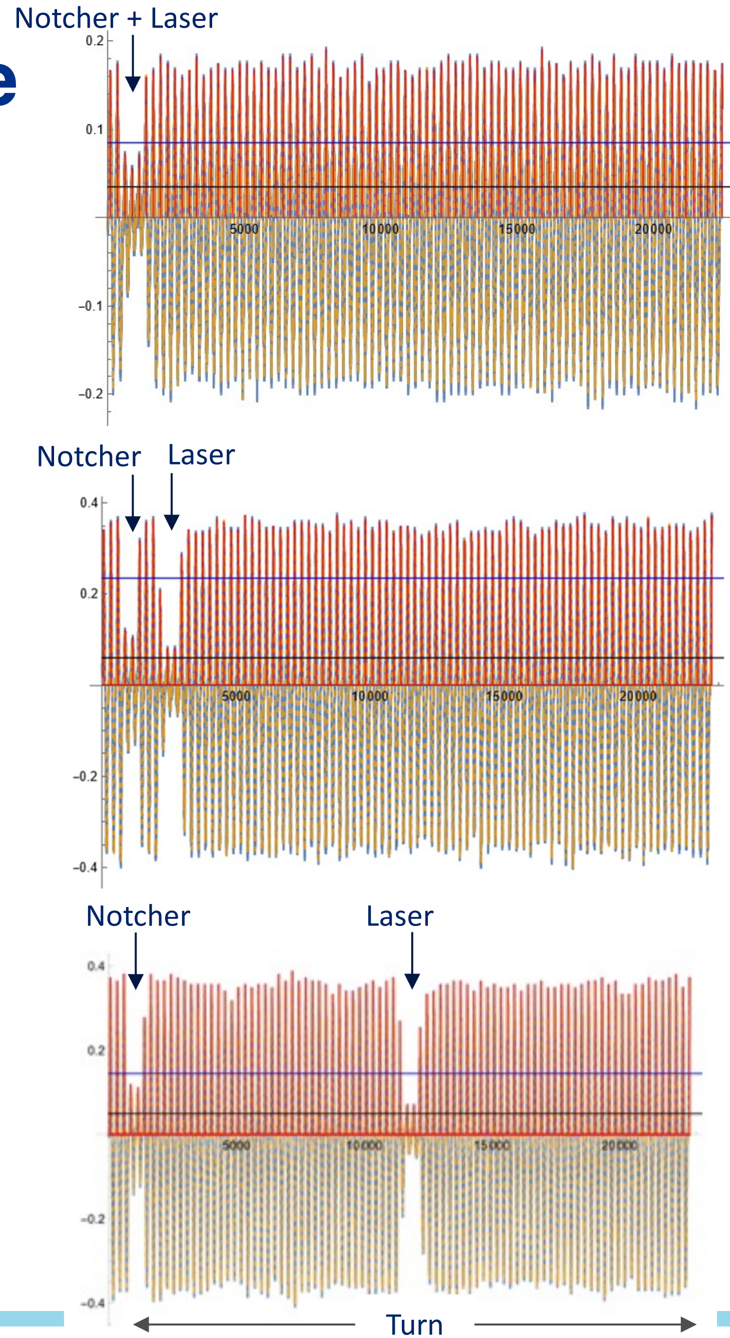
- Following the clearing bunch technique, different gaps were introduced in the bunch structure to study the electron cloud effect

- In the Booster, we have the laser notcher and the notcher 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: 4.5×10^{12} ppp
  Low intensity: 1.9×10^{12} ppp

- Each data set was aligned per turn with these bunch structures

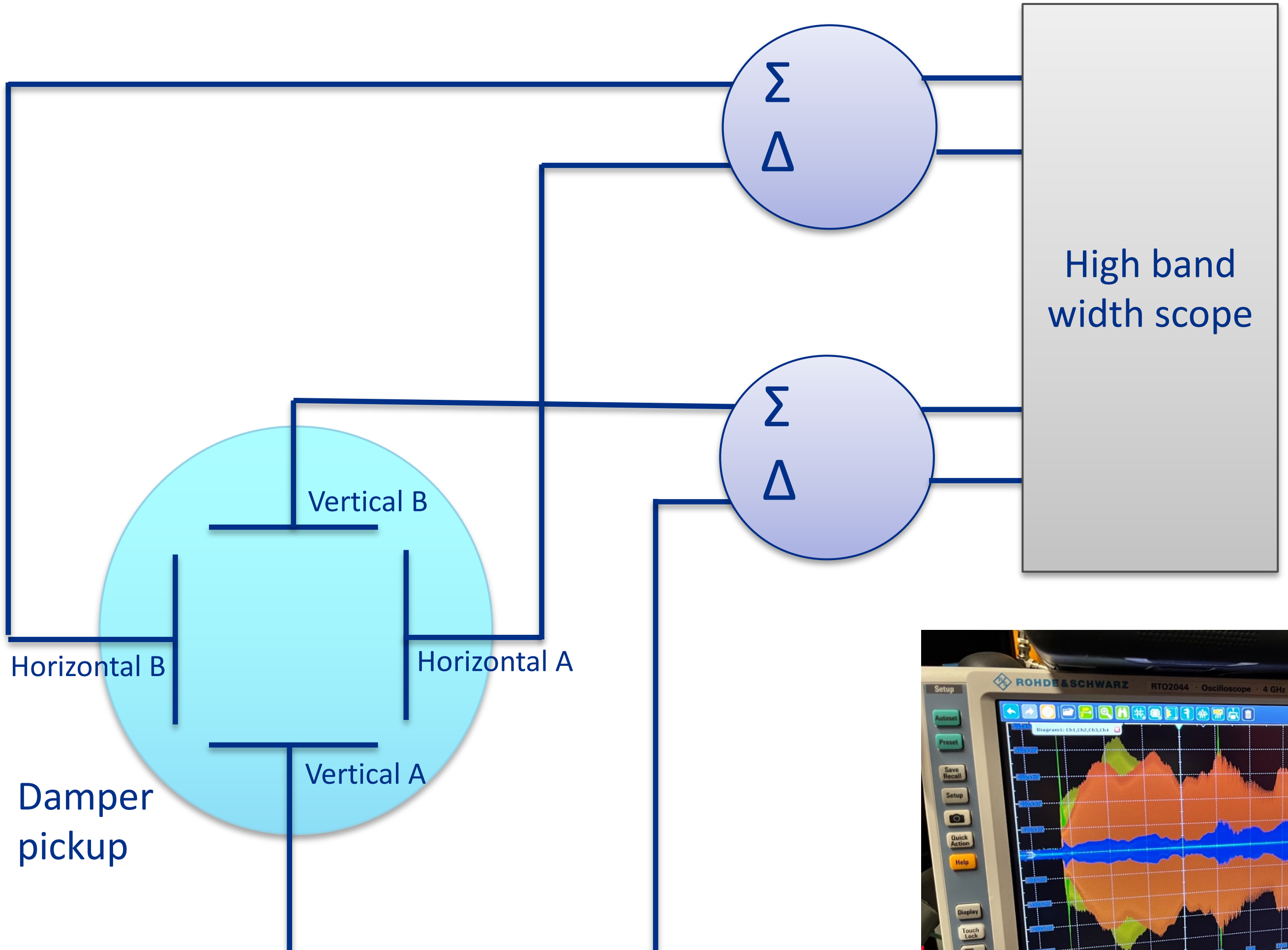


Single-notch structure with laser notcher and the notch kicker are aligned.

