Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

# Stripline Data on Naturally-Ocurring Instabilities in the Recycler Ring

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MI Department Meeting

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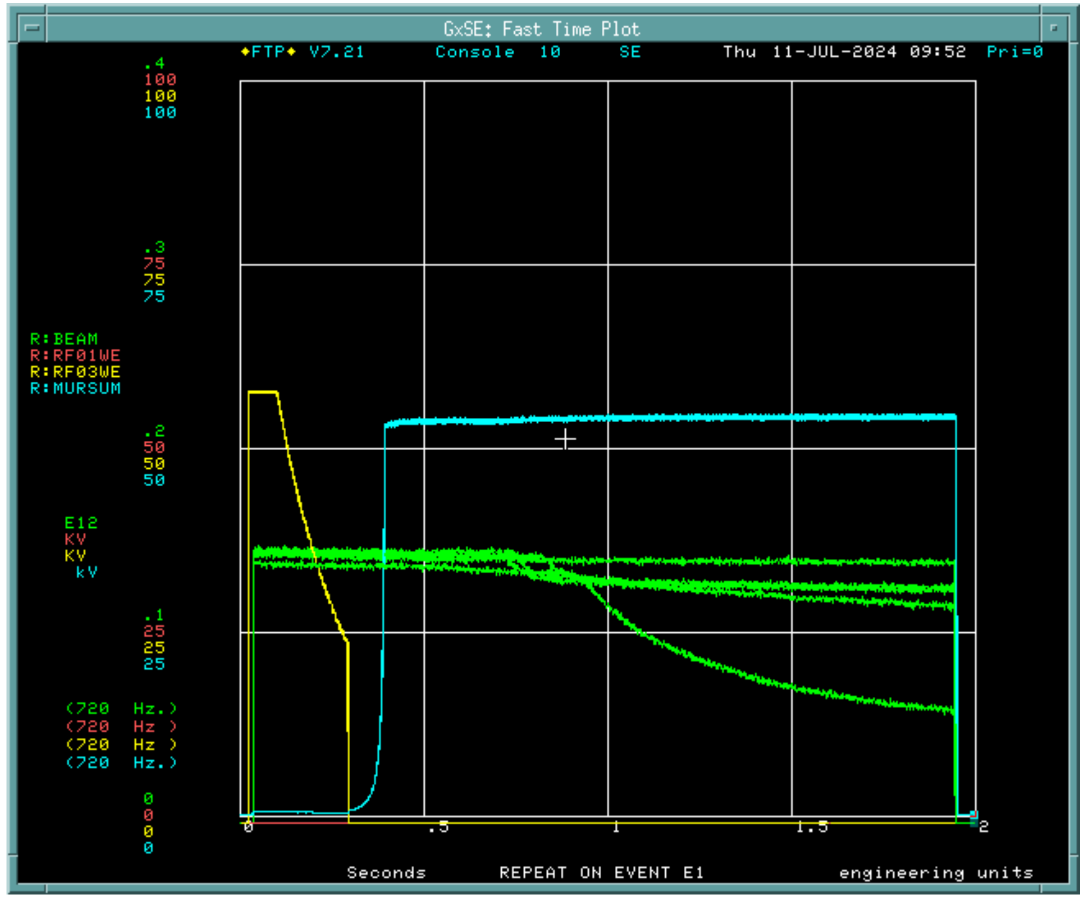
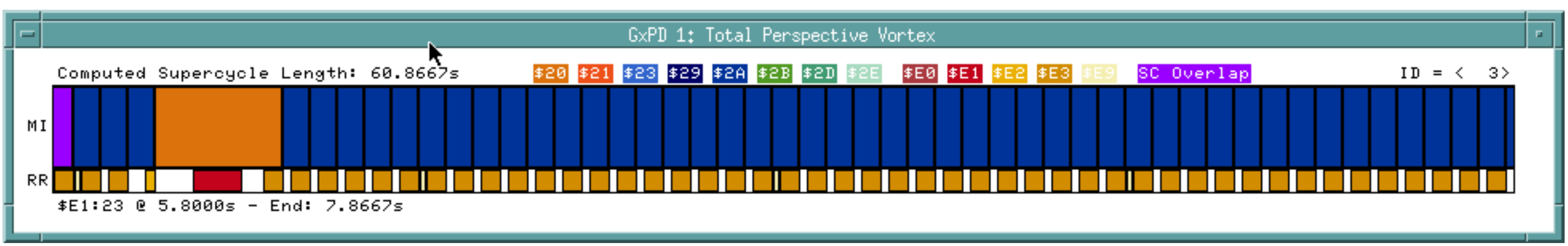
# Studies on $E1

Special beam for studies:

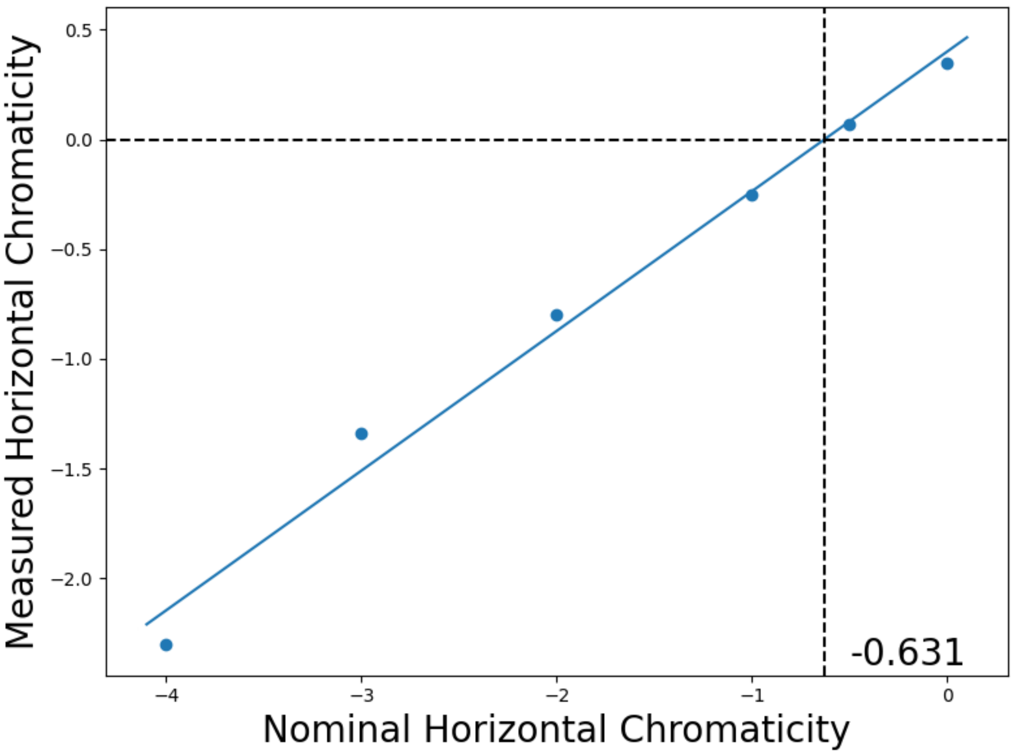
- Utilize $E1 event under the $20 to perform experiments parasitically
- Rebunch beam from 53 MHz to 2.5 MHz and get longer bunches
- Kick all but one of the longer bunches out of the Recycler Ring
- Goal is to study collective instabilities in the Recycler
- Transverse dampers were ON at some gain and phase

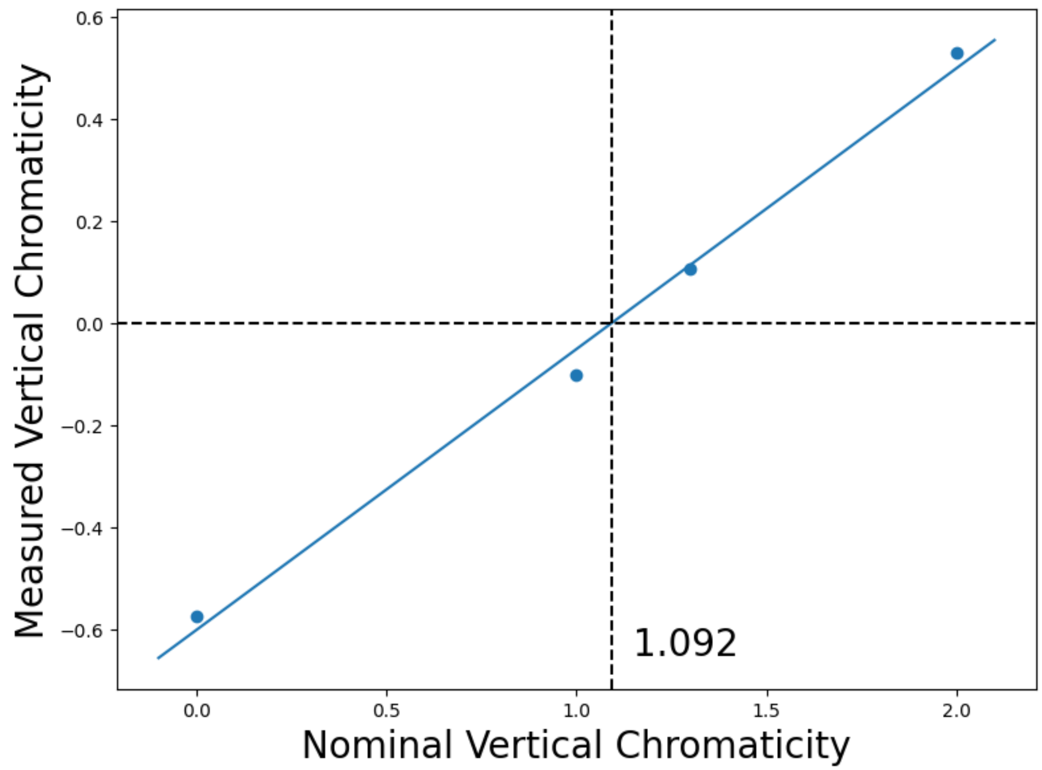


# Studies on $E1

Zero chromaticity setting is set into R2[$E1] around 0.58 seconds into the cycle

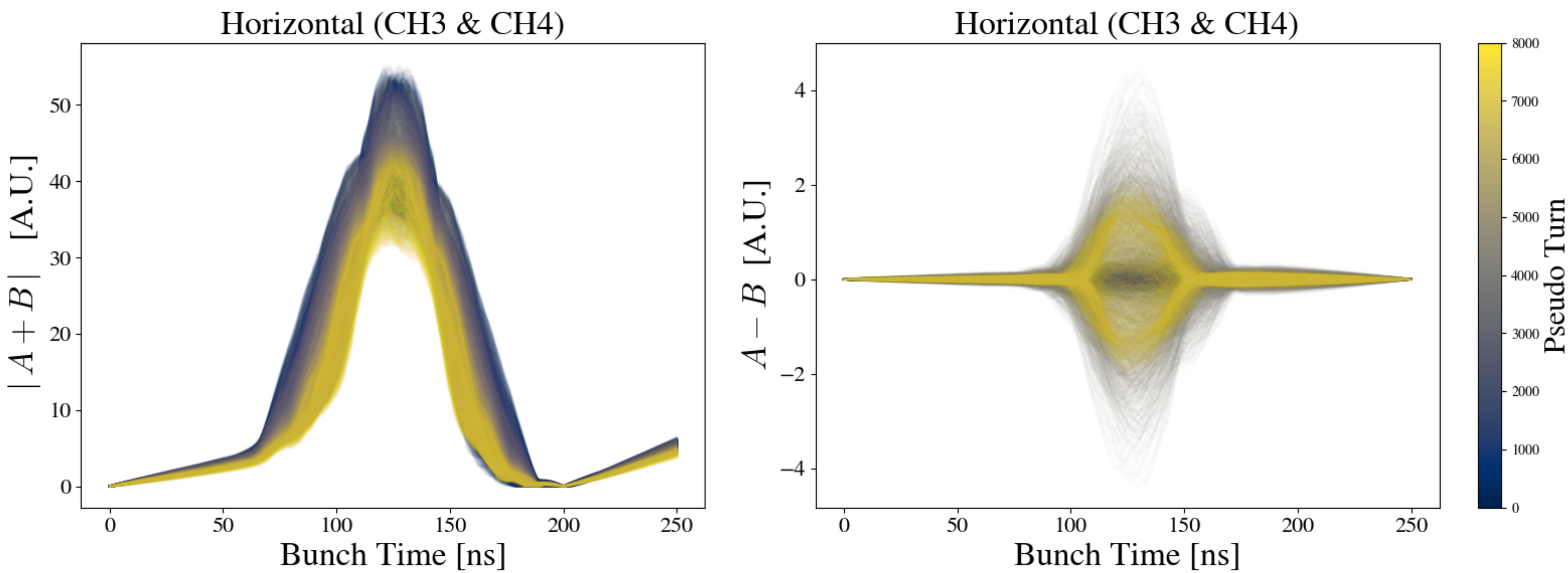


# Stripline data on RS Scope

We can grab $A + B$ (related to bunch profile) and $A - B$ (related to the dipole moment). Signal $\frac{A - B}{A + B}$ will be related to the transverse displacement along bunch.

