Booster Modeling with SciBmad

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Cornell University

Talk overview

1. **Booster Modeling & Benchmarking**
   Build the SciBmad Booster model and benchmark lattice, optics, orbit, tune, scalability, and operational access.
2. **2025 Tune Measurement**
   Analyze the 2025 Booster turn-by-turn data with FFT and damped-oscillation fits, and compare with SciBmad Twiss results.
3. **Tune Measurement Simulation**
   Reproduce the tune-measurement procedure with SciBmad tracking using single particles and bunches.
4. **2026 Tune Measurement**
   Compare kicker-OFF/ON data and use Gaussian band-pass filtering and decoherence fitting for the noisier 2026 data.
5. **Multi-BPM Analysis**
   Develop a multi-BPM tune and phase-advance analysis for future measurements and benchmark it against SciBmad Twiss.

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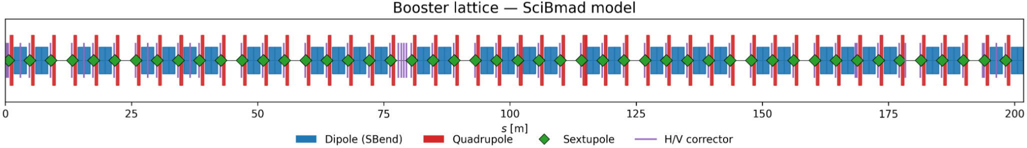
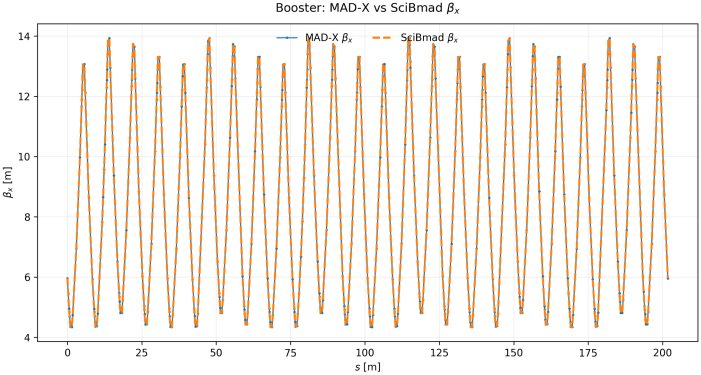
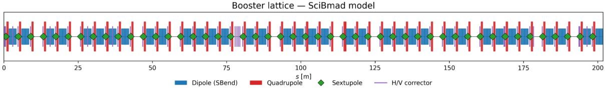
Booster lattice converted from MAD-X to SciBmad



- Reconstructed the Booster lattice in SciBmad from the MAD-X model.
- Model includes dipoles, quadrupoles, sextupoles, and horizontal/vertical correctors.

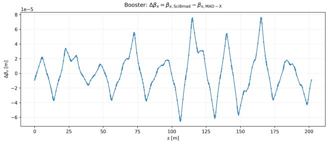
Twiss benchmark: horizontal beta function





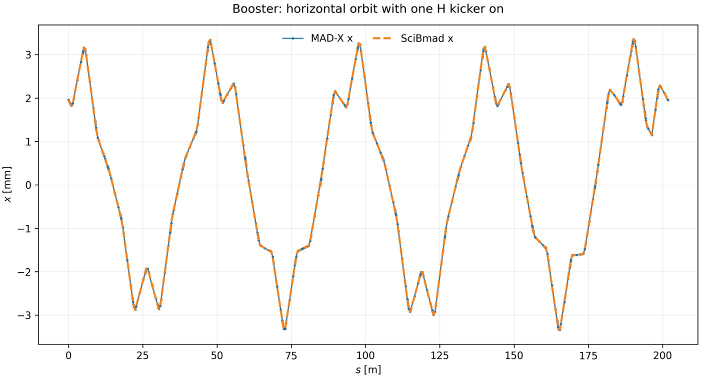
MAD-X vs. SciBmad

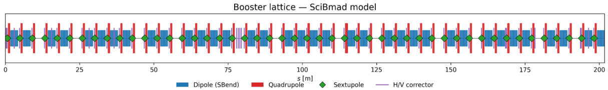
- $\beta_x(s)$ overlaps across the full Booster lattice.
- Point-by-point residuals are at the $10^{-5}\,\mathrm{m}$ scale in this comparison.



$$\Delta\beta_x = \beta_{x,\mathrm{SciBmad}} - \beta_{x,\mathrm{MAD-X}}$$

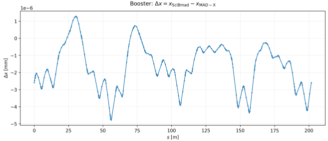
Orbit benchmark: response to one horizontal kicker





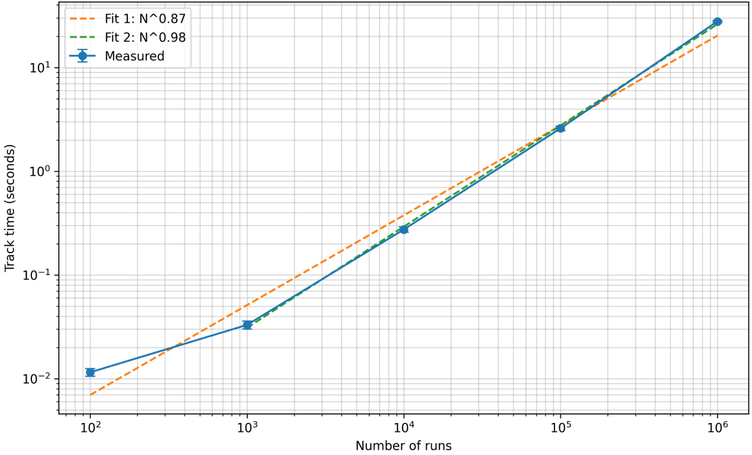
One H kicker on

- Compare the resulting horizontal closed orbit $x(s)$.
- MAD-X and SciBmad reproduce the same mm-scale orbit response.
- Residuals are at the $10^{-6}\,\mathrm{mm}$ scale in this comparison.