Double-notch structure with laser notcher misaligned from the notch kicker by 6 buckets.

Opposite-notch structure with laser notcher misaligned from the notch kicker by 42 buckets.

Experimental Set up



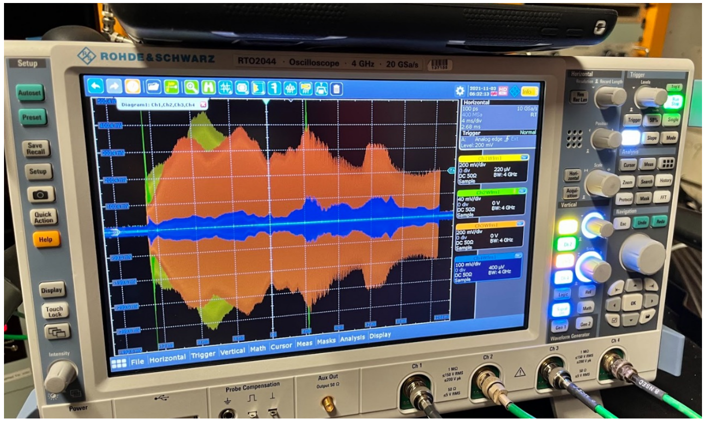
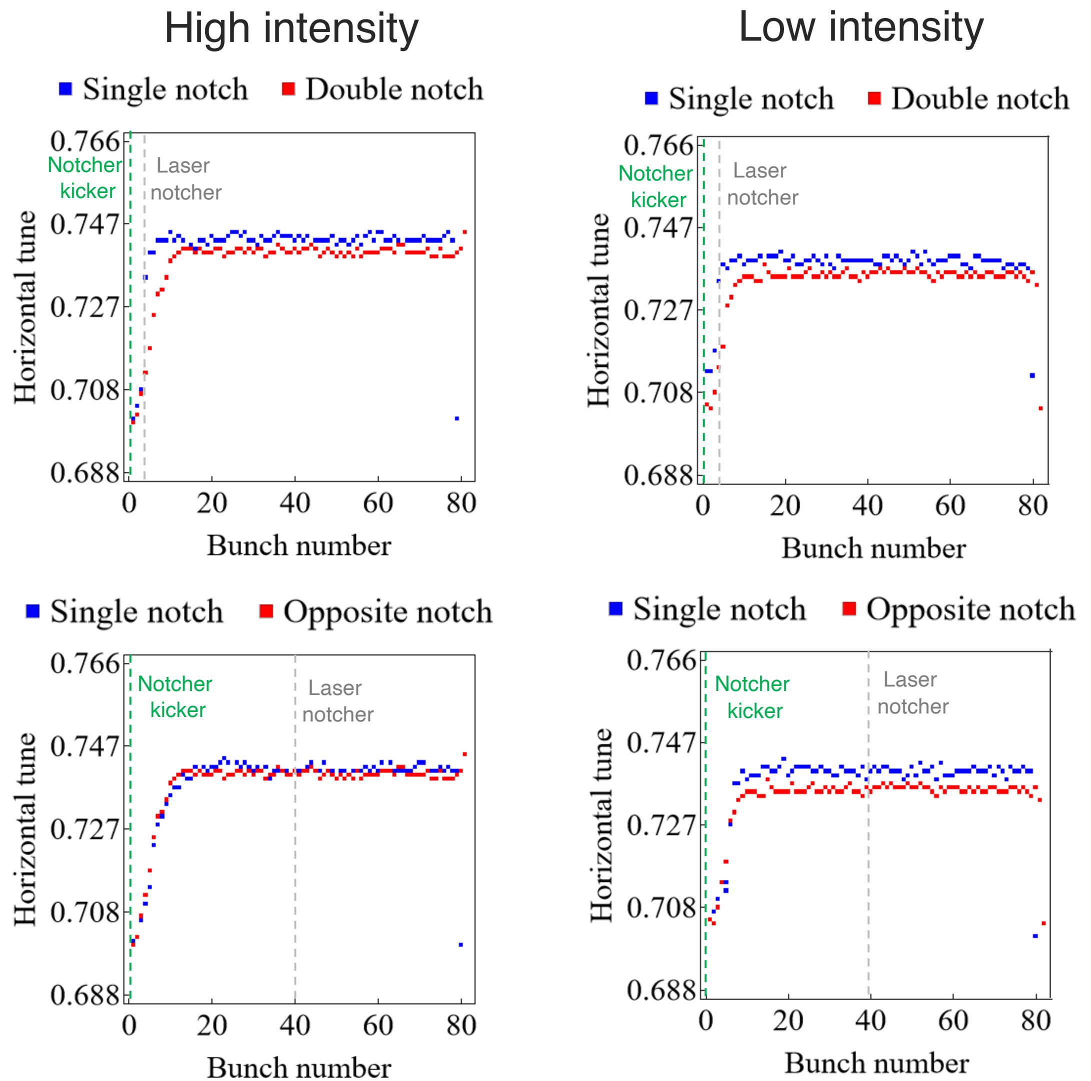


Fig. 6: Scope signal includes horizontal sum and difference, vertical sum and difference.

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 notcher kicker.
- There is no visible tune shift from the laser notcher