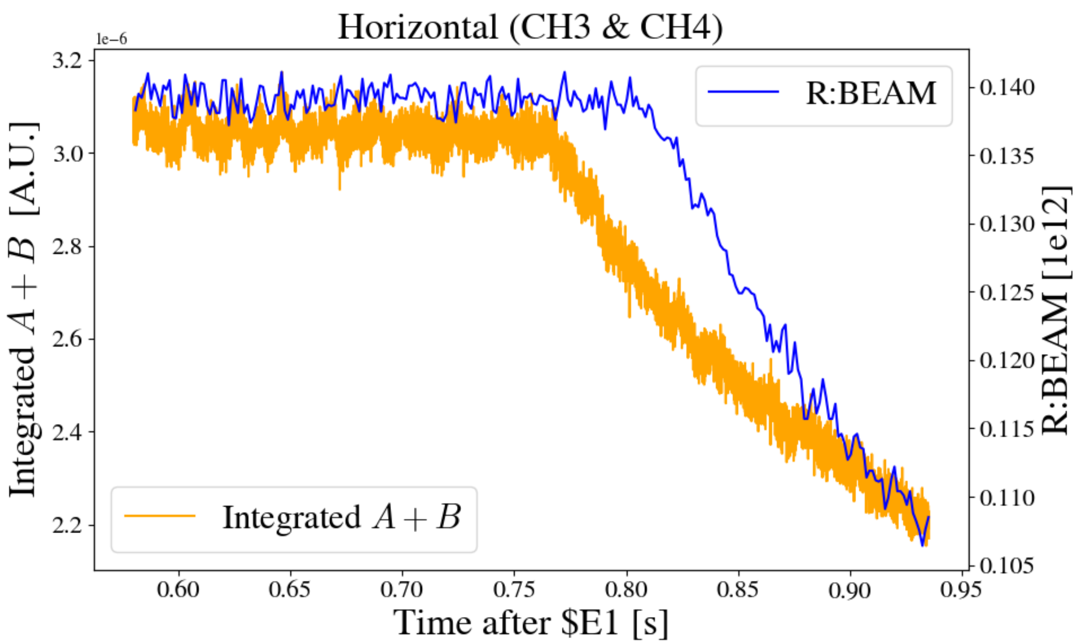
- Triggered the scope with the new trigger box every 4 turns at 0.58 seconds into the $E1 recording for 8000 triggers/pseudoturns (32000 turns ~ 0.355 seconds)

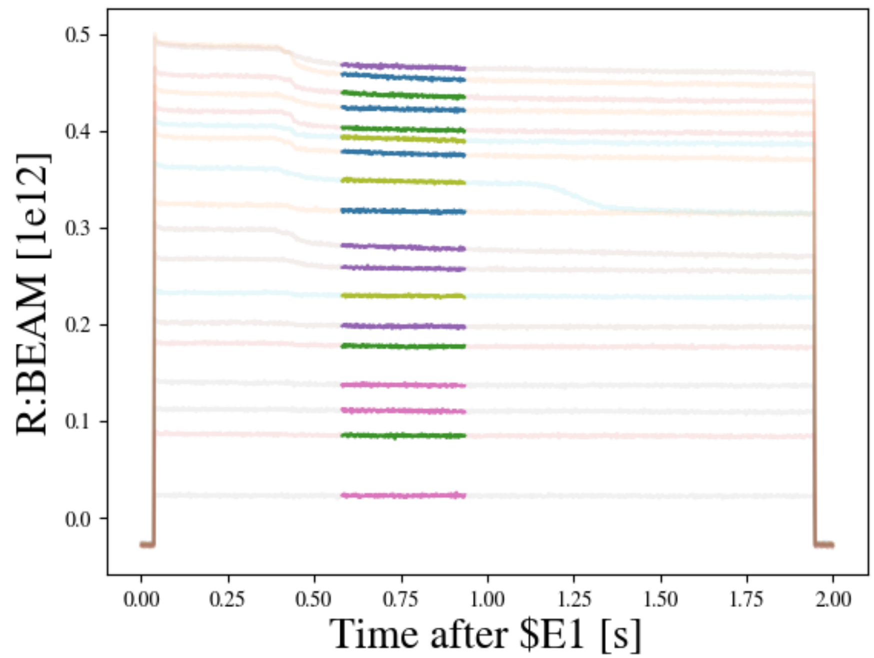


# Calibrating A+B Signal

The $A + B$ signal (related to bunch profile) can be integrated to get $\int \lambda(z)dz$.

- R:BEAM (coming from a DCCT) sampled at the same time as RS scope data can be used to calibrate this integrated signal.
- Did not set the zero-chromaticity settings for this experiment

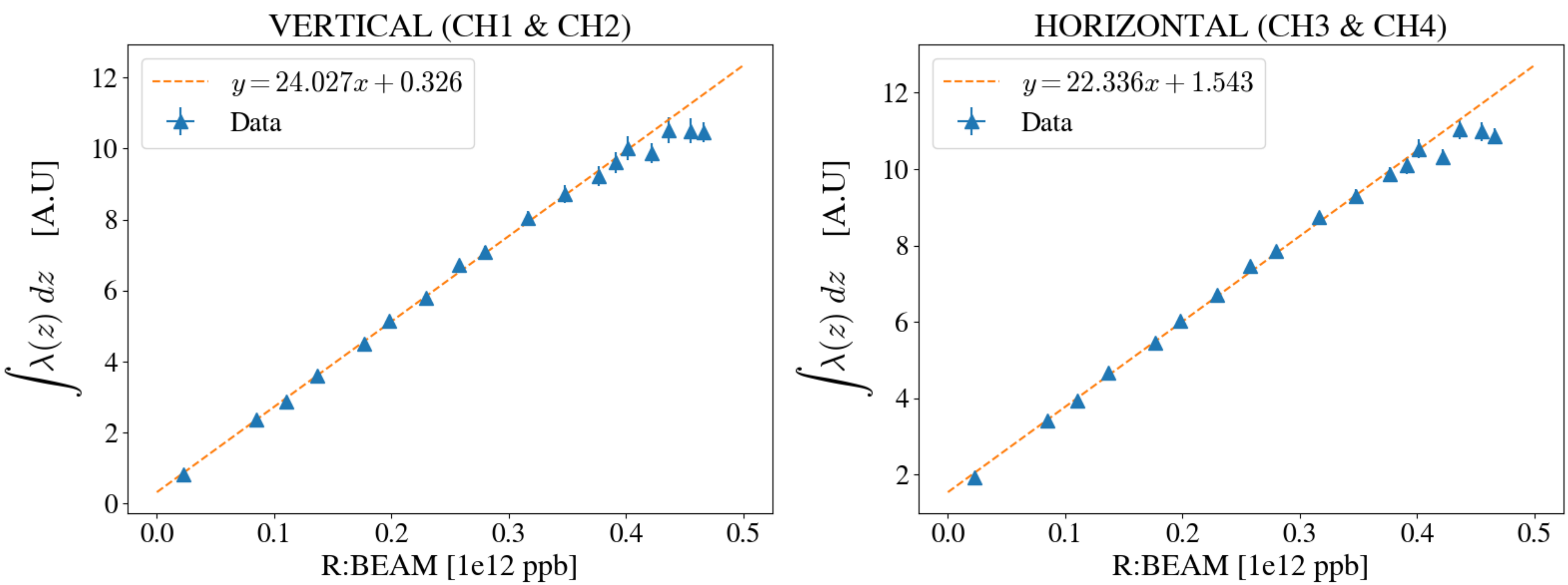


# Calibrating A+B Signal

As a sanity check, integrated $A + B$ should follow R:BEAM

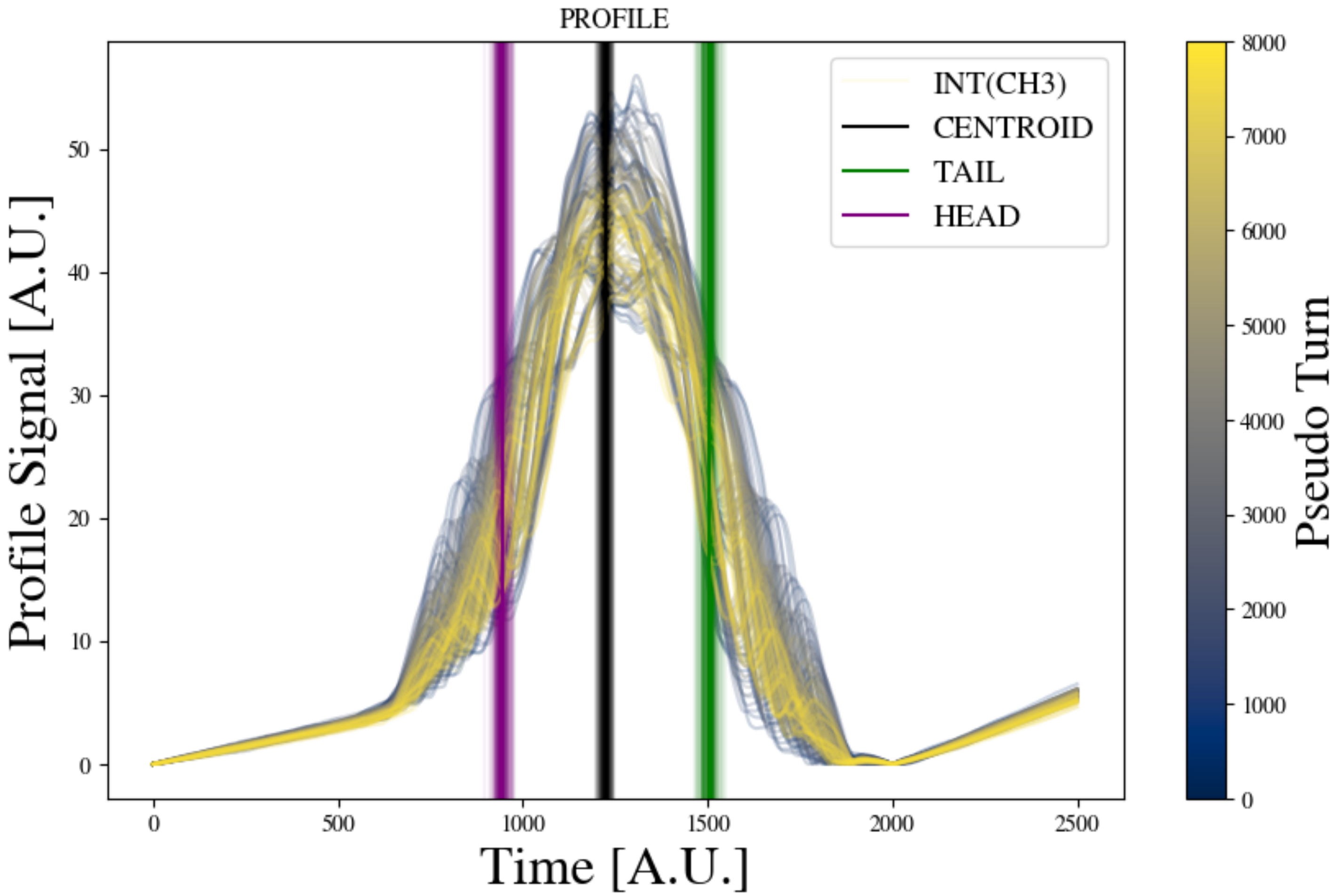
- Vertical stripline was connected to CH1 and CH2
- Horizontal stripline was connected to CH3 and CH4



# A+B Signal (Head and Tail Definitions)

Head and Tail of the beam can be defined with $A + B$ signal

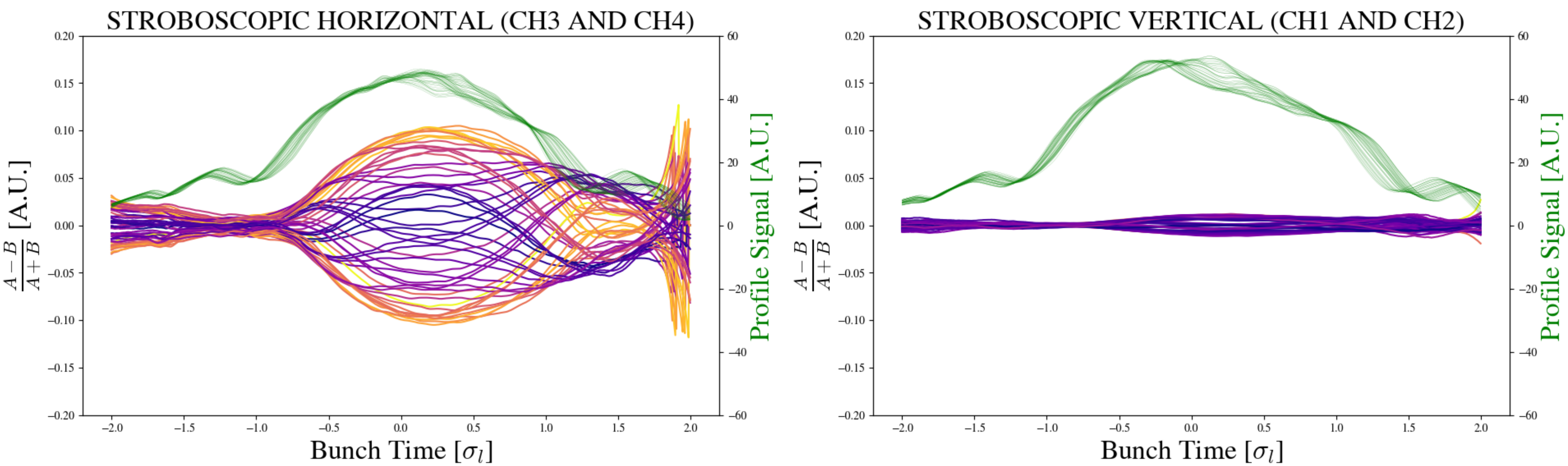
- Head is $-1\sigma$ of bunch profile sigma centered at the bunch centroid
- Tail is $+1\sigma$ of bunch profile sigma centered at the bunch centroid



# Calibrate (A-B)/(A+B) Signal (Pending)

To calibrate $\frac{A-B}{A+B}$ (transverse displacement), we would need a known transverse displacement maybe through a 3-bump and BPM reading close to stripline