$$\Delta x = x_{\mathrm{SciBmad}} - x_{\mathrm{MAD-X}}$$

Scalability test: tracking time

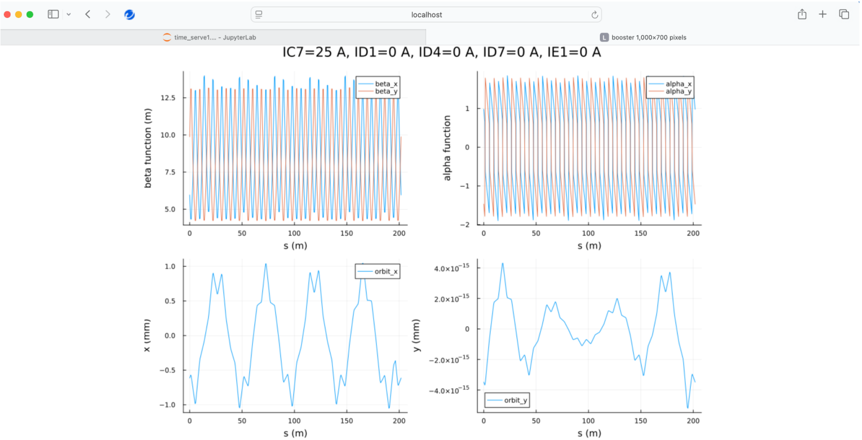


Tracking performance

- Tested from 10^2 to 10^6 particles.
- Full-range fit: $T \propto N^{0.87}$.
- For 10^3–10^6: $T \propto N^{0.98}$.
- Large-bunch tracking is therefore approximately linear in particle count.

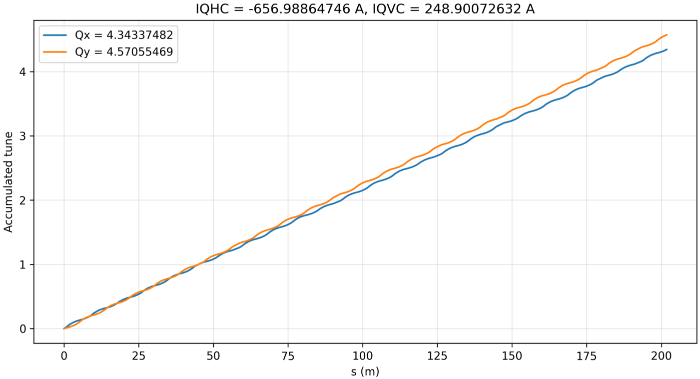
SciBmad model as an HTTP server

`http://localhost:8081/booster?IC7=25&ID1=0&ID4=0&ID7=0&IE1=0`



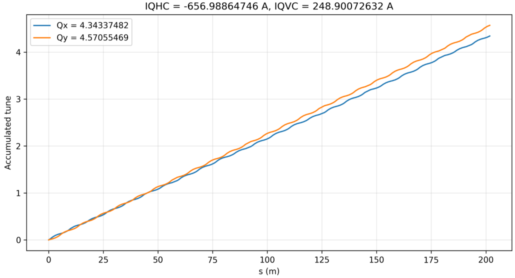
- ▶ Expose the SciBmad Booster model through a local HTTP server and pass machine settings as URL query parameters.

Tune calculation: accumulated tune

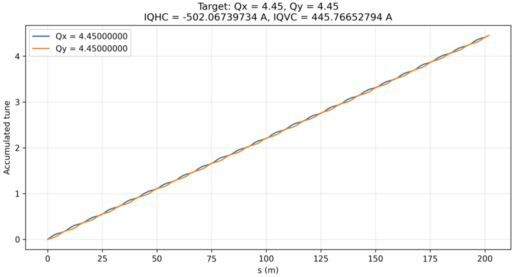


- ▶ Calculate the accumulated horizontal and vertical tune along the Booster lattice.
- ▶ Extract the final values as the one-turn tunes Q_x and Q_y.

Tune matching: Jacobian-based magnet adjustment



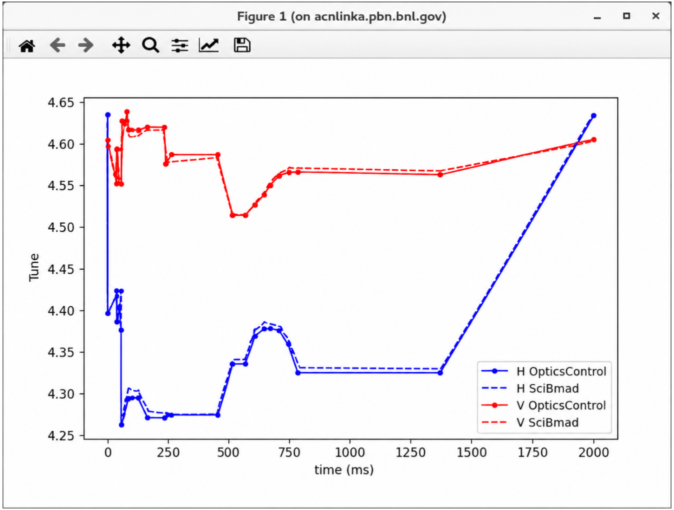
Initial tunes



Matched to target $Q_x = Q_y = 4.45$

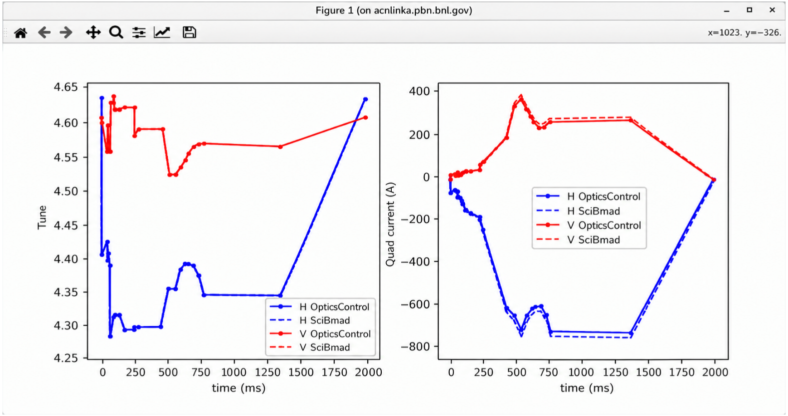
- Use the Jacobian of (Q_x, Q_y) with respect to (I_{QHC}, I_{QVC}) to calculate magnet-current corrections.
- Iterate until the final tunes reach the specified target.