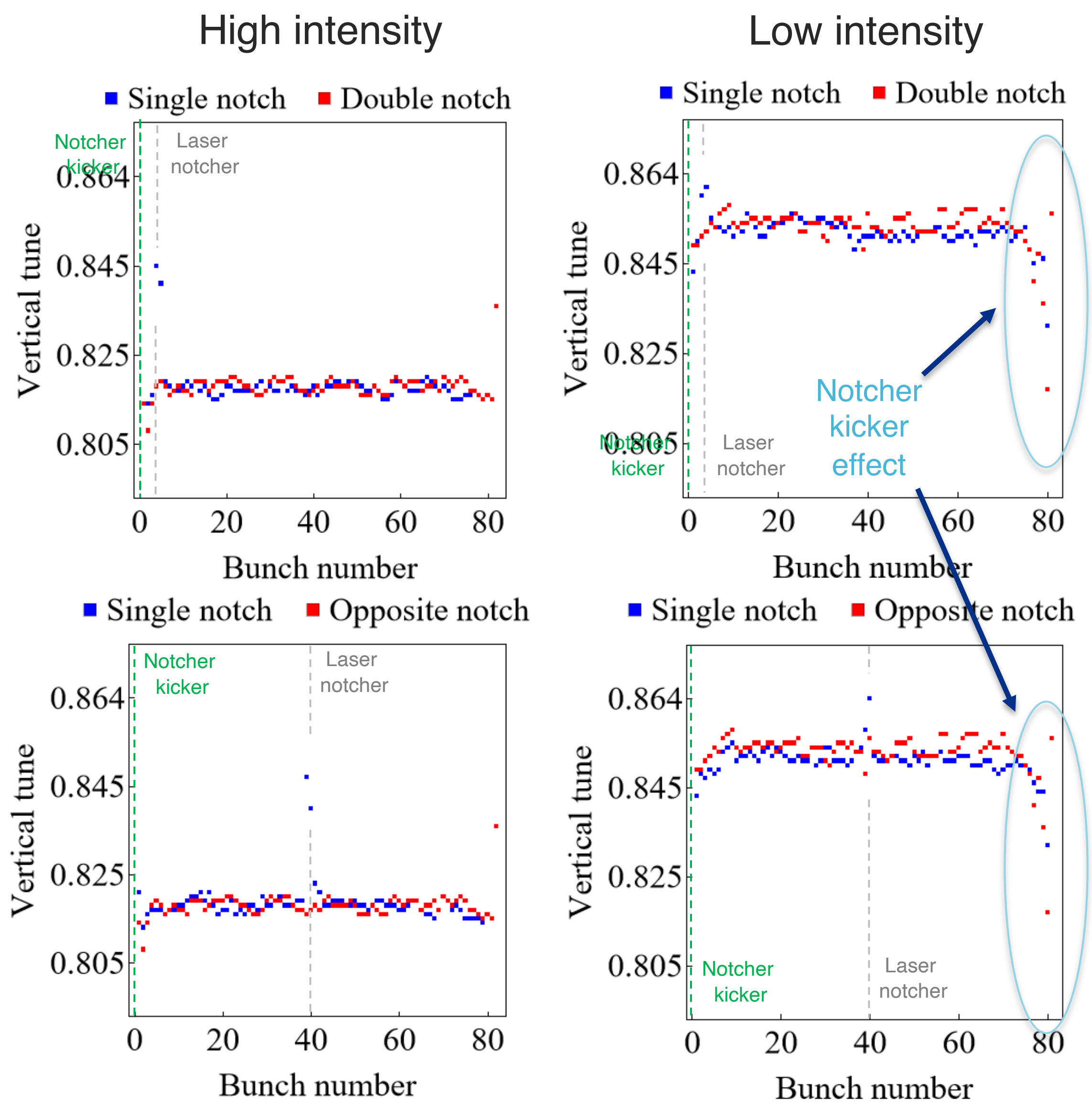


For single notch both notcher kicker and laser notcher are placed on top of each other

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



■ 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

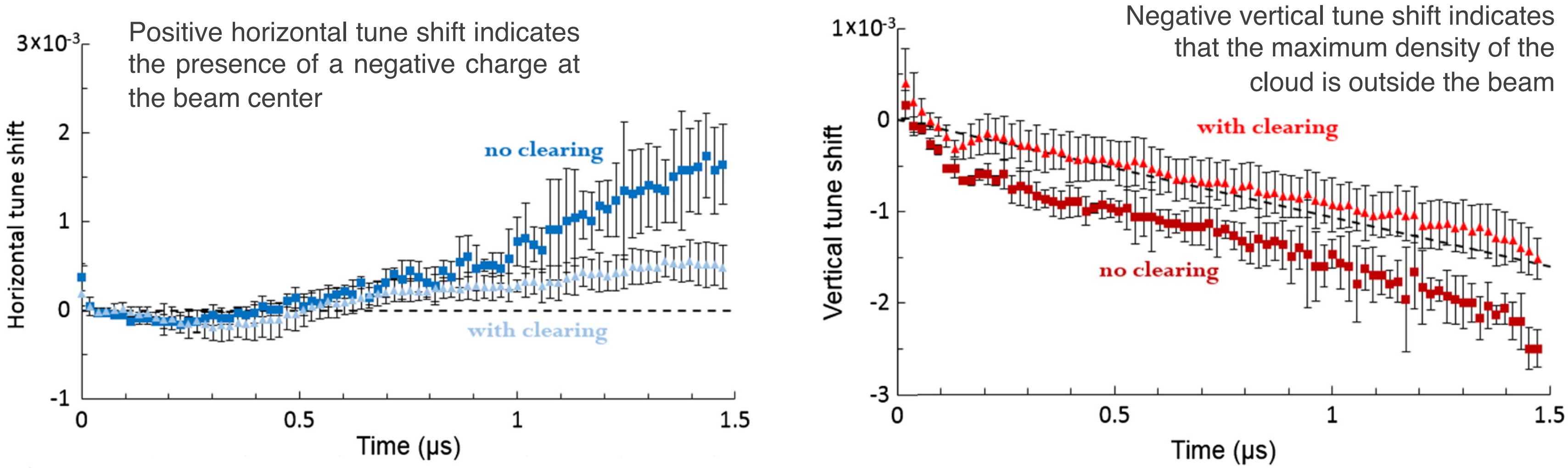


Fig. 7: Betatron tune shift within the 80-bunch train with respect to the first bunch, measured over 600 revolutions with a stripline detector in the Recycler.

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).

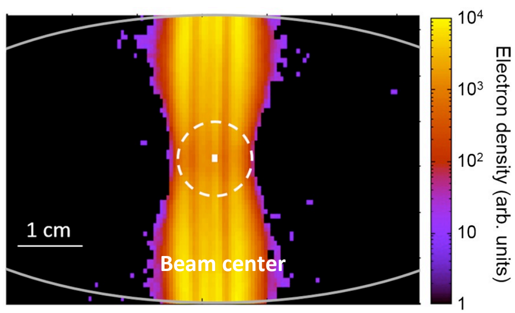


Fig. 8: Distribution of the cloud density from Antipov's paper

- 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

Tune comparison near transition

Horizontal data

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

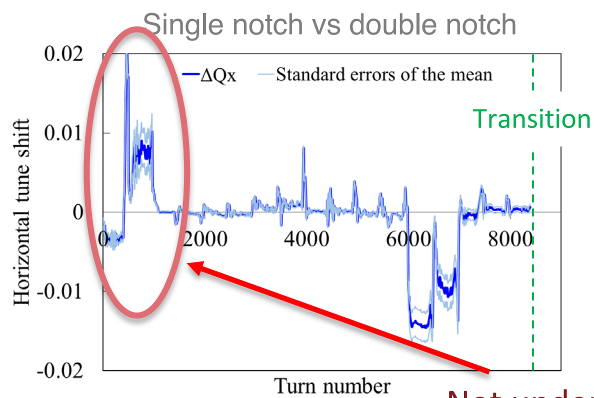
For single notch vs double notch: $\Delta Q_x = Mean(Q_x)_{\substack{double \\ notch}}$- $Mean(Q_x)_{\substack{sinlge \\ notch}}$