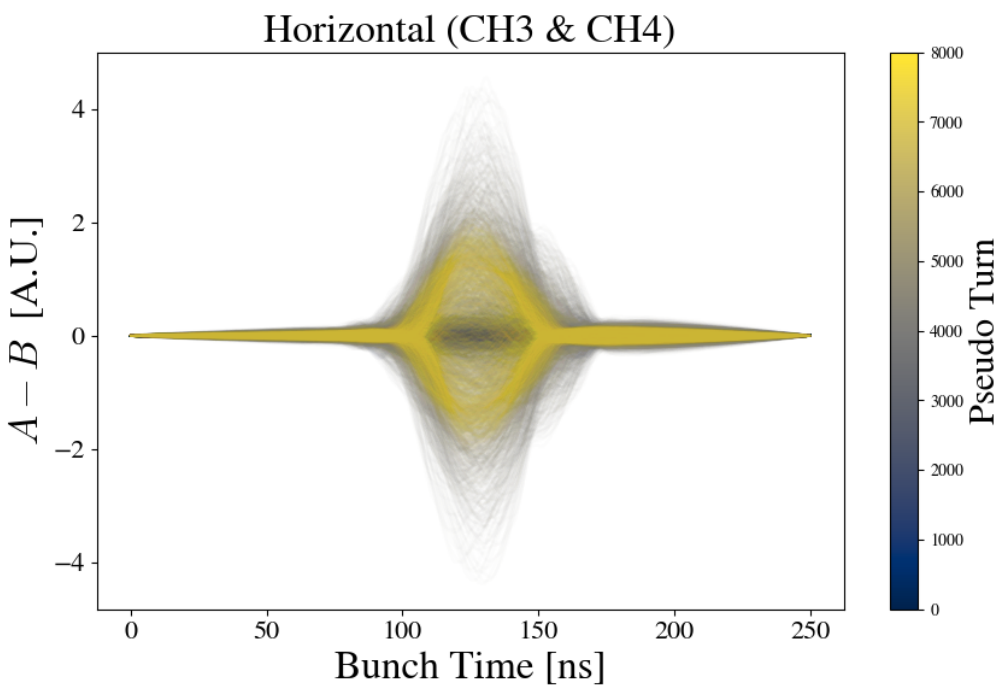
- We don't know the order of magnitude of these oscillations
- Stroboscopic data can be taken around maximum tail excursions (more on this later)
- Head and tail are defined to be -1$\sigma$ and +1$\sigma$ from bunch profile

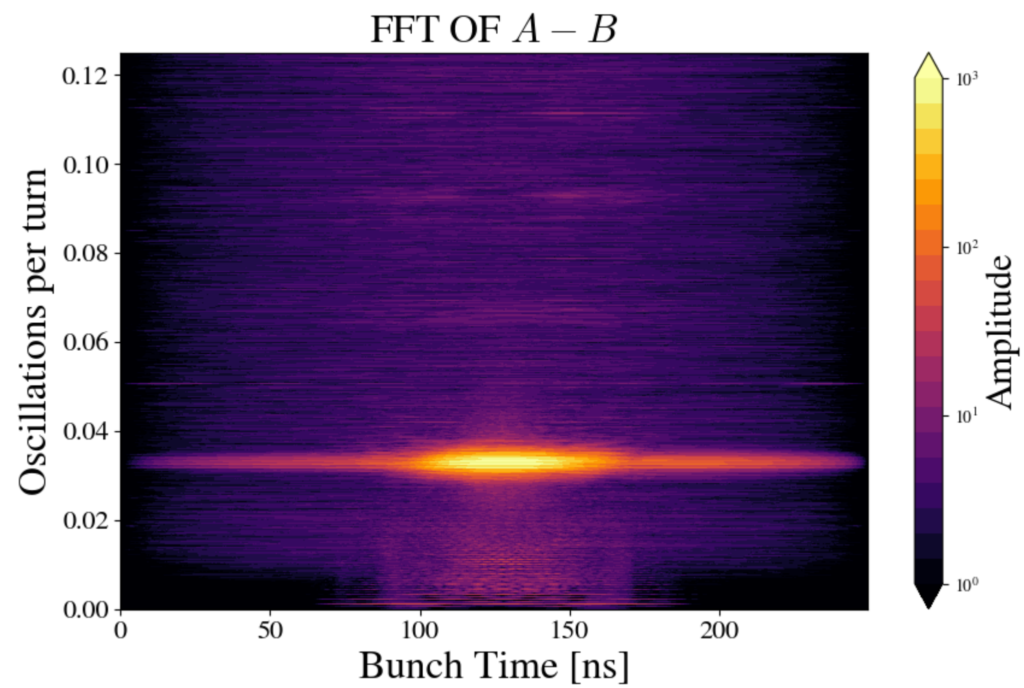


# FFT of A-B

FFT-ing $A - B$ should give us the oscillation of the collective motion

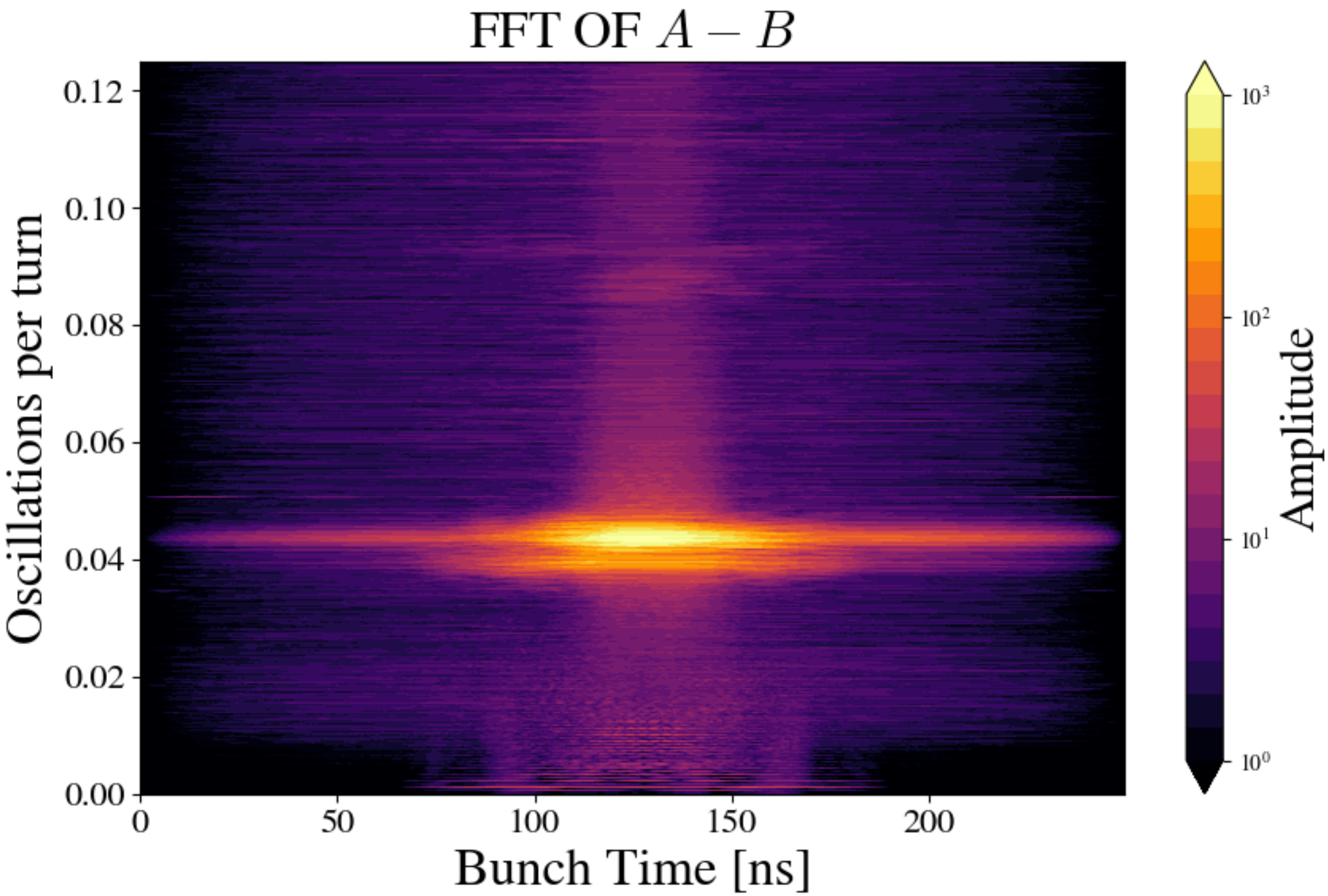
- Each bin in oscilloscope can be FFT-ed against pseudoturns.
- Given that we're sampling every 4 turns the tune range goes up to 0.125.
- Larger frequencies will be reflected on the FFT range (Aliasing correction)



# FFT of A-B (Qualitative observation other harmonics)

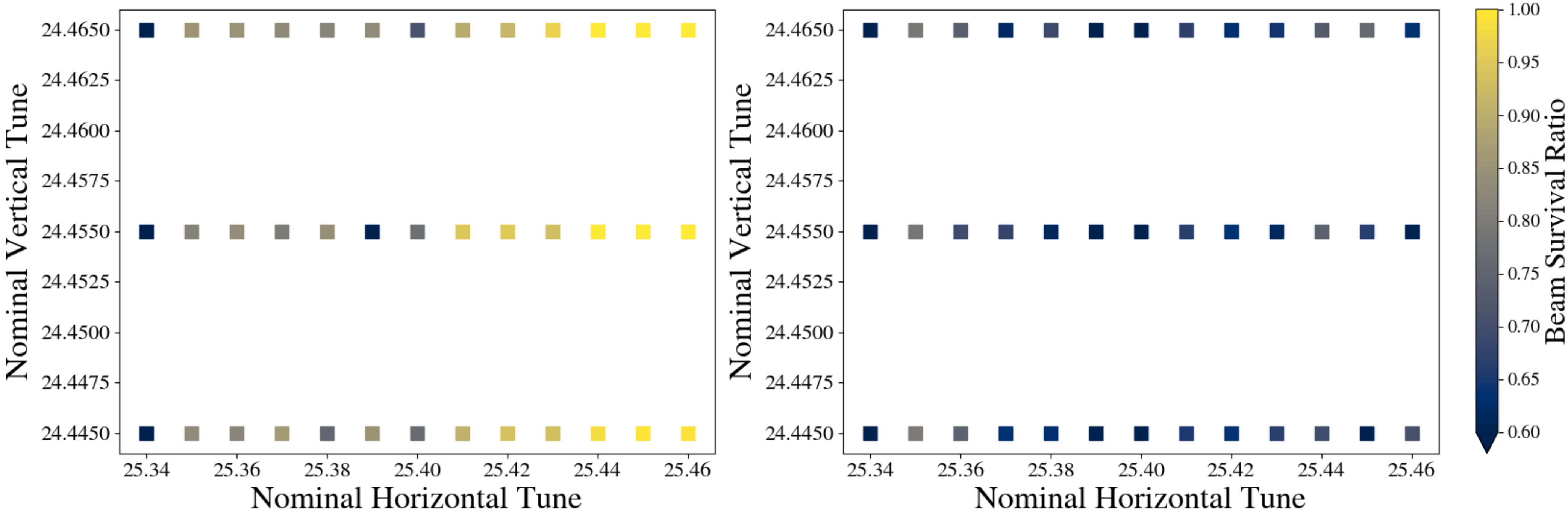
Work is ongoing to analyze different harmonics in $A - B$. For now, I've only looked at the main one (harmonic with largest amplitude).



## Static Tune Scan

Vary the nominal horizontal and vertical tune, while recording stripline data and R:BEAM data, in order to calculate beam survival ratio.