Booster tune control during the 2000 ms ramp



- Desired horizontal and vertical tune setpoints are defined through the 2000 ms Booster ramp; quadrupole currents vary through the same cycle.
- **OpticsControl** converts between tune setpoints and quadrupole currents using matrix/inverse-matrix calculations with hardcoded coefficients.
- **SciBmad** calculates the optics using the Twiss/tracking model.
- On the CAD server, SciBmad can read live Booster settings, run the simulation, and post results.

Tune matching: SciBmad vs. OpticsControl



- Use the same tune setpoints as targets throughout the ramp.
- In SciBmad, adjust quadrupole currents so the calculated tunes match the target setpoints.
- The required SciBmad quadrupole currents are slightly different from those calculated by OpticsControl.

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Experimental tune measurement in the Booster

Measurement procedure

- Apply a **single-turn H or V kick** to excite coherent betatron motion.
- Record the beam position **turn-by-turn** after the kick.
- Extract the fractional tune from the oscillation frequency.

2025 measurement data

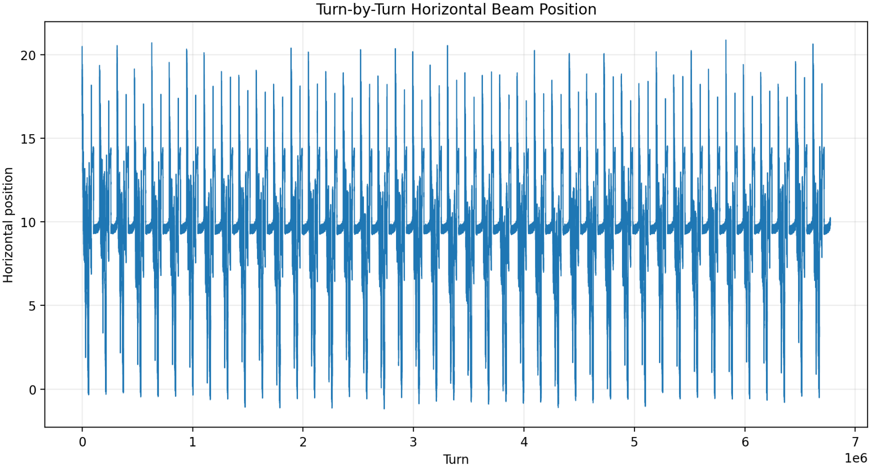
The data presented here were taken from a Booster tune measurement performed by **Lucy in 2025**.

The **horizontal data are noisier** and do not show a clear damped-cosine pattern.

Both horizontal and vertical data are presented:

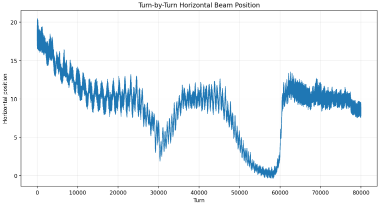
- **Horizontal:** FFT analysis only.
- **Vertical:** FFT plus damped-cosine/decoherence fitting.

Horizontal tune measurement: 10-minute turn-by-turn data

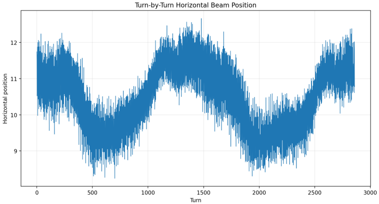


10-minute turn-by-turn horizontal measurement

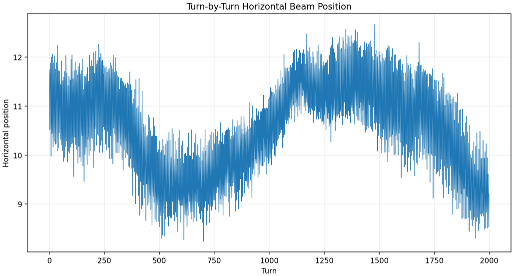
Horizontal tune measurement: selecting the analysis window



Selected measurement interval



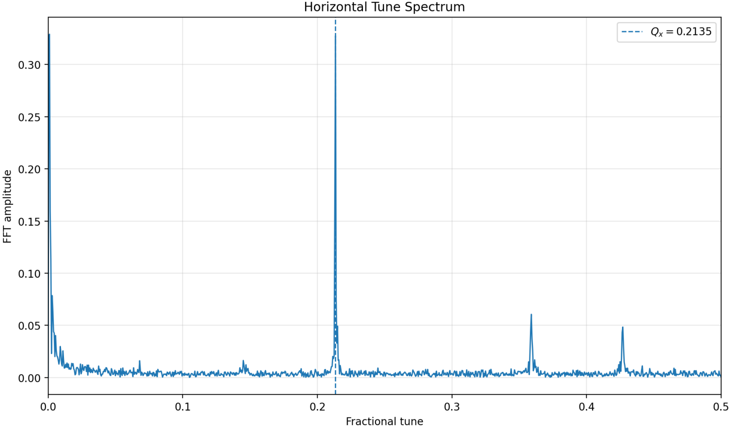
Horizontal oscillation region



2000-turn analysis window

- H and V kicks were applied **simultaneously**, so the two TBT signals share the same timing.
- Because the H signal is noisier, the successive zooms and analysis window are selected from the **cleaner V data**.
- The **same 2000-turn window** is then applied to H and used for the FFT tune analysis.

Horizontal tune extraction from the FFT spectrum



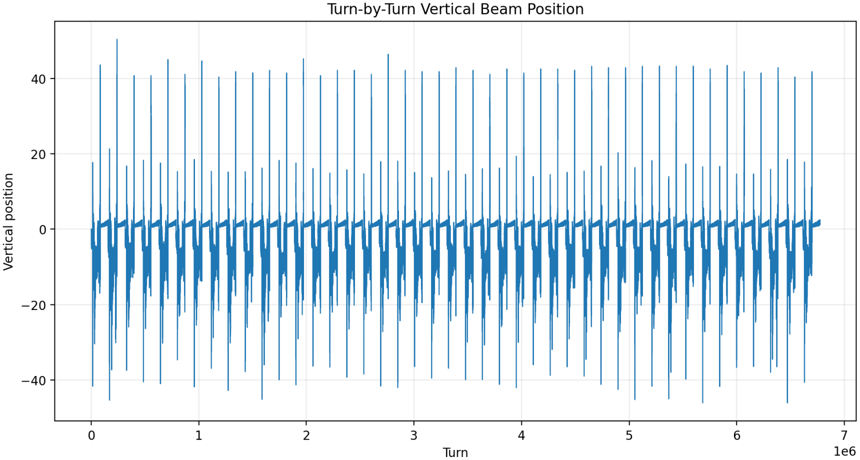
FFT tune analysis

- Remove the DC component from the selected **2000-turn** horizontal waveform.
- Calculate the FFT and search $0 < Q_x < 0.5$.
- The dominant spectral peak gives

$$\boxed{Q_x = 0.2135}$$

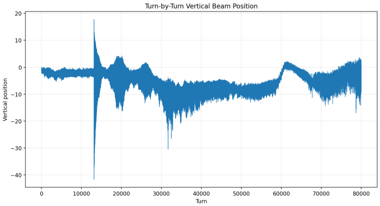
- With 2000 turns, $\Delta Q_{\mathrm{FFT}} = 1/2000 = 0.0005$.