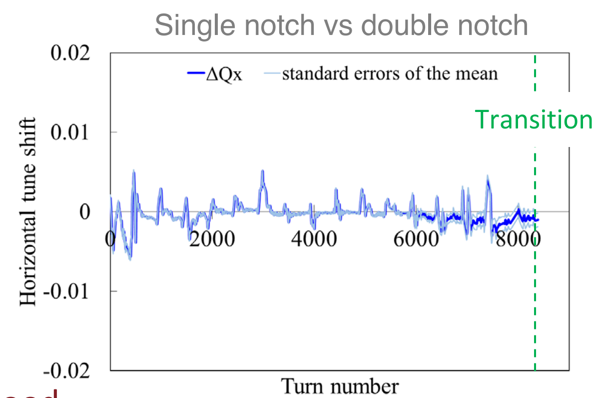
For single notch vs opposite notch: $\Delta Q_x = Mean(Q_x)_{\substack{opposite \\ notch}}$- $Mean(Q_x)_{\substack{sinlge \\ notch}}$

- 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

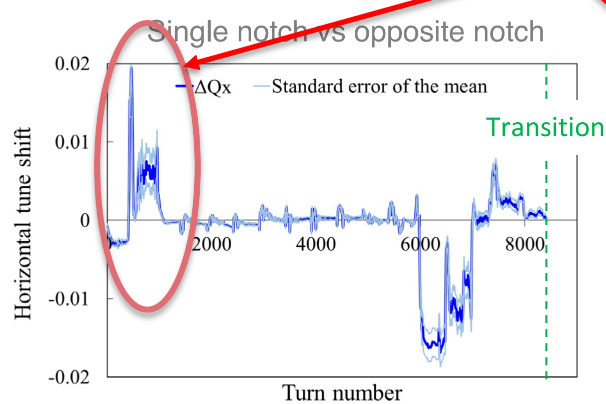
High intensity

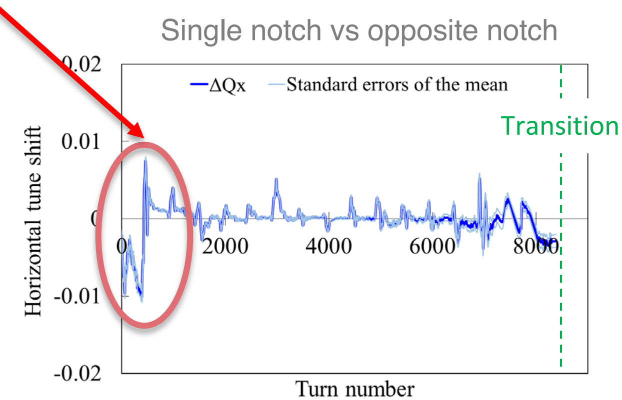
Low intensity





Not understood





Fermilab

Tune comparison near transition

Vertical data

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

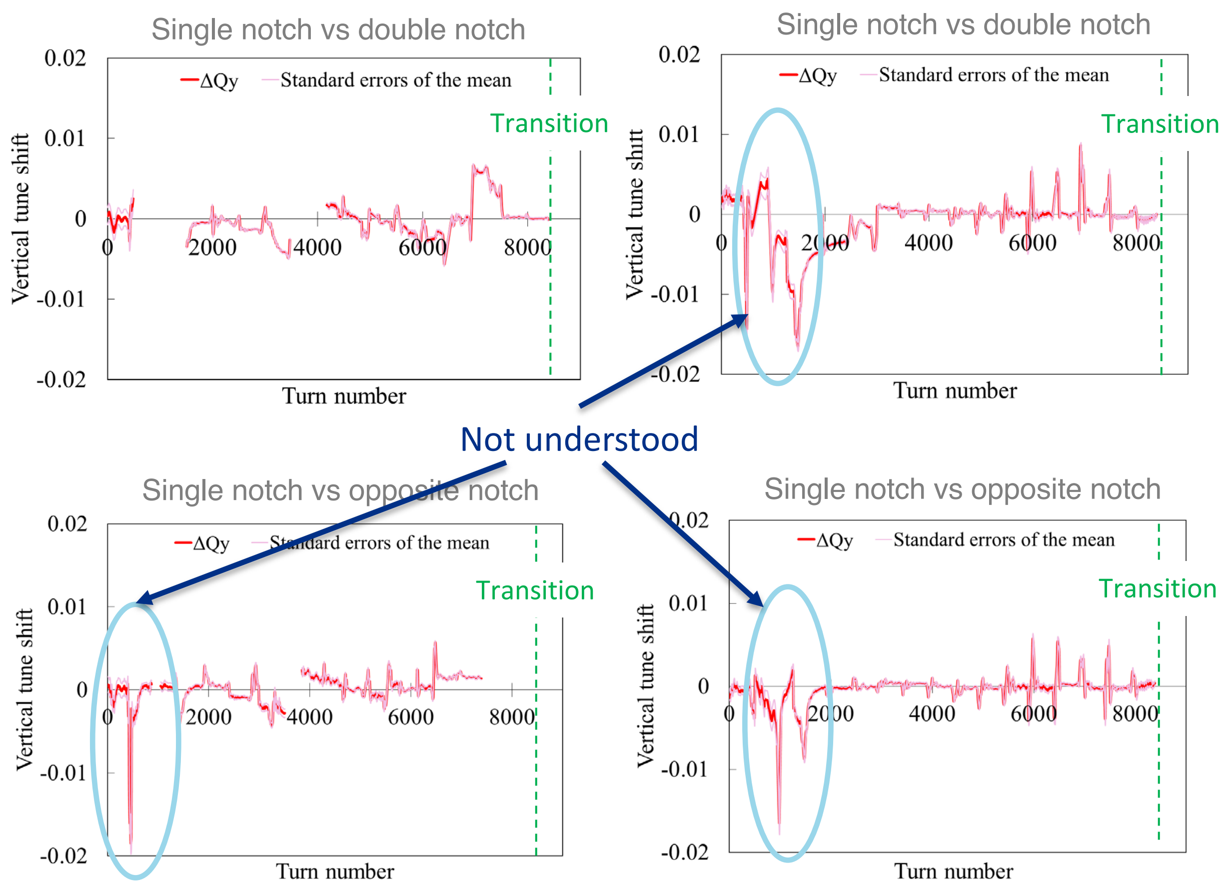
For single notch vs double notch: $\Delta Q_y = Mean(Q_y)_{\substack{double\\notch}}$- $Mean(Q_y)_{\substack{sinlge\\notch}}$