- Two initial intensities: 1.5e11 particles per bunch and 2.7 ppb
- Transverse dampers were ON for these experiments



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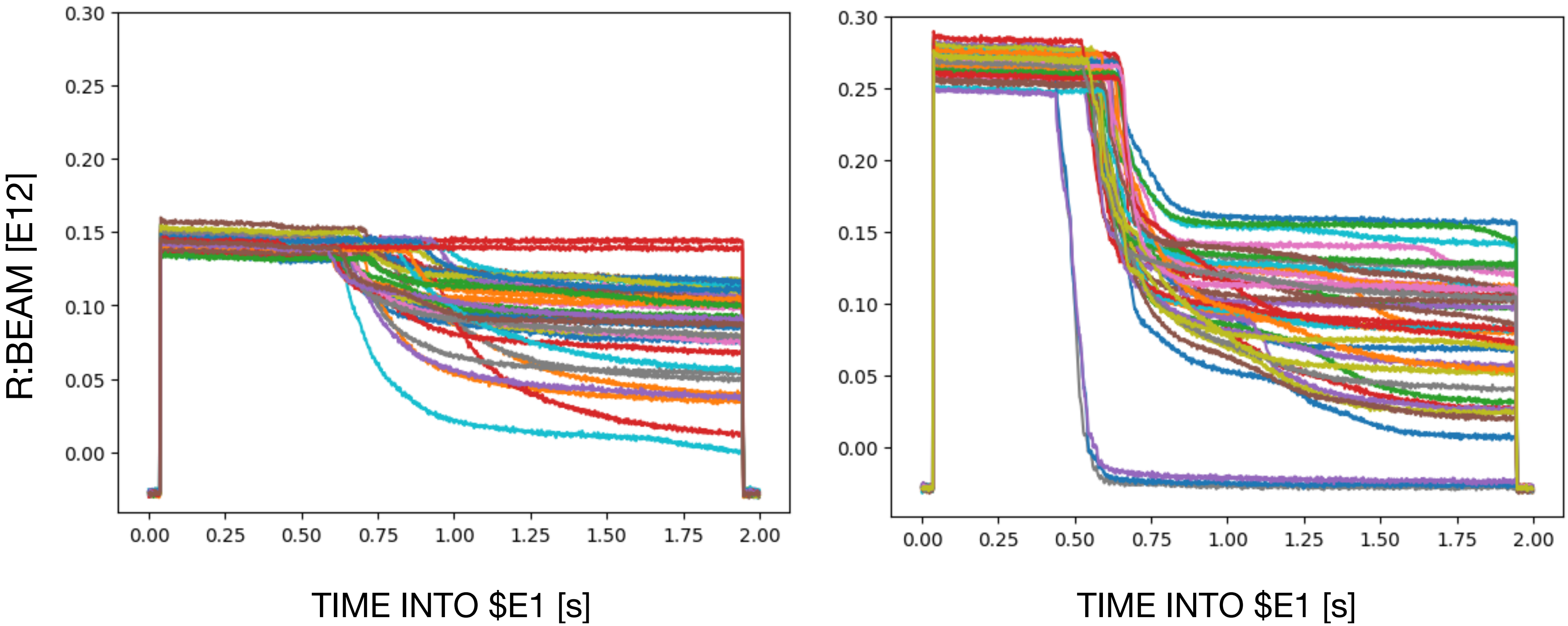


# Static Tune Scan (Important Parameters)

| Parameter | Notation | Value | Unit |
|---|---|---|---|
| Circumference | $C$ | 3319 | m |
| Momentum | $p$ | 8.835 | GeV/c |
| RF Frequency | $f_{rf}$ | 2.5 | MHz |
| RF Voltage | $V_{rf}$ | 60 | kV |
| Revolution Frequency | $f_0$ | 89.9 | kHz |
| Harmonic Number | $h$ | 588 | |
| Synchrotron Tune | $Q_s$ | 0.0005 | |
| Slip Factor | $\eta$ | $-8.6 \times 10^{-3}$ | |
| Horizontal Chromaticity | $C_x$ | 0 | |
| Vertical Chromaticity | $C_y$ | 0 | |
| 95% Normalized Emittance | $\varepsilon_{n,95\%}$ | 15 | $\pi$ mm mrad |
| Bunch Length | $2\sigma_l$ | 15 | m |

Space charge parameter

$$q = \frac{\Delta Q_{sc}}{Q_s}$$

Wake parameter

$$w = \frac{N_p r_0 R_0 W_0}{4\pi\gamma\beta^2 Q_\beta Q_s}$$

Burov, A. (2019). Convective instabilities of bunched beams with space charge. Phys. Rev. Accel. Beams, 22, 034202.

# Static Tune Scan (Important Parameters)

The Recycler can be assumed as one big broadband resonator

Space charge parameter

$$q = -\frac{\Delta Q_{sc}}{Q_s}$$

$$N_p = 1.5 \times 10^{11}\ ppb \longrightarrow q \approx 10$$

$$N_p = 2.7 \times 10^{11}\ ppb \longrightarrow q \approx 15$$

Wake parameter
(Assuming broadband resonator wake function)

$$w = \frac{N_p r_0 R_0 W_0}{4\pi\gamma\beta^2 Q_\beta Q_s}$$

$$N_p = 1.5 \times 10^{11}\ ppb \longrightarrow w \approx 30$$

$$N_p = 2.7 \times 10^{11}\ ppb \longrightarrow w \approx 60$$

$$W_0 = \frac{R_s k_r^2 c}{\bar{k} Q_r}$$

$$R_s \approx 1\ M\Omega/m$$

$$k_r = \frac{\omega_r}{c} \approx 10\ m^{-1}$$

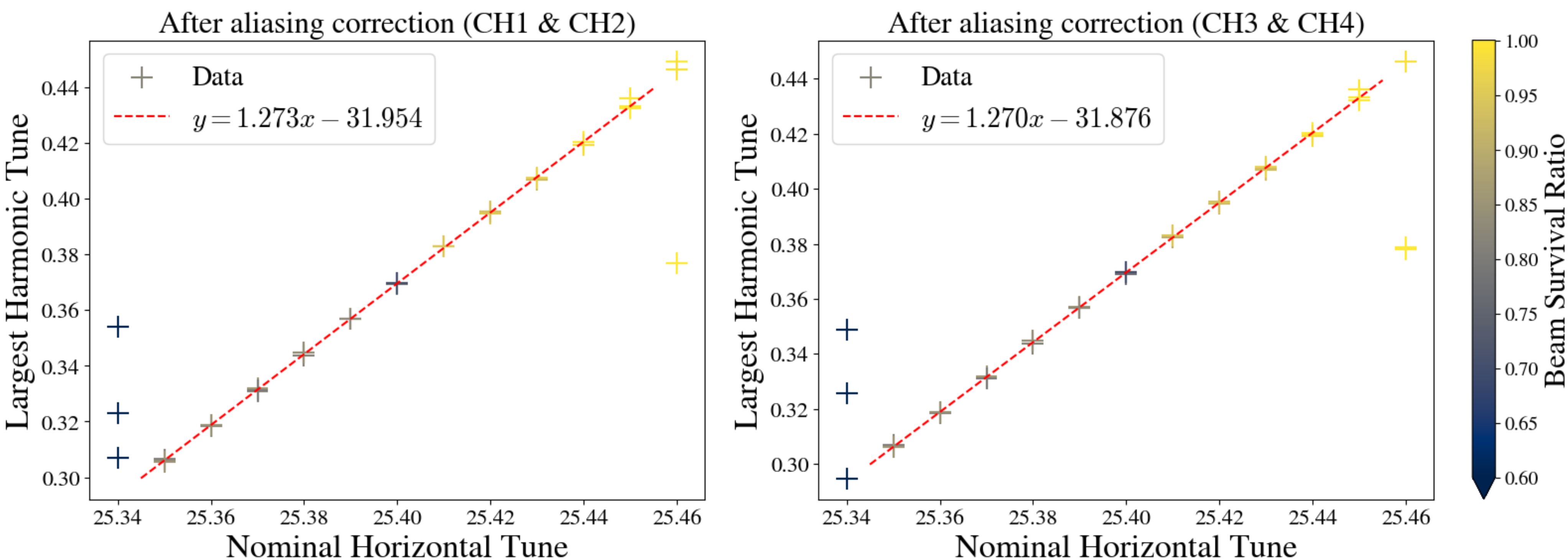
$$Q_r \approx 1$$


- Burov, A. (2019). Convective instabilities of bunched beams with space charge. Phys. Rev. Accel. Beams, 22, 034202.
- Ainsworth, R., Adamson, P., Burov, A., Kourbanis, I., & Yang, M.J. (2016). Estimating the Transverse Impedance in the Fermilab Recycler. In 7th International Particle Accelerator Conference (pp. MOPOY011).
- Burov, Alexey, and Zolkin, Timofey. TMCI with Resonator Wakes. United States: N. p., 2018. Web. doi:10.2172/1480111.
- S.Y. Zhang. CALCULATION OF INCOHERENT SPACE CHARGE TUNE SPREAD. tech. rep. Brookhaven National Laboratory, 1996. url: https://technotes.bnl.gov/PDF? publicationId=30778.

# Static Tune Scan

We varied the nominal horizontal tune and looked at the frequency of the largest harmonic in the FFT data

- Had to correct for aliasing given that we were triggering every 4 turns
- Largest harmonic follows the horizontal tune (frequency of collective instability?)




$N_p = 1.5 \times 10^{11}\ ppb \quad \longrightarrow \quad q \approx 10$

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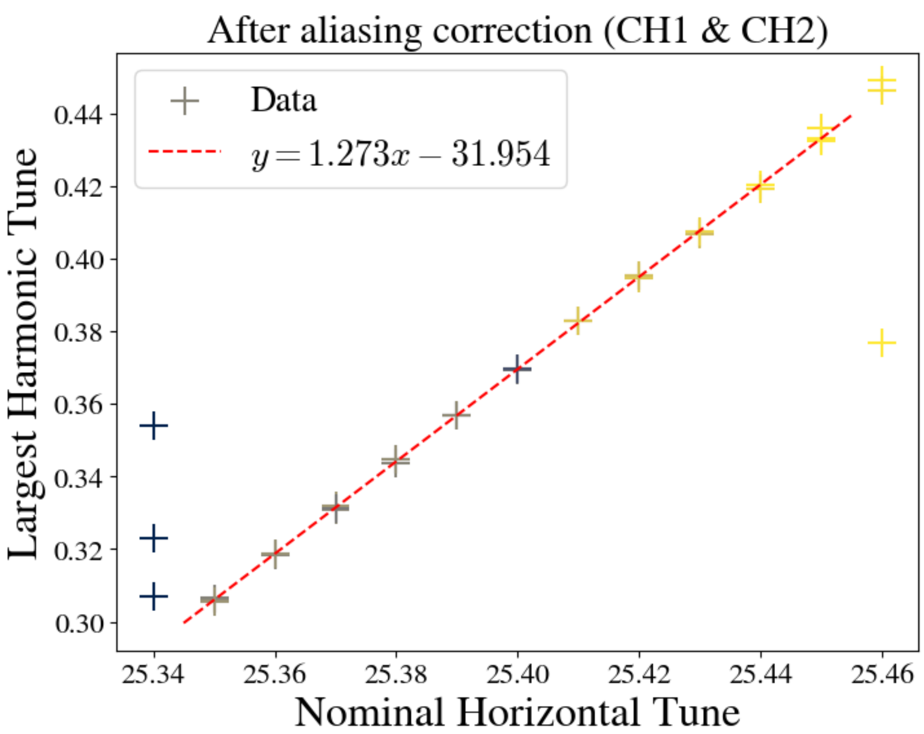
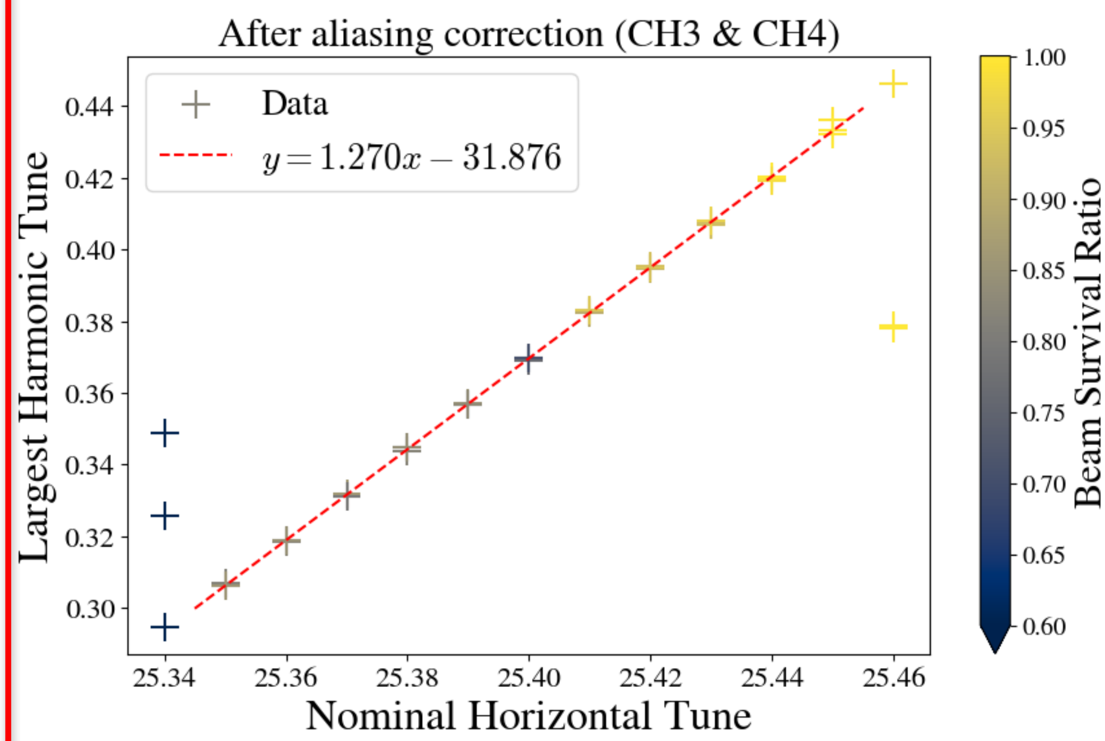