Vertical tune measurement: 10-minute turn-by-turn data

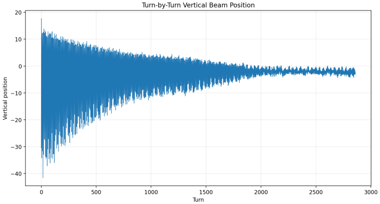


10-minute turn-by-turn vertical measurement

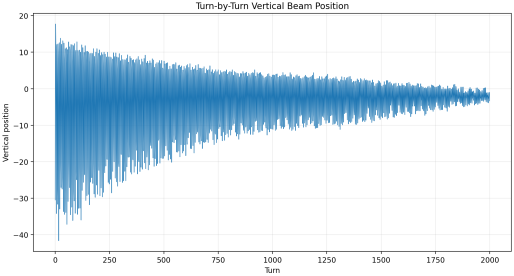
Vertical tune measurement: selecting the analysis window



Selected measurement interval



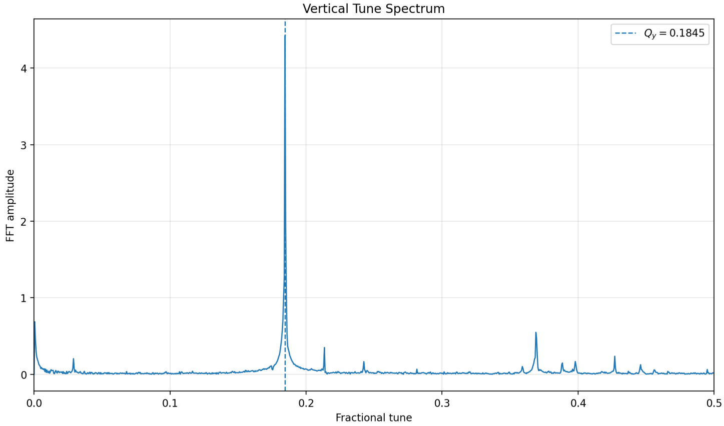
Single excited vertical oscillation



2000-turn analysis window

- Successive zooms isolate a single kick response from the long measurement record.
- The selected **2000-turn** waveform shows the coherent vertical betatron oscillation and its decay.
- This **2000-turn window** is used for the subsequent FFT and time-domain tune fits.

Vertical tune extraction from the FFT spectrum



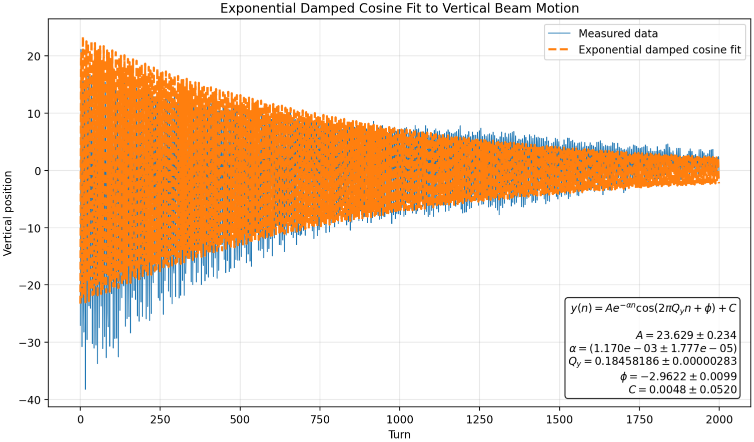
FFT tune analysis

- Remove the DC component from the selected **2000-turn** vertical waveform.
- Calculate the FFT and search $0 < Q_y < 0.5$.
- The dominant spectral peak gives

$$\boxed{Q_y = 0.1845}$$

- With 2000 turns, $\Delta Q_{\mathrm{FFT}} = 1/2000 = 0.0005$.

Vertical tune extraction: exponential damped-cosine fit



Time-domain fit

- Fit the measured **2000-turn** waveform directly with a damped cosine:

$$y(n) = Ae^{-\alpha n}\cos(2\pi Q_y n+\phi)+C.$$

- The fitted tune is

$$\boxed{Q_y = 0.18458186 \pm 0.00000283}$$

FFT gives

$$Q_y = 0.1845.$$

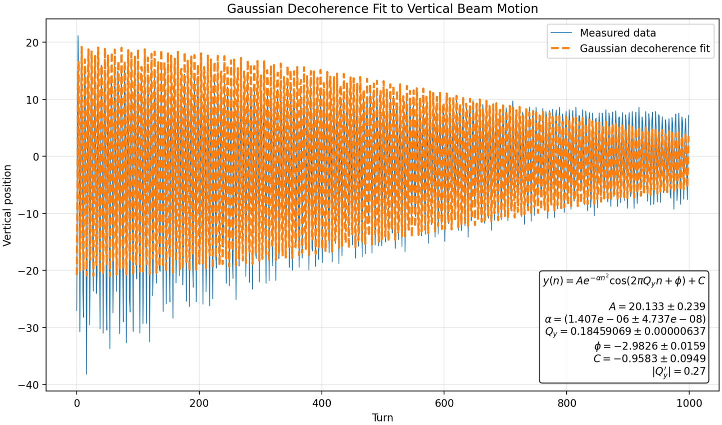
The difference is

$$|\Delta Q_y| = 8.19 \times 10^{-5},$$

which is smaller than the FFT-bin spacing:

$$\Delta Q_{\mathrm{FFT}} = 1/2000 = 0.0005.$$

Vertical tune extraction: Gaussian decoherence fit



Gaussian decoherence fit

- Model the envelope as

$$y(n) = Ae^{-\alpha n^2}\cos(2\pi Q_y n + \phi) + C.$$

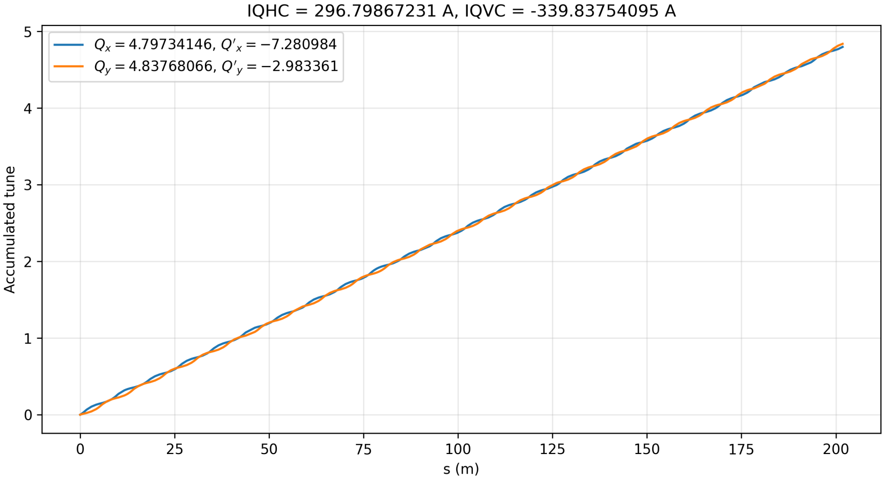
- For RMS energy spread σ_δ,

$$|Q_y'| = \frac{\sqrt{\alpha}}{\sqrt{2}\pi\sigma_\delta}.$$

- Assume $\sigma_\delta = 10^{-3}$.
- Fit the first **1000 turns** for a good match to the measured envelope.
- The fit gives

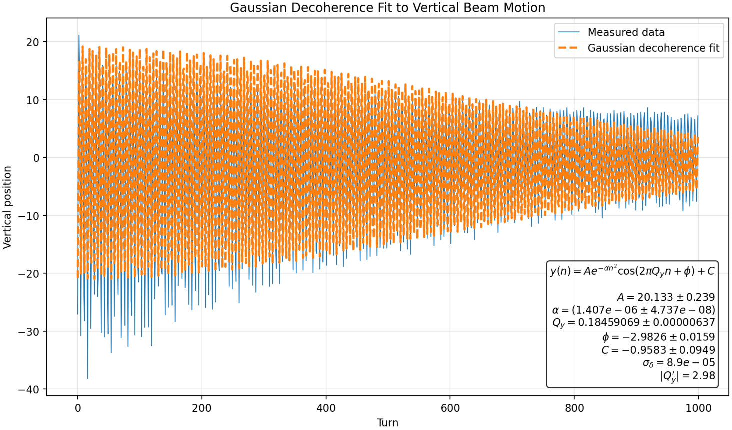
$$\boxed{|Q_y'| \approx 0.27}$$

SciBmad twiss calculation at measurement settings



SciBmad reads the historical Booster settings from the tune measurement and runs the model.

Energy spread required to match SciBmad chromaticity



Match to the Twiss chromaticity

- The SciBmad Twiss calculation gives

$$|Q_y'| \approx 2.98.$$

- For the Gaussian decoherence model,

$$|Q_y'| = \frac{\sqrt{\alpha}}{\sqrt{2}\pi\sigma_\delta}.$$

- To reproduce the Twiss value with the fitted decoherence rate, the required RMS relative energy spread is

$$\boxed{\sigma_\delta \approx 8.9 \times 10^{-5}}.$$

Tune measurement: experiment VS SciBmad twiss calculation

- **Experimental FFT:**

$$Q_x = 0.2135, \qquad Q_y = 0.1845.$$

- A search over 0–0.5 cannot distinguish Q from $1 - Q$:

$$Q_x = 0.2135 \text{ or } 0.7865, \qquad Q_y = 0.1845 \text{ or } 0.8155.$$

- **SciBmad Twiss calculation:**

$$Q_x = 4.797341, \qquad Q_y = 4.837681,$$

corresponding to fractional tunes

$$Q_x = 0.797341, \qquad Q_y = 0.837681.$$

- **Comparison:**

$$Q_{x,\mathrm{exp}} = 0.7865 \quad \text{vs.} \quad Q_{x,\mathrm{SciBmad}} = 0.797341,$$
$$Q_{y,\mathrm{exp}} = 0.8155 \quad \text{vs.} \quad Q_{y,\mathrm{SciBmad}} = 0.837681.$$

Questions for the tracking study:

- Can SciBmad reproduce the experimental tune signal?
- Can the kicker/BPM optics explain the weak horizontal response?
- Can tracking reproduce decoherence and chromaticity?

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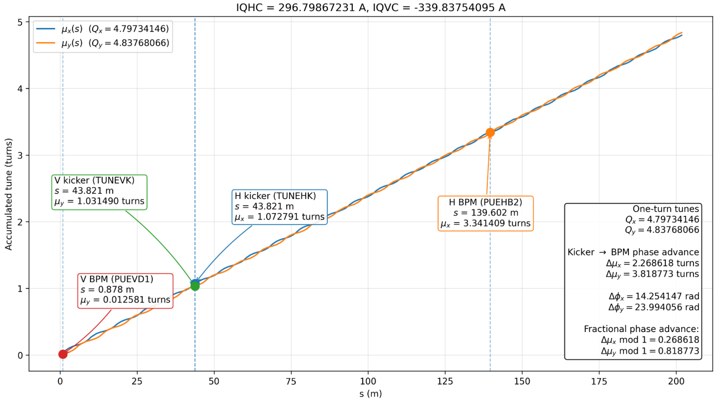
Simulate the tune measurement with SciBmad tracking

Reproduce the experimental procedure in simulation

- Add **H/V kickers** and **H/V turn-by-turn BPMs** to the SciBmad Booster lattice, and estimate the **H/V optical response** using the kicker-to-BPM phase advance and the beta functions at the kicker and BPM.
- Place these elements at locations corresponding to the **actual Booster tune kickers and TBT BPMs**.
- Track either a **single particle** or a **particle bunch** through the Booster.
- Apply simultaneous **single-turn H/V kicks**, following the experimental tune-measurement procedure.
- Record the horizontal and vertical beam positions **turn-by-turn** at the corresponding BPMs.
- Analyze the simulated TBT signals using the same methods as the experimental data: FFT for tune extraction and, for bunch tracking, decoherence fitting for chromaticity.