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

- 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

High intensity

Low intensity

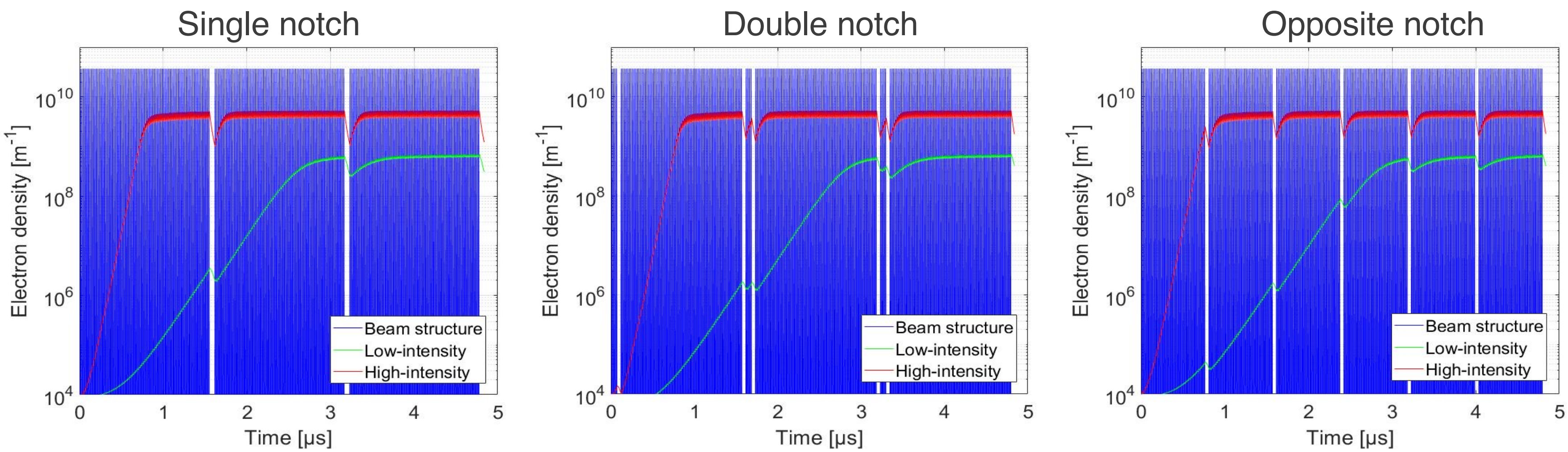


PyECLOUD simulations

G. Iadarola, PyECLOUD Version 8.6.0, CERN, 2021

- 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 diploe 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, σ [m]	0.253
SEY, δ	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 despite 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) and likely due to the notcher kicker. The vertical data also 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 the 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 era Booster

Acknowledgment

I would like to thank:

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- R. Ainsworth and A. Schreckenberger

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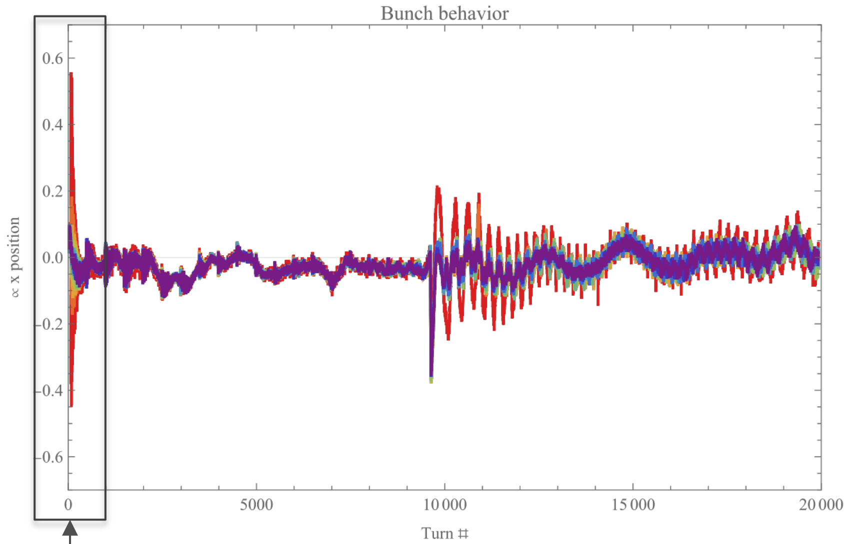
Thank you!