$N_p = 1.5 \times 10^{11}\ ppb \longrightarrow q \approx 10$

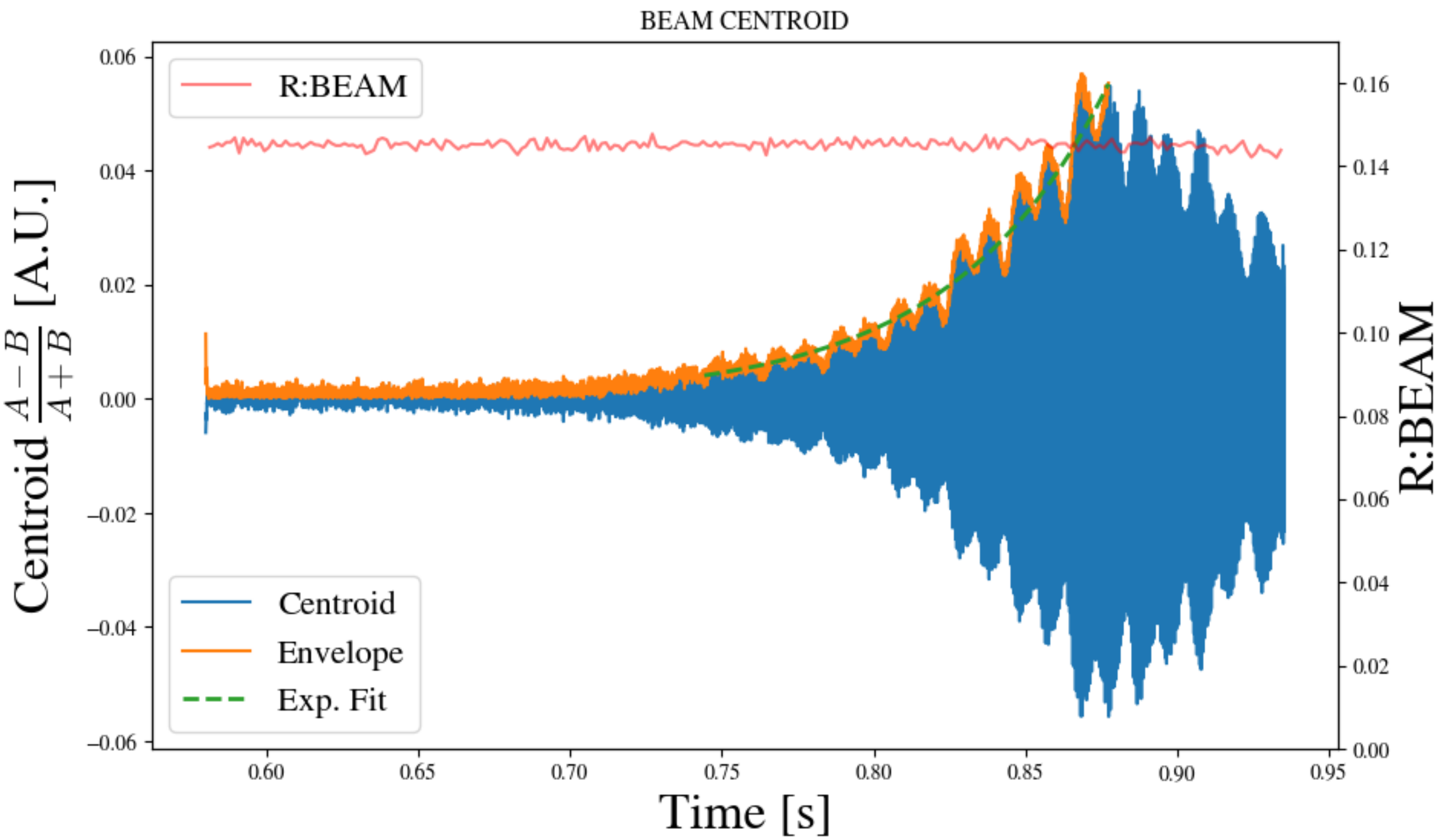



$N_p = 2.7 \times 10^{11}\ ppb \longrightarrow q \approx 15$

# Static Tune Scan (Growth Rates)

Another quantity we can extract is the growth rate $\tau^{-1}$,i.e., $\exp\left[t\ \tau^{-1}\right]$

- Calculated envelopes following MaryKate's method with Hilbert transform
- Nominal $Q_x = 25.45$ and $Q_y = 24.455$



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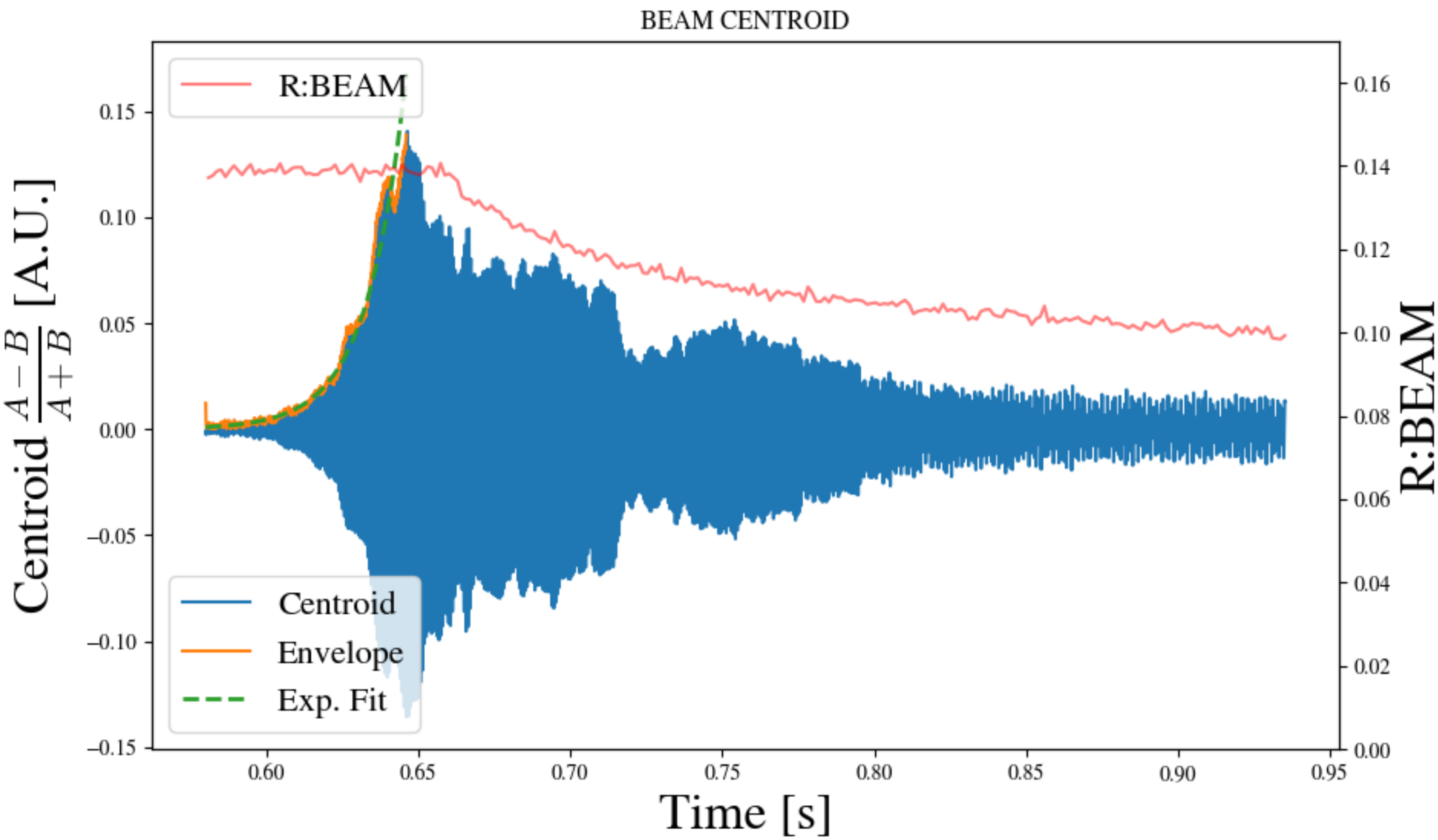
# Static Tune Scan (Growth Rates)

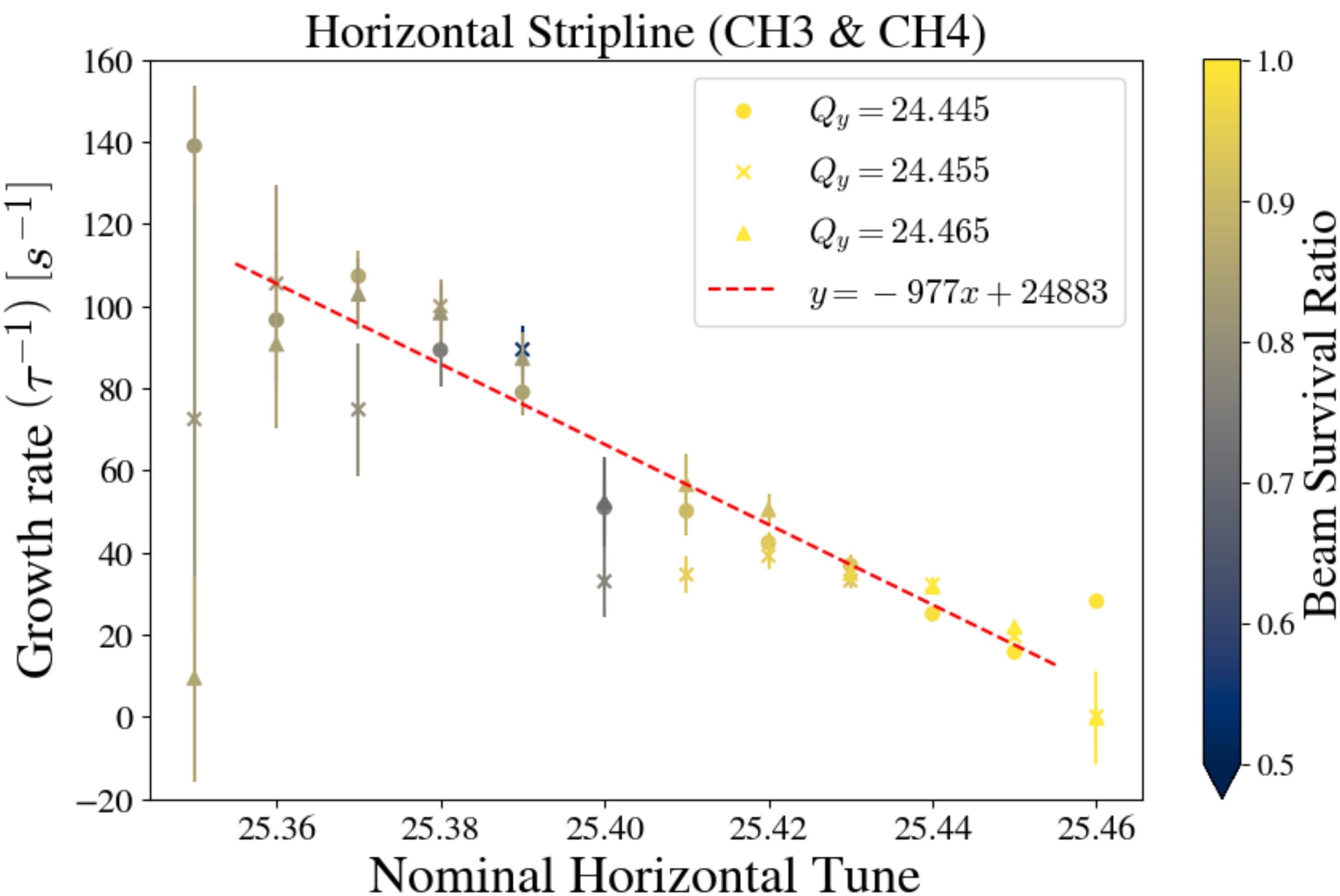
Another quantity we can extract is the growth rate $\tau^{-1}$,i.e., $\exp\left[t\ \tau^{-1}\right]$

- Calculated envelopes following MaryKate's method with Hilbert transform
- Nominal $Q_x = 25.39$ and $Q_y = 24.445$



# Static Tune Scan (Growth Rates)

There was a correlation between growth rates and the horizontal tune.