SciBmad lattice $\longrightarrow$ **single-turn H/V kick** $\longrightarrow$ **TBT BPM data** $\longrightarrow$ **FFT / fitting** $\longrightarrow$ **tune & chromaticity**

Tune-measurement optics: kicker-to-BPM phase advance



- Evaluated the accumulated horizontal and vertical phase at the actual H/V kicker and TBT BPM locations.
- H kicker → H BPM:

$$\Delta\mu_x = 2.2686$$

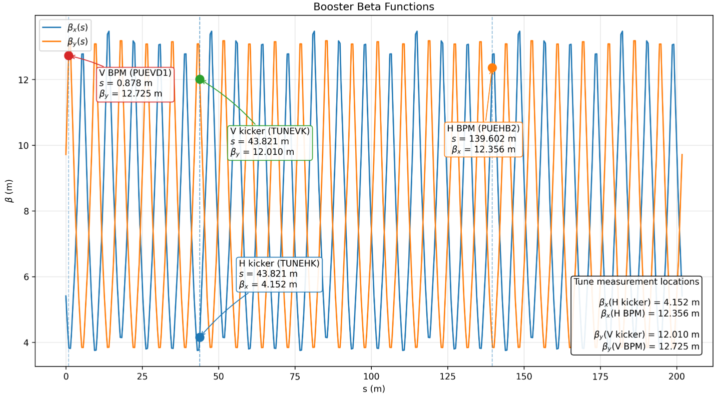
$$\Delta\mu_x \bmod 1 = 0.2686$$

- V kicker → V BPM:

$$\Delta\mu_y = 3.8188$$

$$\Delta\mu_y \bmod 1 = 0.8188$$

Tune-measurement optics: beta functions at kicker and BPM



- Beta functions at the tune-measurement elements:

$$\begin{aligned} \beta_x(\text{H kicker}) &= 4.152 \text{ m}, \\ \beta_x(\text{H BPM}) &= 12.356 \text{ m}, \\ \beta_y(\text{V kicker}) &= 12.010 \text{ m}, \\ \beta_y(\text{V BPM}) &= 12.725 \text{ m}. \end{aligned}$$

- For an angular kick,

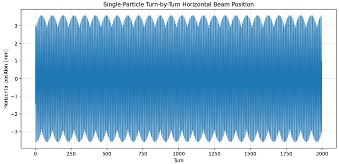
$$R \propto \sqrt{\beta_K \beta_{\text{BPM}}} \sin(2\pi\Delta\mu).$$

The optics give $|R_x| \simeq 7.11$ m and $|R_y| \simeq 11.23$ m:

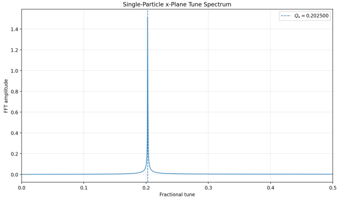
$$|R_x/R_y| \simeq 0.63.$$

- Thus the H optical response is about 63% of V for equal angular kicks.

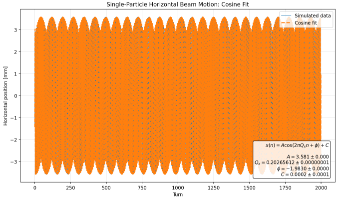
Single-particle tracking: horizontal tune



Turn-by-turn horizontal position



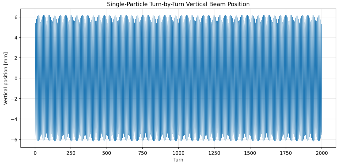
FFT tune spectrum



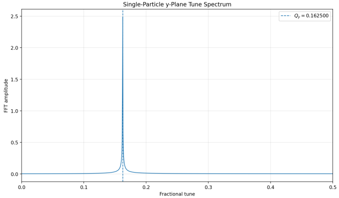
Cosine fit

- Track a single particle with simultaneous single-turn H/V kicks and record turn-by-turn BPM positions.
- No damping term is needed for the single-particle signal; a regular cosine describes the oscillation.
- FFT gives $Q_x = 0.2025$; the cosine fit gives $Q_x = 0.20265612 \pm 0.00000001$. The difference is $1.56 \times 10^{-4} < \Delta Q_{\mathrm{FFT}} = 0.0005$.

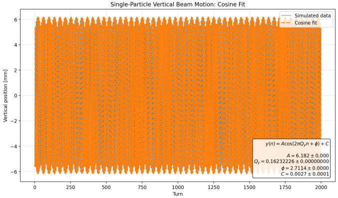
Single-particle tracking: vertical tune



Turn-by-turn vertical position



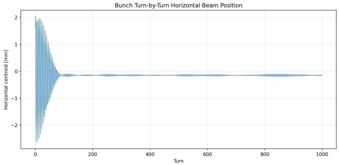
FFT tune spectrum



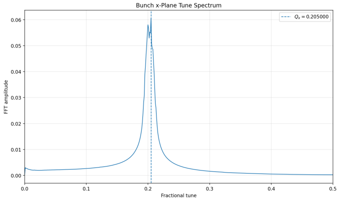
Cosine fit

- The same simultaneous single-turn H/V-kick procedure is used for the vertical plane.
- A regular cosine fit is sufficient for the single-particle vertical signal.
- FFT gives $Q_y = 0.1625$; the cosine fit gives $Q_y = 0.16232226 \pm 0.00000000$. The difference is $1.78 \times 10^{-4} < \Delta Q_{\mathrm{FFT}} = 0.0005$.

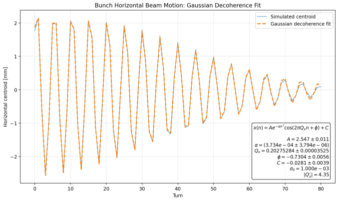
Bunch tracking: horizontal tune and chromaticity



Turn-by-turn horizontal centroid



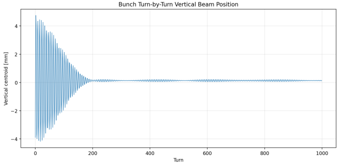
FFT tune spectrum



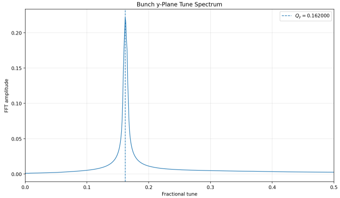
Gaussian decoherence fit

- Track a **10,000-particle bunch** with RMS relative energy spread $\sigma_\delta = 10^{-3}$ and simultaneous single-turn H/V kicks.
- Record the horizontal bunch centroid turn-by-turn; the FFT gives $Q_x = 0.2050$.
- Gaussian decoherence fit gives $Q_x = 0.20275284 \pm 0.00003525$ and, using $\sigma_\delta = 10^{-3}$, $|Q'_x| = 4.35$.