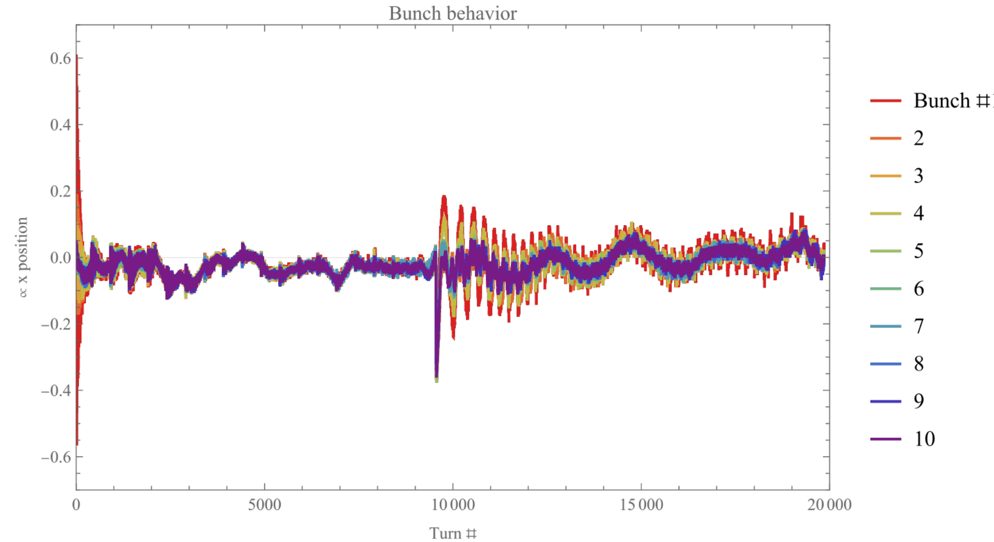
Backup

Bunch behavior

Single notch

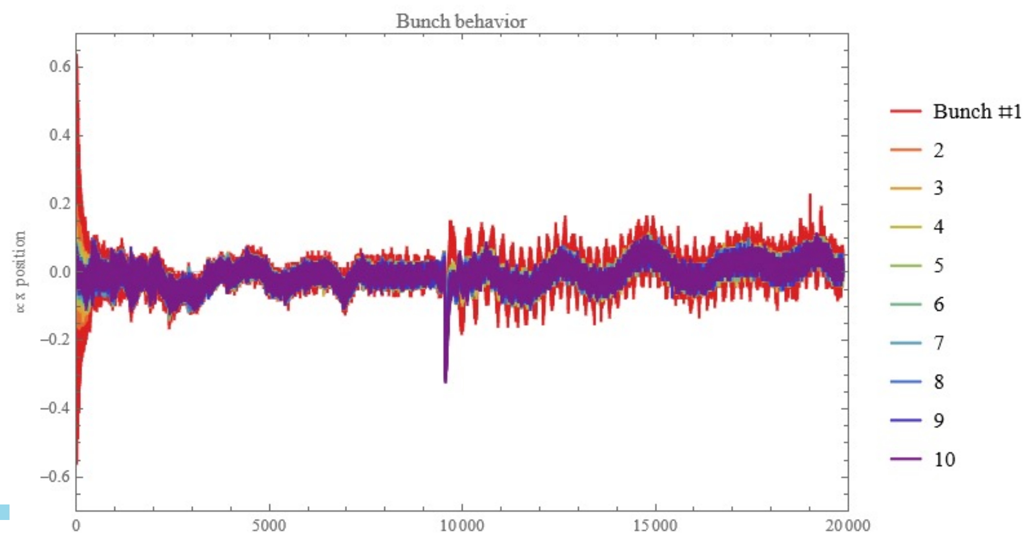


Double notch



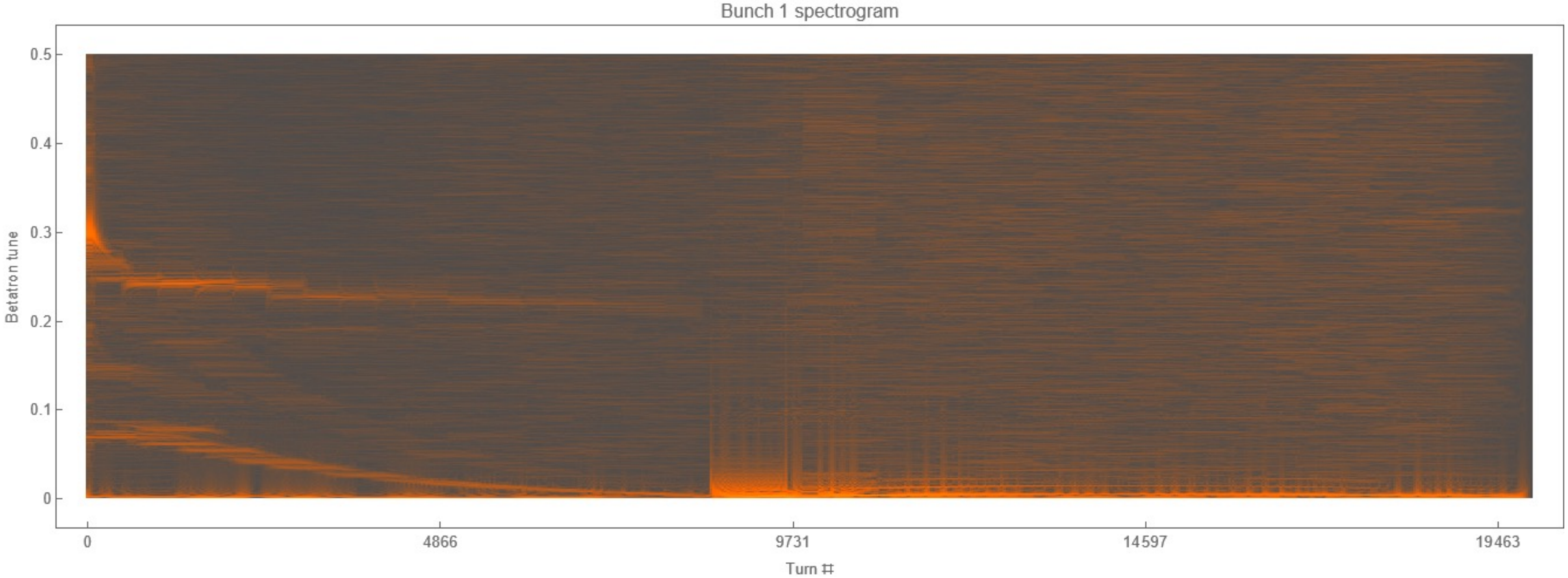
Large excursion on bunch #1
Notcher kicker effect
Large orbit distortion