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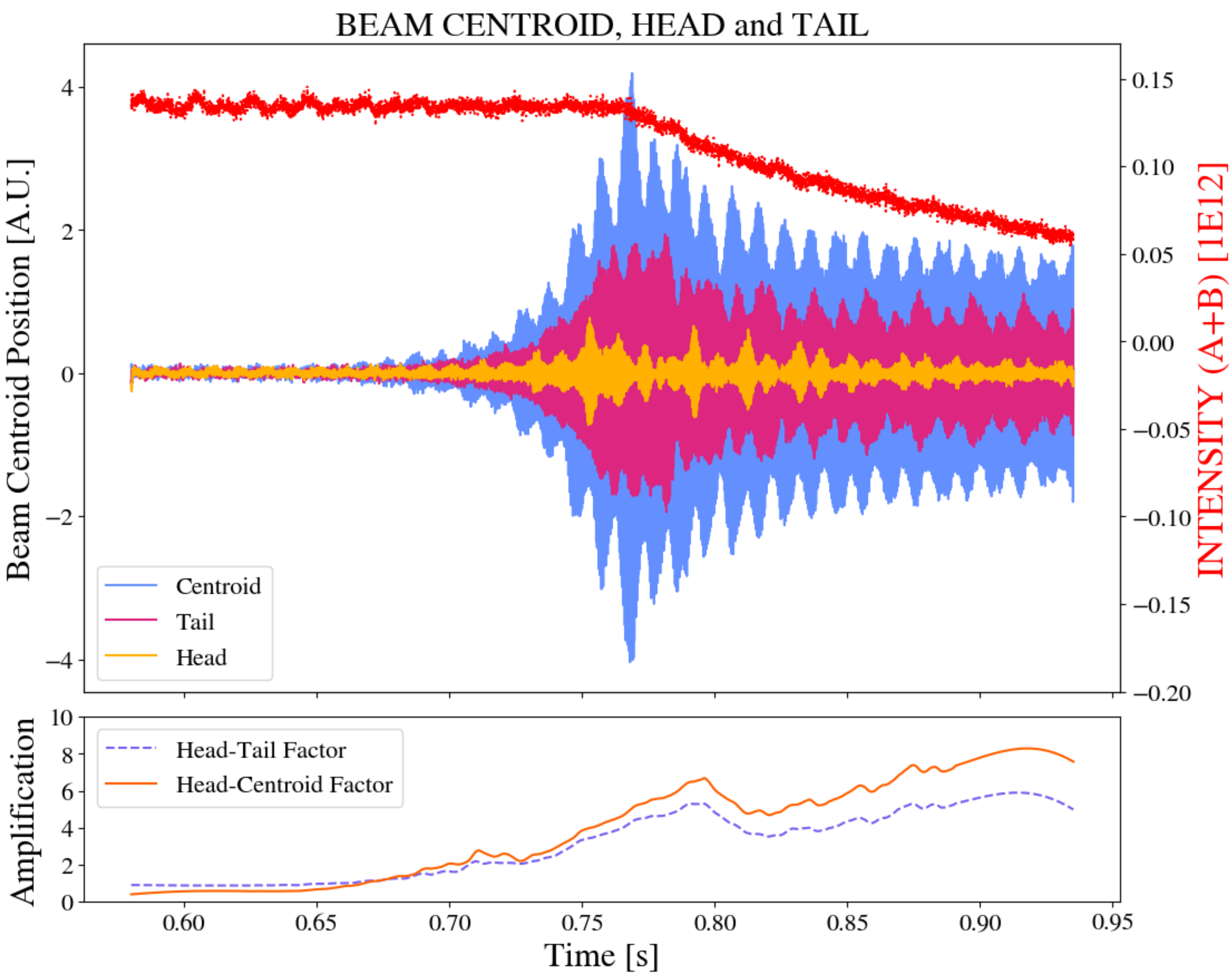
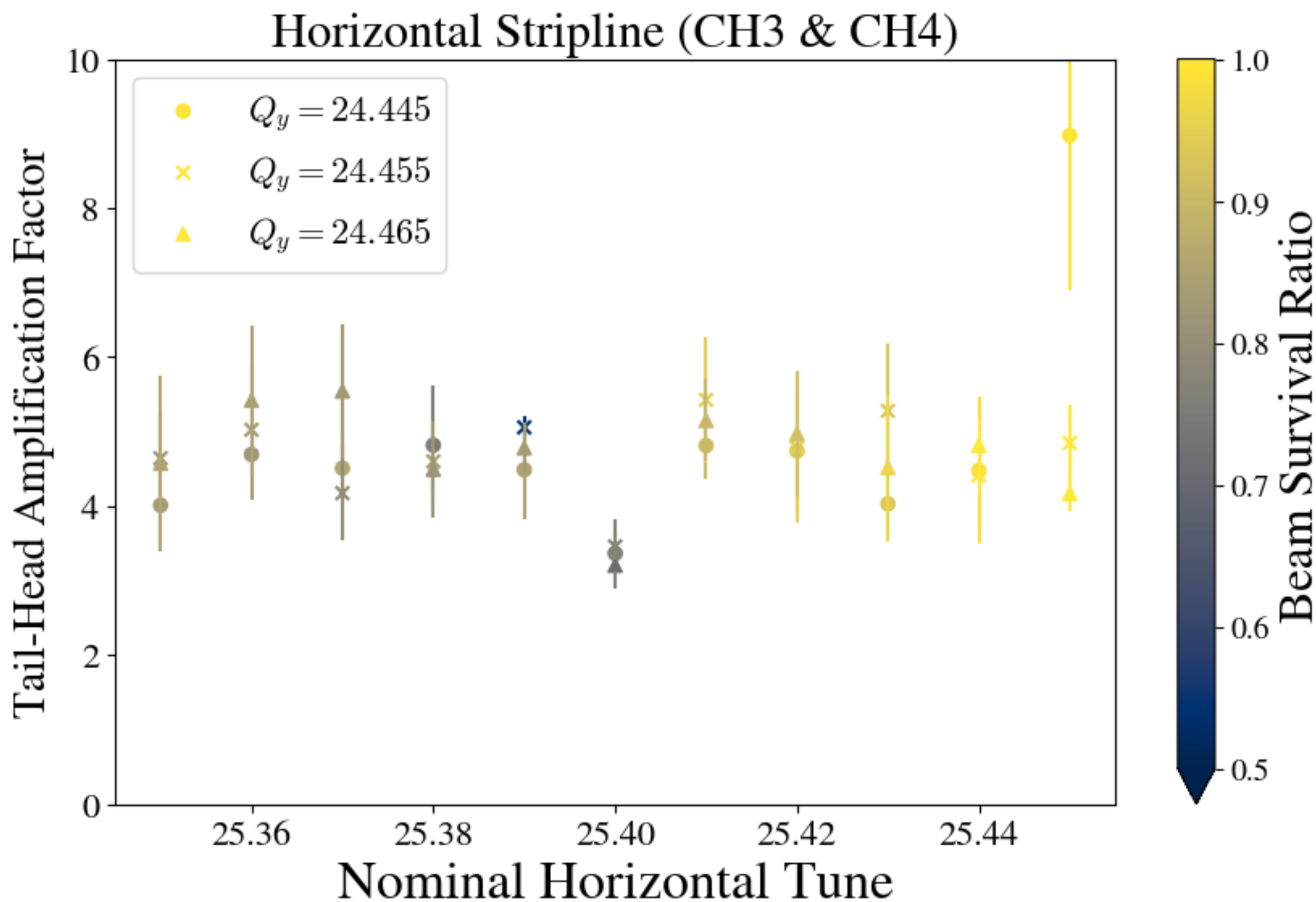
# Static Tune Scan (Head, Tail and Centroid)



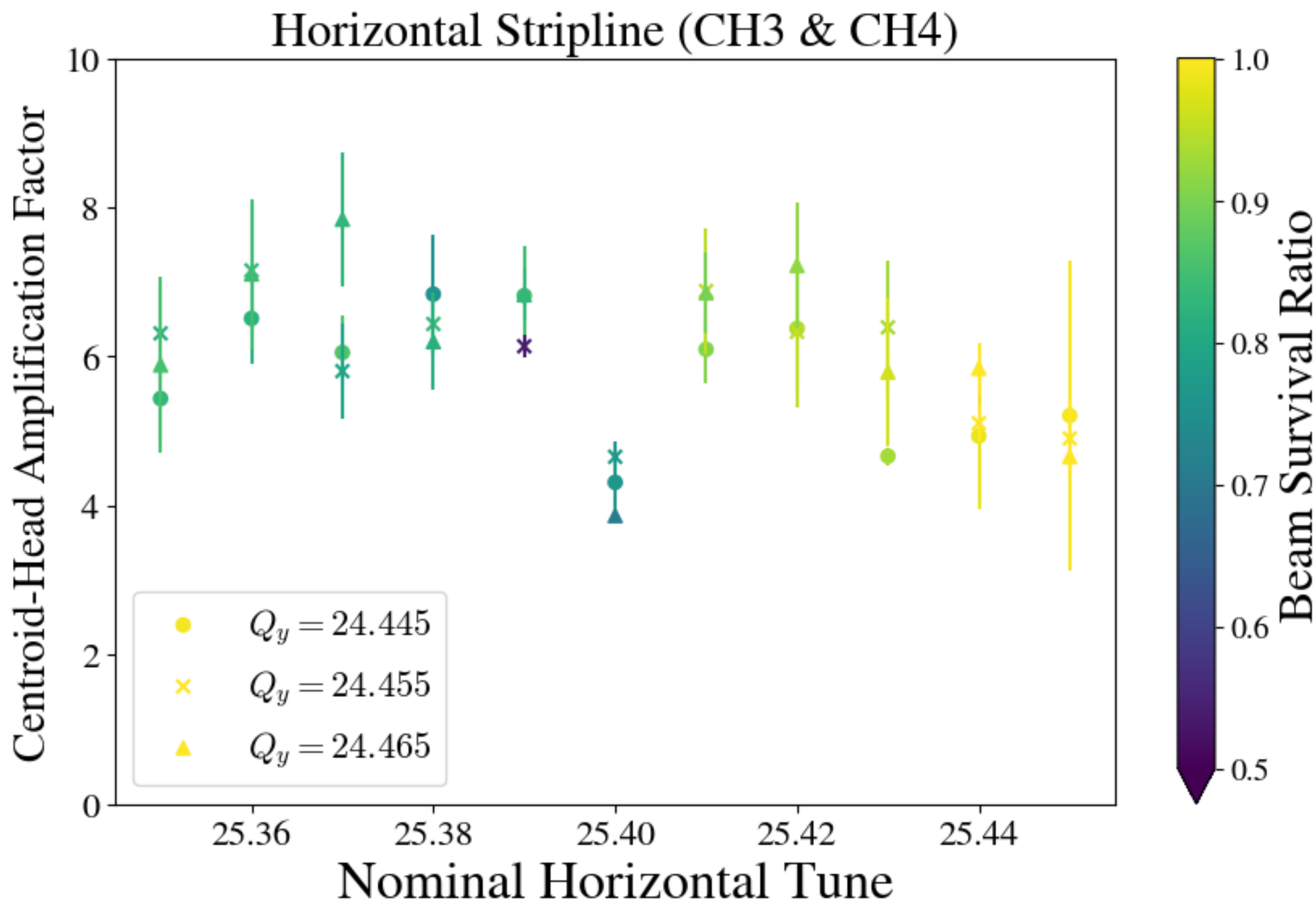
# Static Tune Scan (Tail-Head Amplification)

Tail-Head amplification factor calculated at the largest tail amplitudes remain constant as a function of horizontal tune



## Static Tune Scan (Centroid-Head Amplification)

Centroid-Head amplification factor calculated at the largest centroid amplitudes remain constant as a function of horizontal tune



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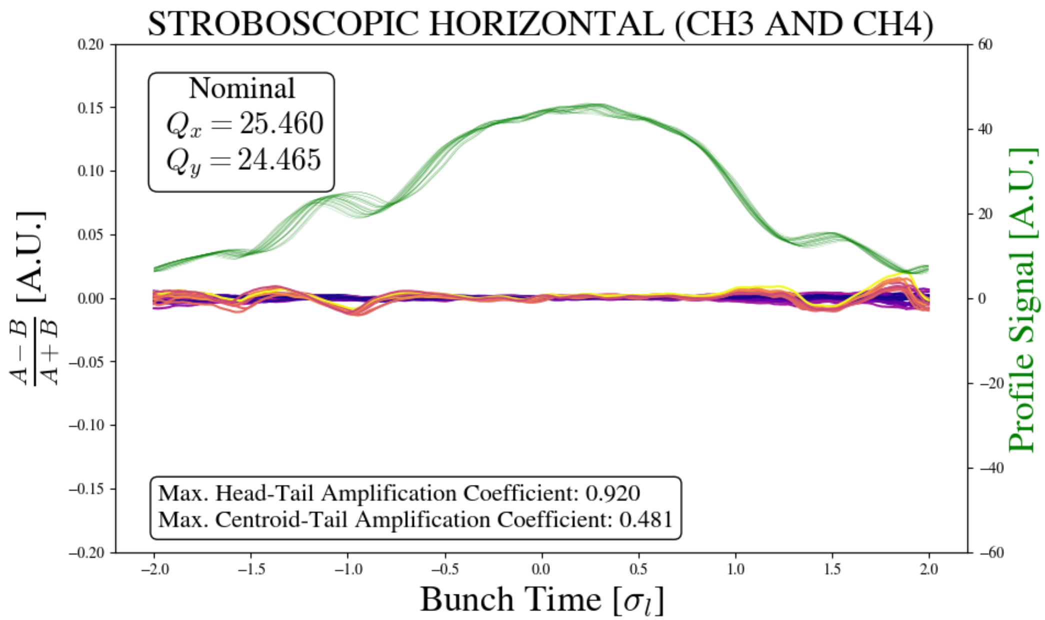
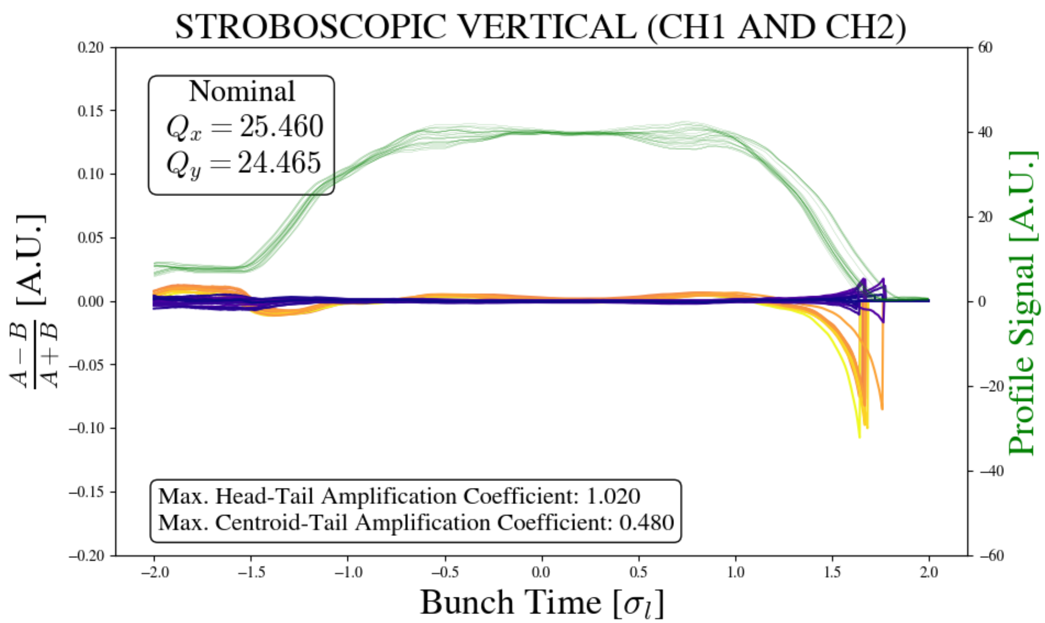
# Stroboscopic plots at "low" intensity