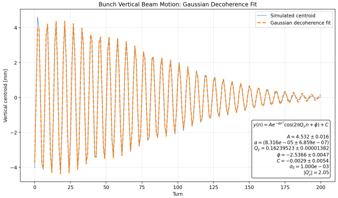
Bunch tracking: vertical tune and chromaticity



Turn-by-turn vertical centroid



FFT tune spectrum



Gaussian decoherence fit

- The same **10,000-particle bunch** and $\sigma_\delta = 10^{-3}$ are used for the vertical-plane analysis.
- Record the vertical bunch centroid turn-by-turn; the FFT gives $Q_y = 0.1620$.
- Gaussian decoherence fit gives $Q_y = 0.16239523 \pm 0.00000138$ and, using $\sigma_\delta = 10^{-3}$, $|Q'_y| = 2.05$.

Chromaticity: Twiss calculation vs. bunch decoherence fit

	Twiss	Gaussian fit
Q'_x	-7.281	$\lvert Q'_x \rvert = 4.35$
Q'_y	-2.983	$\lvert Q'_y \rvert = 2.05$

The fit assumes

$$\sigma_\delta = 10^{-3}, \qquad \alpha = 2\pi^2 (Q')^2 \sigma_\delta^2.$$

Why are the fitted values smaller?

- Twiss Q' is the lattice chromaticity, i.e. the local derivative $dQ/d\delta$.
- The bunch fit infers $|Q'|$ indirectly from the centroid decoherence and assumes an ideal Gaussian tune-spread model.
- The inferred value depends on the actual bunch σ_δ and on the chosen fit interval; the decoherence envelope also contains effects beyond the simple linear model.

The decoherence fit is a model-dependent chromaticity estimate, not a direct replacement for the Twiss derivative.

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2. **2025 Tune Measurement**
   Analyze the 2025 Booster turn-by-turn data with FFT and damped-oscillation fits, and compare with SciBmad Twiss results.

3. **Tune Measurement Simulation**
   Reproduce the tune-measurement procedure with SciBmad tracking using single particles and bunches.

4. **2026 Tune Measurement**
   Compare kicker-OFF/ON data and use Gaussian band-pass filtering and decoherence fitting for the noisier 2026 data.

5. **Multi-BPM Analysis**
   Develop a multi-BPM tune and phase-advance analysis for future measurements and benchmark it against SciBmad Twiss.

2026 Booster tune measurement

Measurement campaign

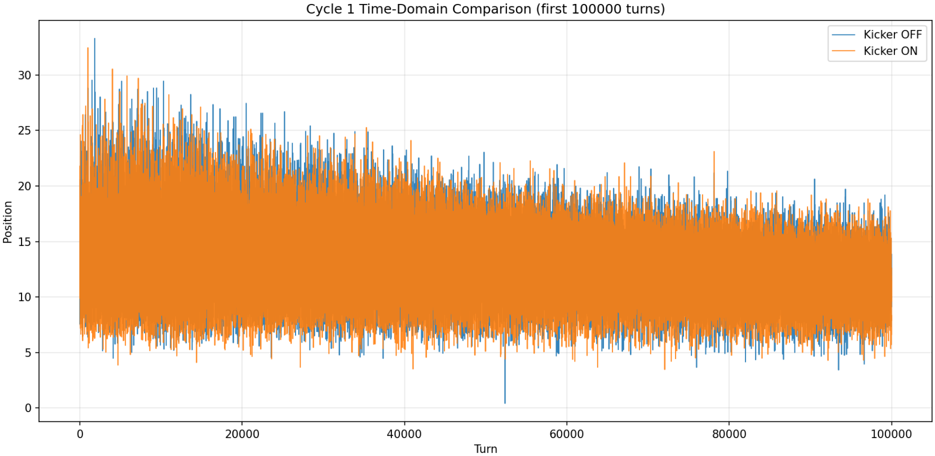
- Tune measurement performed in 2026 by **Kiel, Lucy, Eiad, and Jun**.
- The measurement was carried out near the **end of the run**, with limited machine time available.
- Due to the limited time and problems with the **horizontal kicker**, only the **vertical tune measurement** was completed.

Turn-by-turn data

- Apply the vertical single-turn kick and record the vertical beam position turn-by-turn.
- The 2026 vertical TBT signal is **noisier than the 2025 horizontal data**.
- The larger noise level is attributed to the **lower beam intensity** during this measurement.

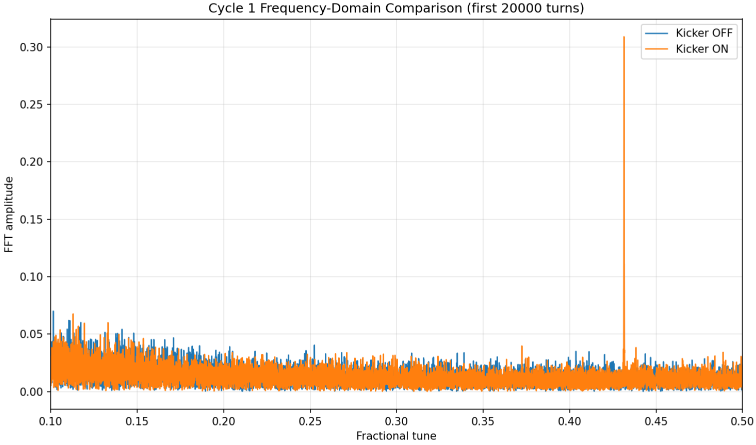
2026 measurement: vertical plane only, with lower-intensity and noisier TBT data.