Opposite notch

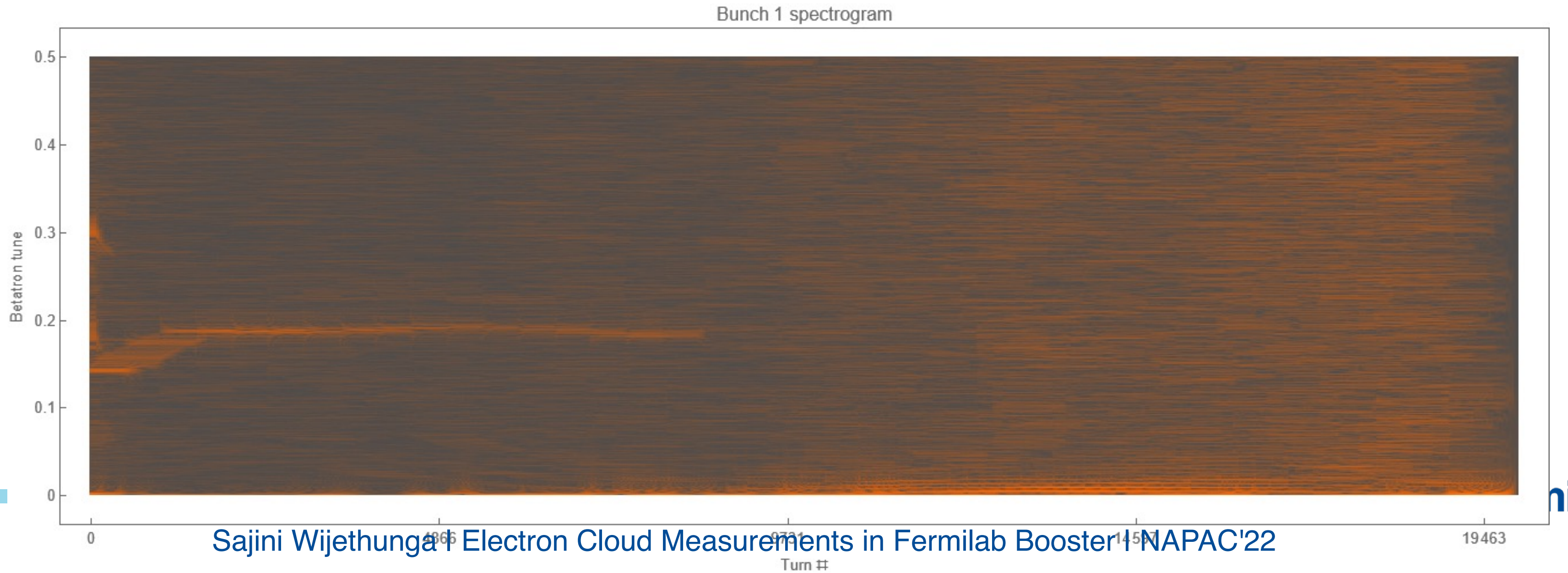


Fermilab

High intensity(15 turns) single (+0) horizontal ping

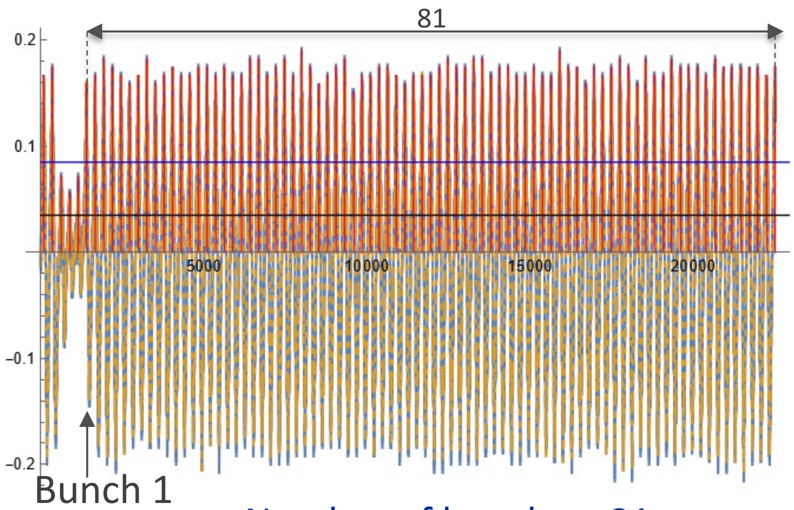


High intensity(15 turns) single (+0) vertical ping



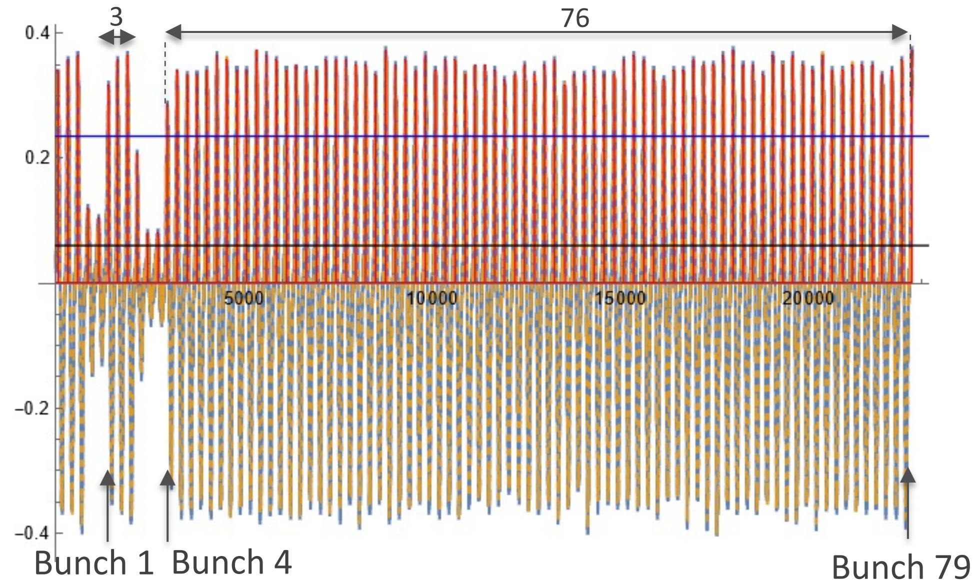
High intensity, horizontal ping

Single notch



Number of bunches: 81

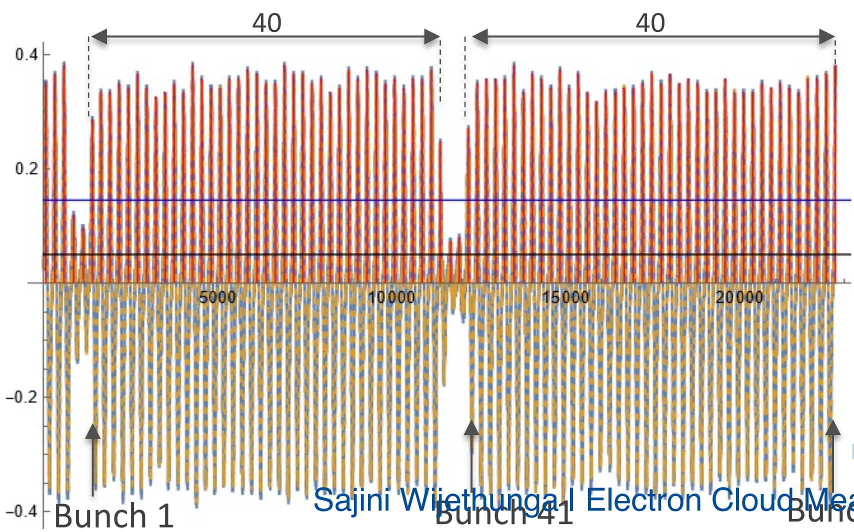
Double notch



Number of bunches: 79

Notcher kicker started at turn 58

Opposite notch



Number of bunches: 80