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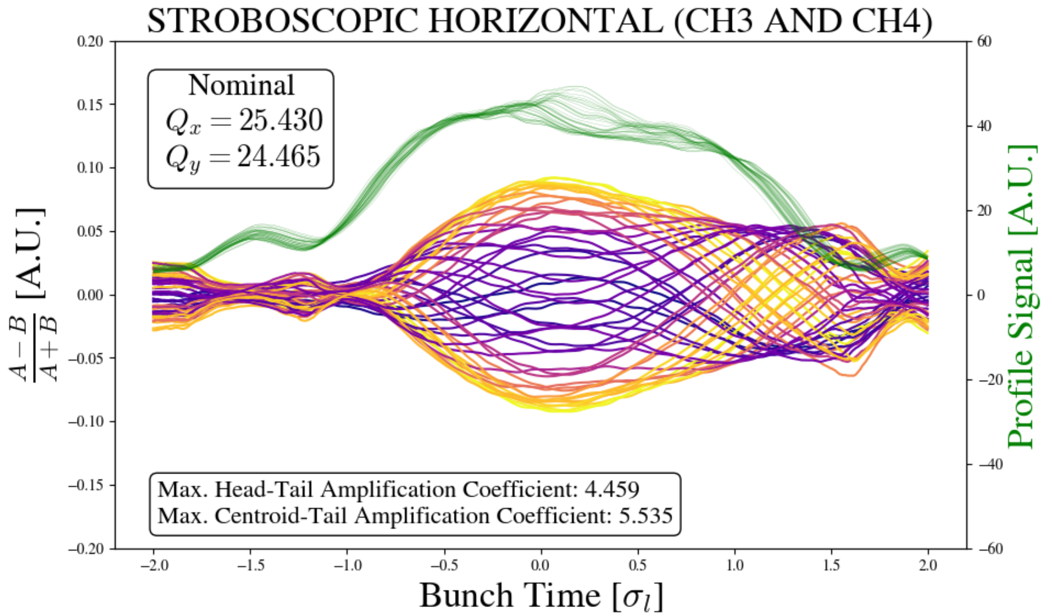


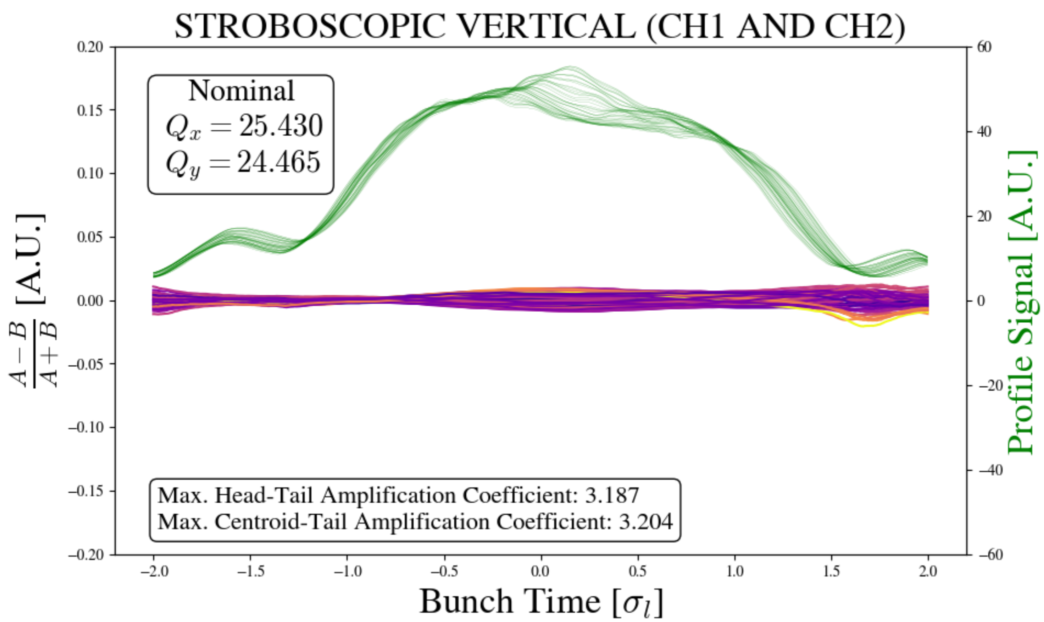

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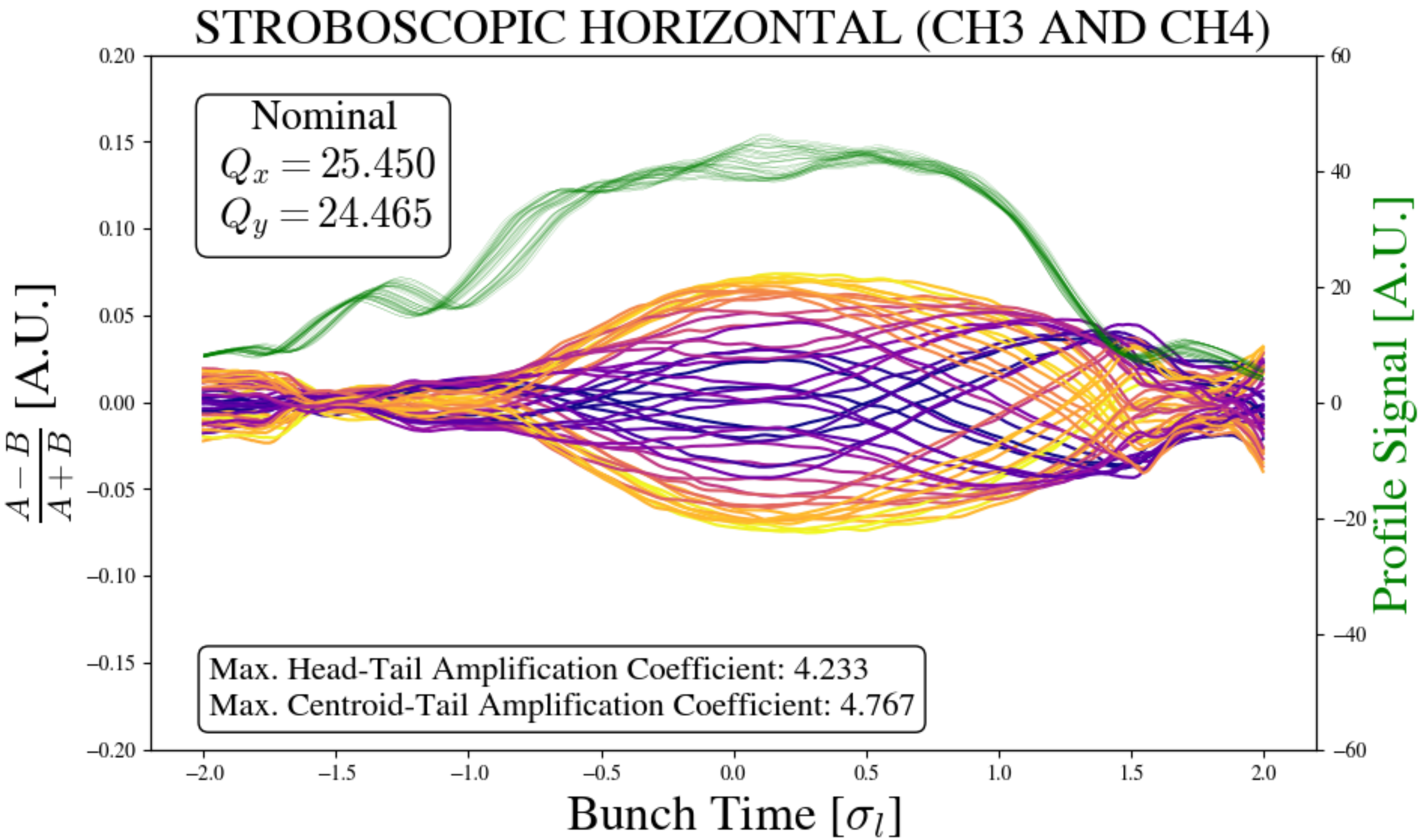

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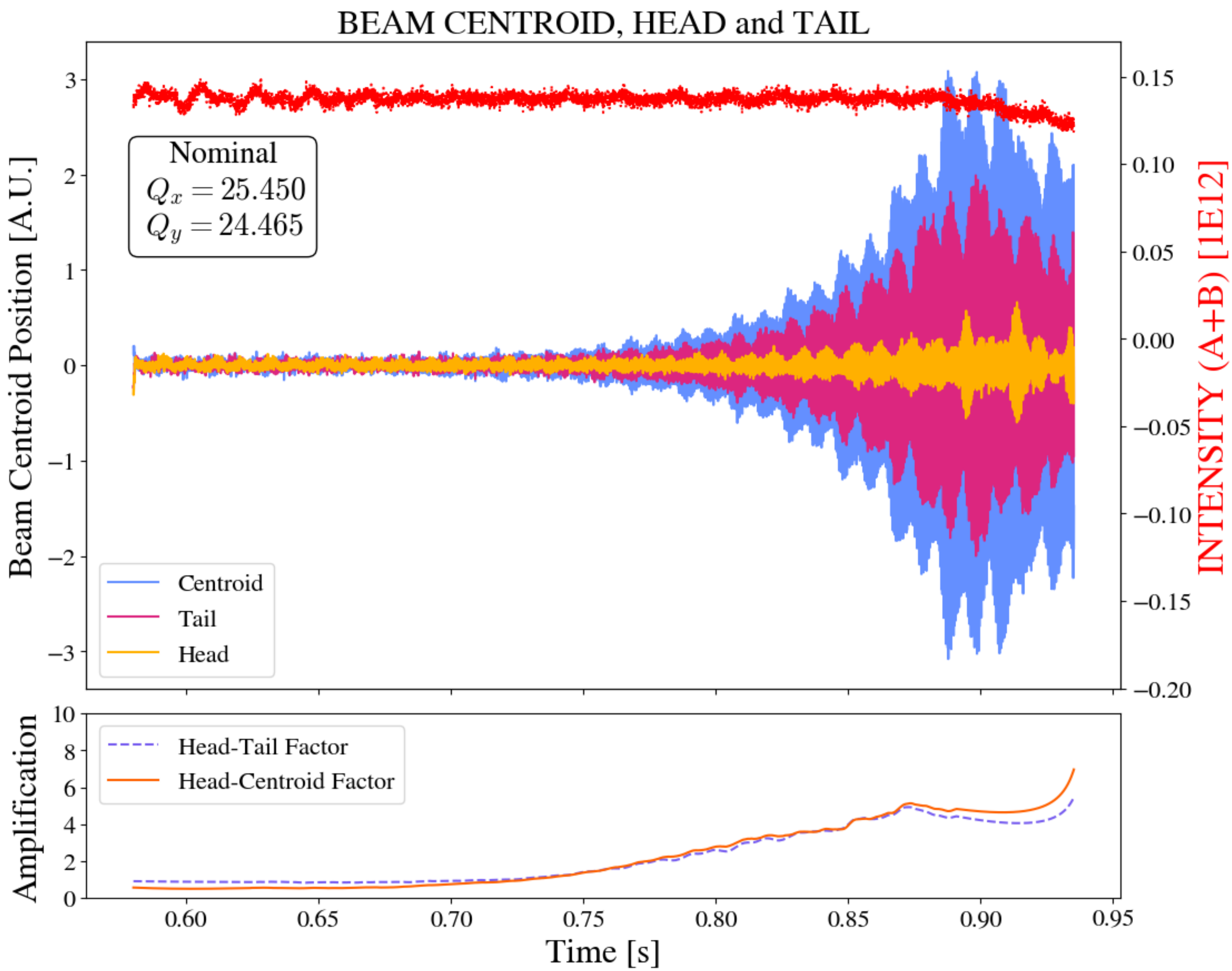




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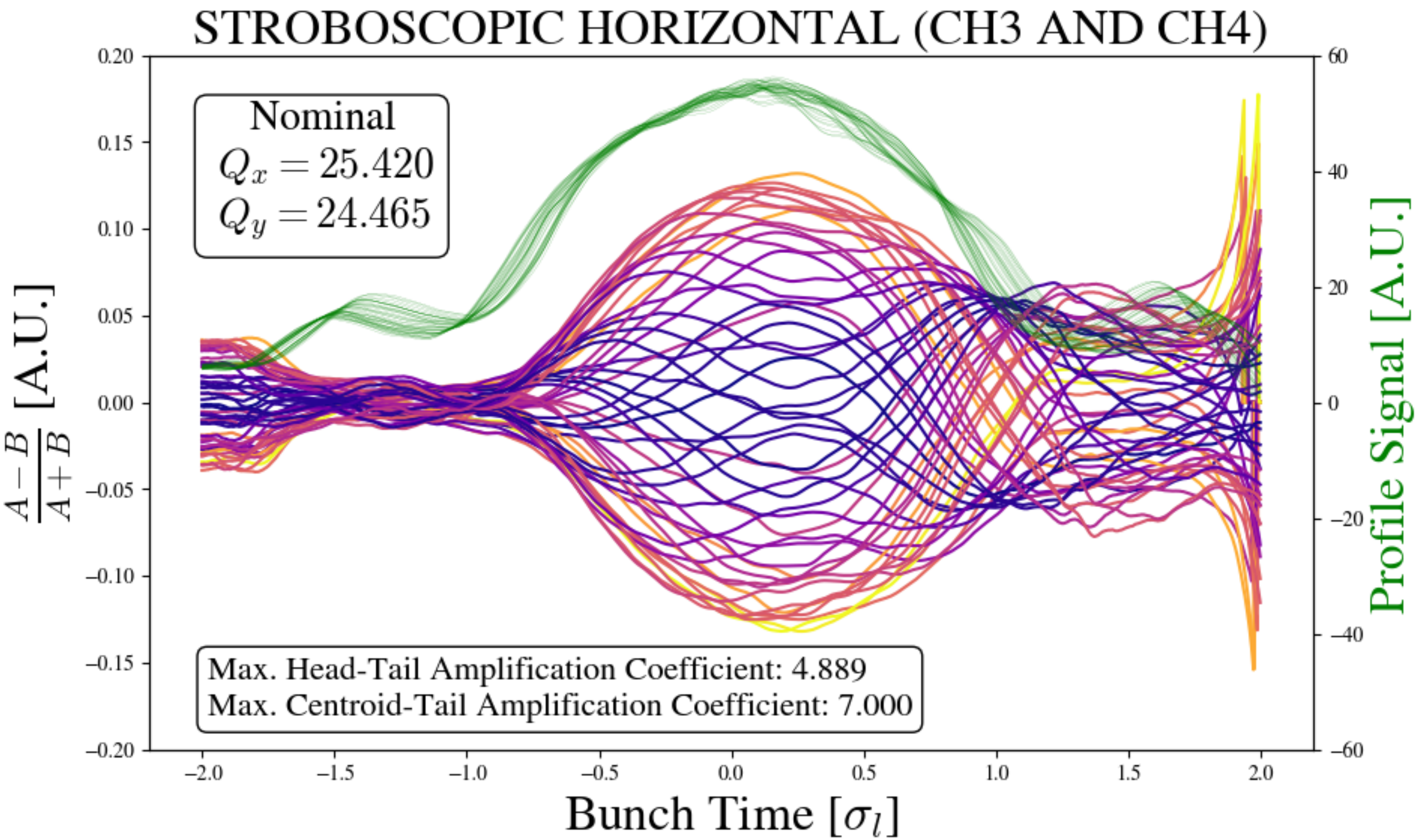

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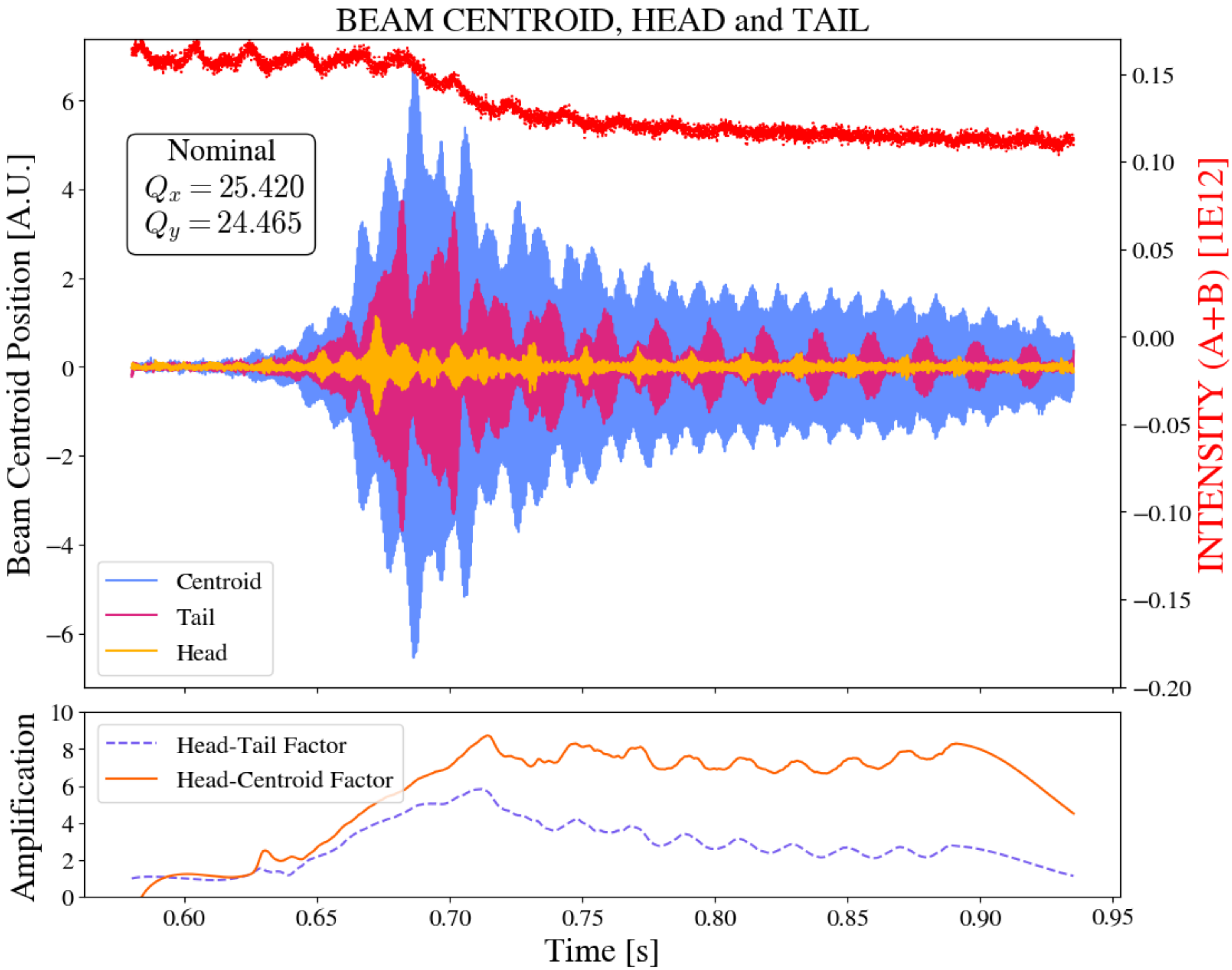

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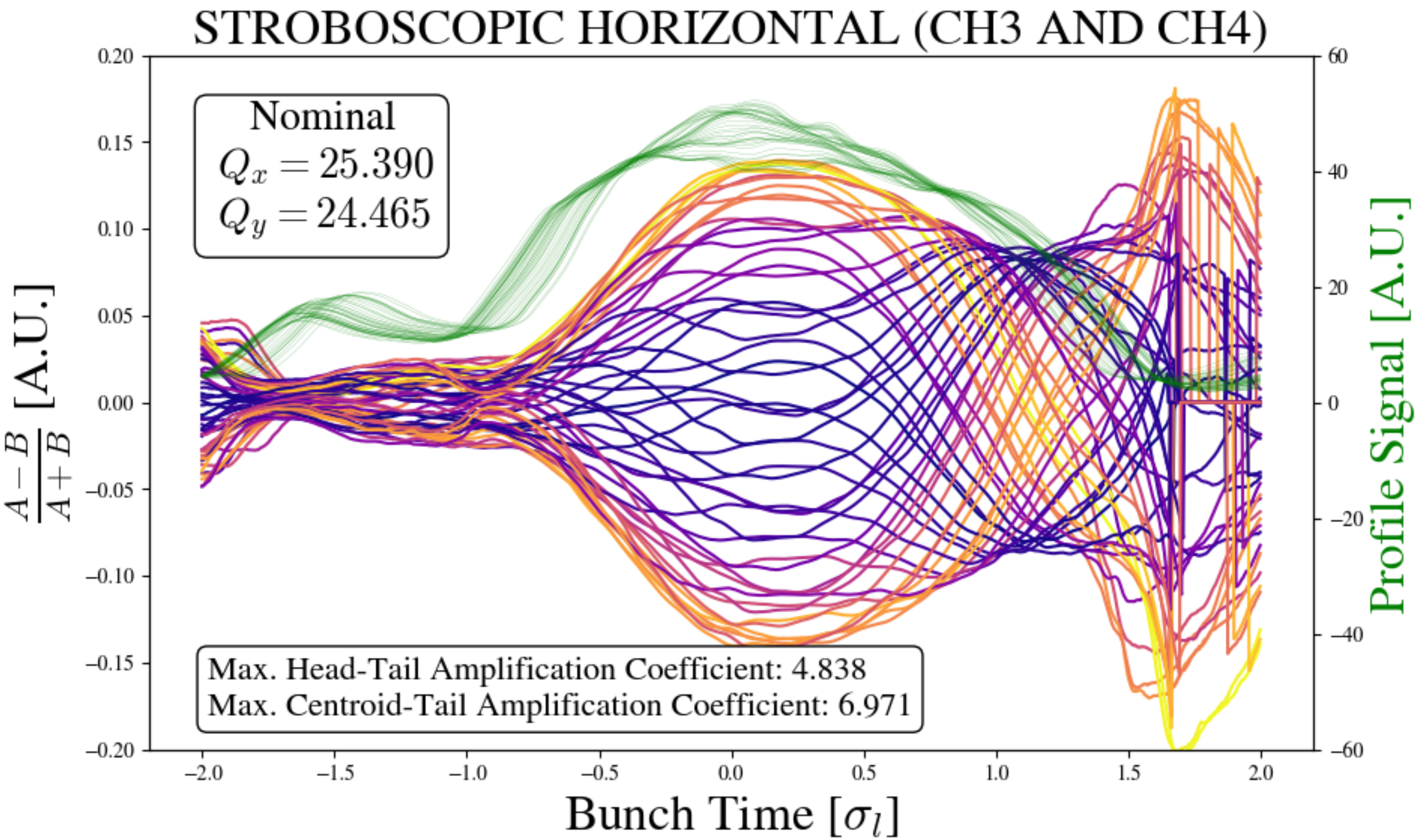

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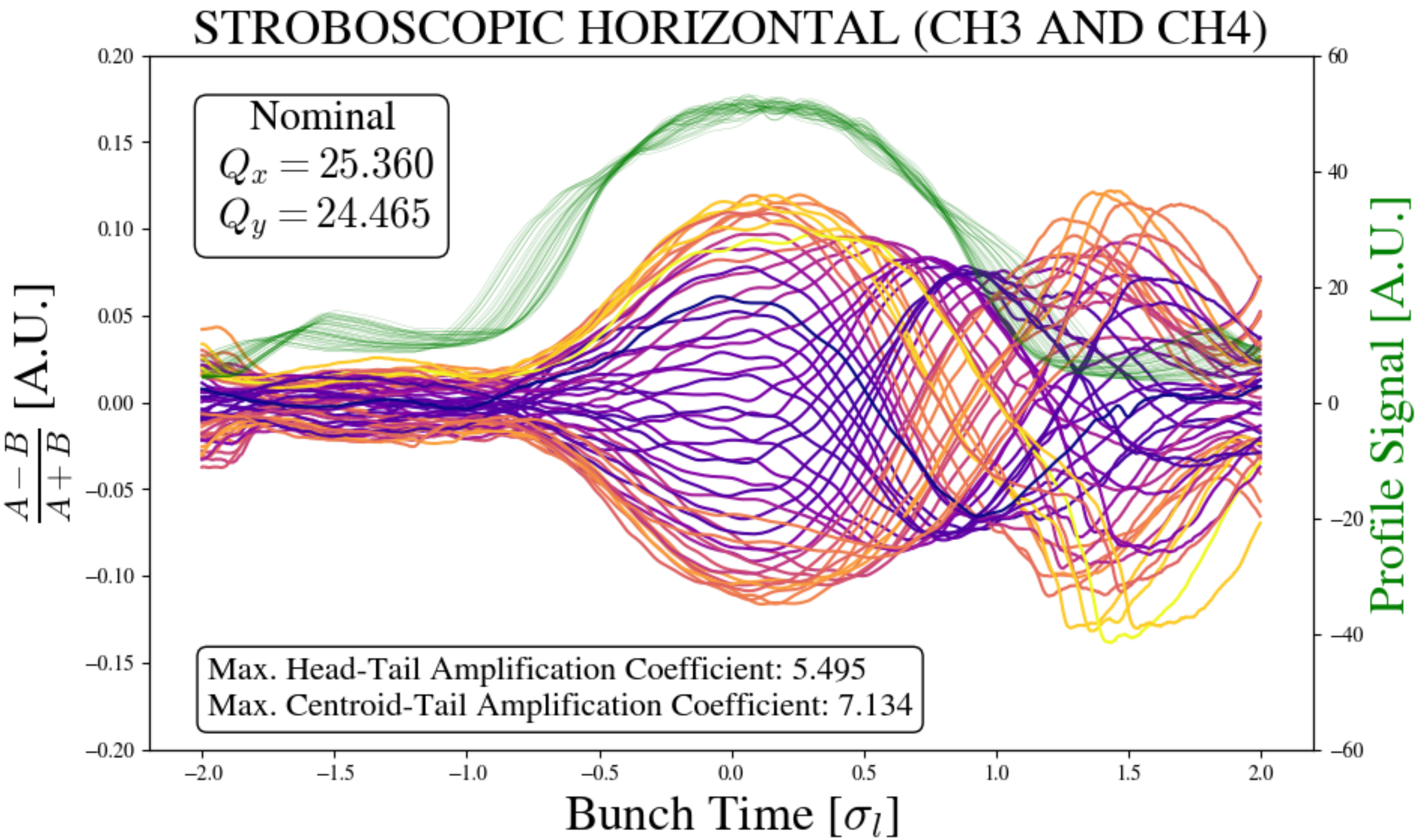

## Conclusions and future work

- We performed a study on collective instabilities in the Recycler Ring. Analysis of data is still ongoing.
- We see a collective instability manifest in the horizontal plane.
- We see a collective instability whose frequency shows a one-to-one correlation with the horizontal tune.
- We see a collective instability whose growth rate scales down with the horizontal tune. No correlation with the vertical tune.
- We see a collective instability dominated by centroid and tail motion. With maximum tail and centroid amplification factors of around 5-10.
- More simulation work, while comparing to theory, has to be done in order to better understand this experimental data
- Look at damper settings against growth rates and amplification factors
  - Alexey Burov. (2018). Transverse Instabilities of a Bunch with Space Charge, Wake and Feedback.
- Calibrate $\frac{A-B}{A+B}$ to get an estimate of the transverse excursions in meters.

# Wake amplitude [A.U.] vs. Position [m]