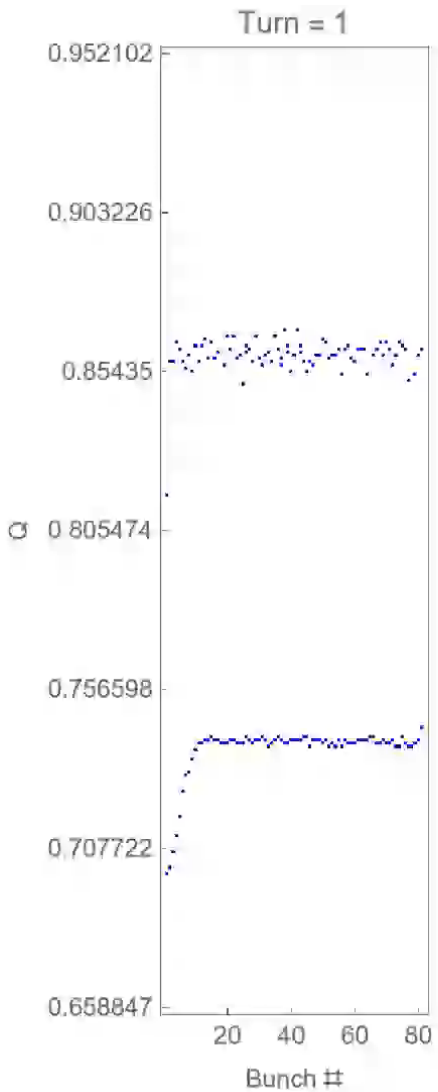
Notcher kicker started at turn 75

Each data set was aligned per turn with the above scheme

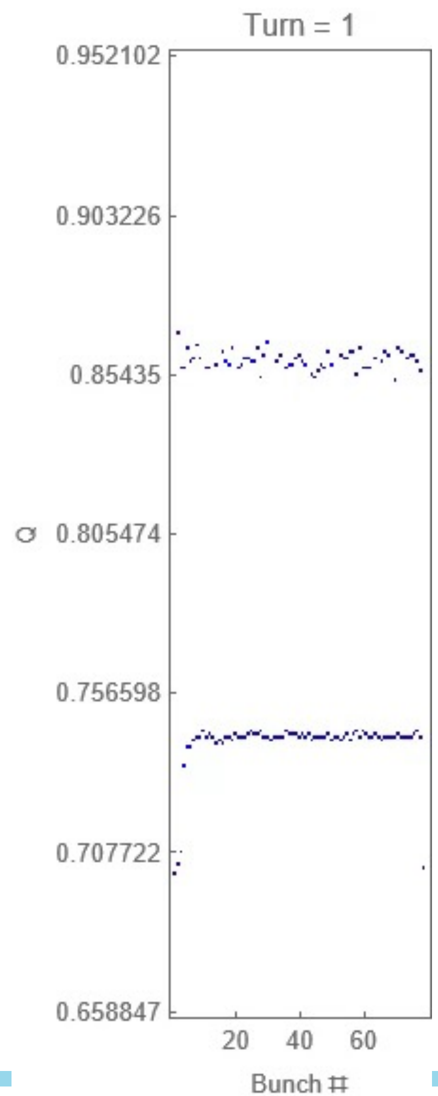
Horizontal data

High intensity (15 turns)

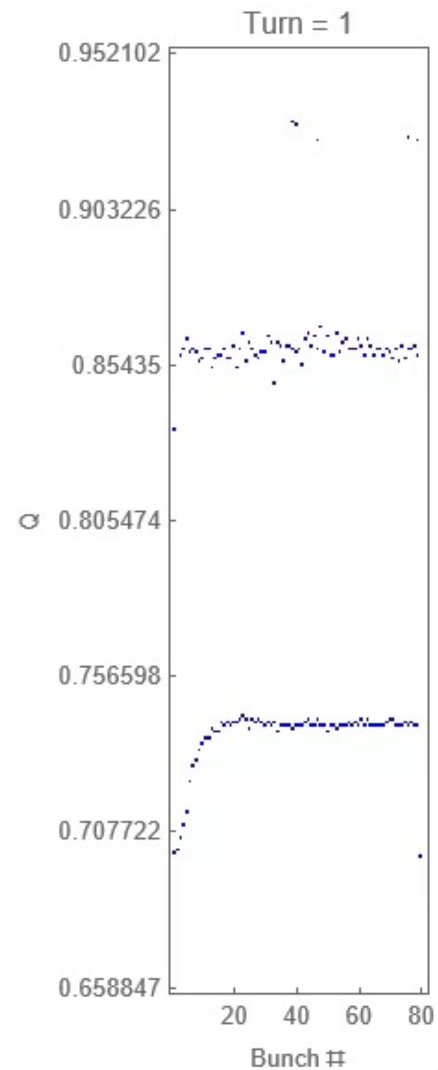
+0 notch



+6 double notch



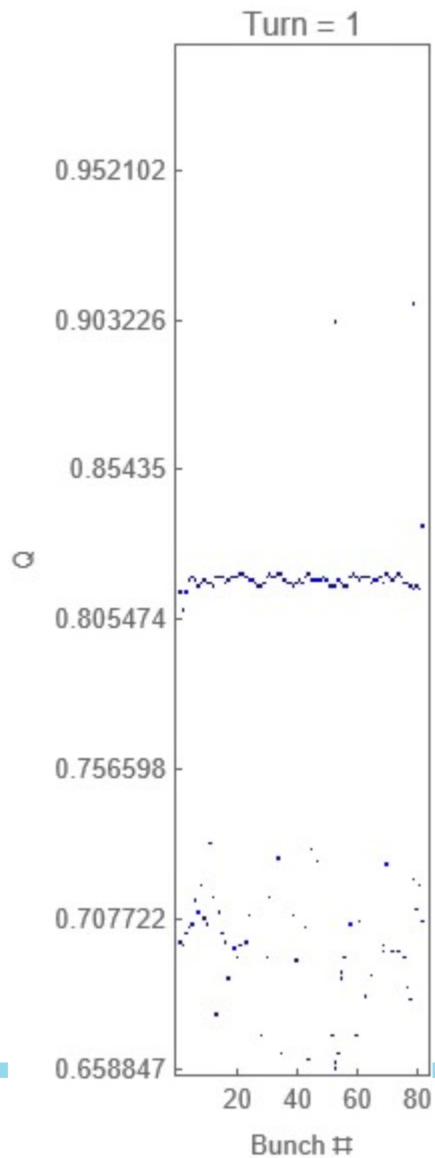
+42 opposite notch



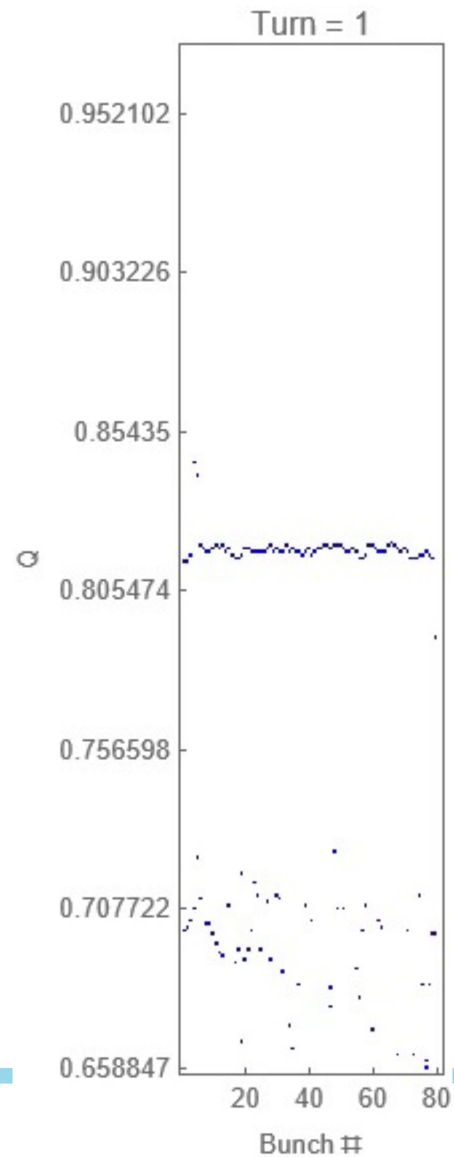
Vertical data

High intensity (6 turns)

+0 notch



+6 double notch



+42 opposite notch