2026 measurement: kicker OFF vs ON in time domain



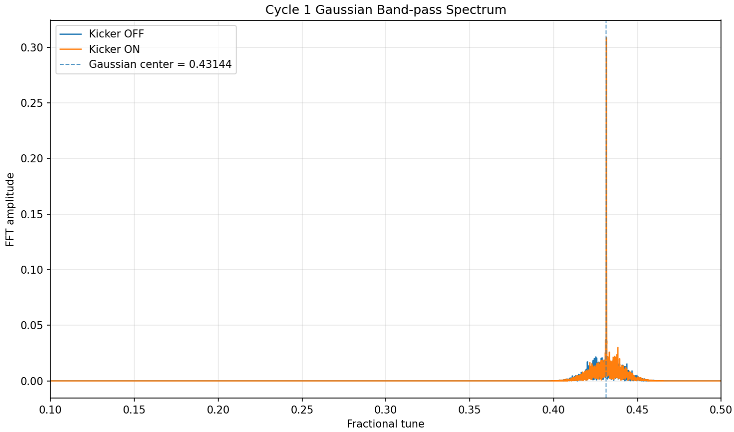
Compare the first 100,000 turns of cycle 1 with the vertical kicker OFF and ON.

2026 measurement: kicker OFF vs ON in frequency domain



FFT of the first 20,000 turns. A strong tune peak near $Q \simeq 0.431$ appears when the kicker is ON, while it is not visible with the kicker OFF.

Gaussian band-pass around the vertical tune



- Use the full **100,000-turn** cycle for the FFT.
- Apply the same Gaussian band-pass to kicker OFF and ON data.
- Gaussian center:

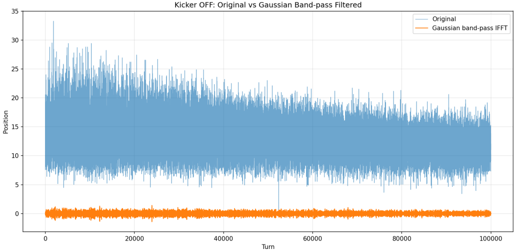
$$Q_0 = 0.43144$$

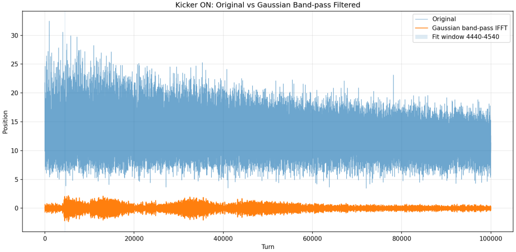
- Gaussian width:

$$\sigma_Q = 0.010$$

- Inverse FFT gives the tune-band time-domain signal.

Gaussian band-pass IFFT: kicker OFF and ON



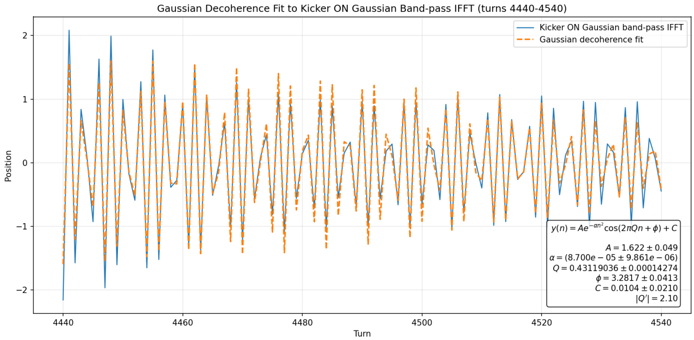


Kicker OFF: no clear coherent tune signal after filtering.

Kicker ON: a coherent oscillation is isolated by the Gaussian band-pass.

The Gaussian filter is applied in frequency space to the full cycle, followed by an inverse FFT back to the time domain.

2026 measurement: Gaussian decoherence fit



- Fit the kicker-ON Gaussian-bandpass IFFT signal over turns **4440–4540**.
- Gaussian decoherence model:

$$y(n) = Ae^{-\alpha n^2} \times \cos(2\pi Q n + \phi) + C$$

- Fitted tune:

$$Q = 0.43119036 \pm 0.00014274$$

  The 0–0.5 spectrum corresponds to $Q_y = 0.43119$ or $1 - Q_y = 0.56881$; a direct SciBmad comparison requires the corresponding 2026 historical machine settings.
- Using $\sigma_\delta = 10^{-3}$ gives

$$|Q'| = 2.10.$$

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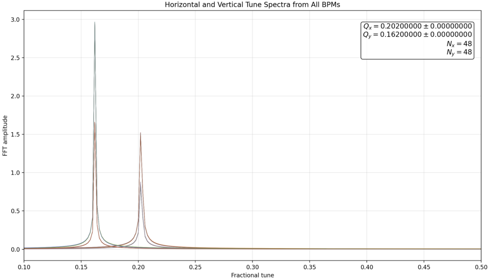
   Develop a multi-BPM tune and phase-advance analysis for future measurements and benchmark it against SciBmad Twiss.

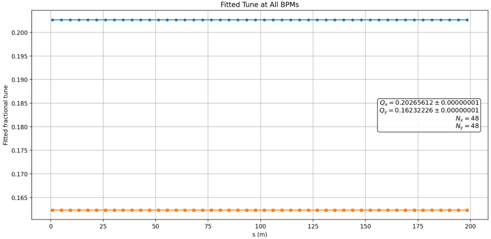
Multi-BPM tune analysis for future measurements

- Previous Booster tune measurements used a single horizontal TBT BPM and a single vertical TBT BPM.
- Develop a multi-BPM analysis tool in SciBmad for future tune measurements.
- In simulation, apply simultaneous single-turn H/V kicks and record turn-by-turn positions at multiple BPMs around the Booster. At each BPM, use FFT and oscillation fitting to extract Q_x and Q_y; the multiple BPM estimates allow the average and uncertainty of Q_x and Q_y to be calculated.
- **FFT:** obtain a robust tune estimate at each BPM, limited by the FFT-bin spacing.
- **Fit:** obtain sub-bin tune estimates and the fitted phase at each BPM; use the phases to reconstruct the phase advance through the beam line and benchmark it against the accumulated SciBmad Twiss phase.

Multi-BPM tune extraction: FFT and fit

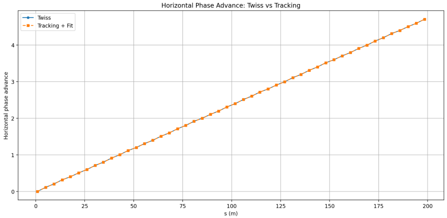


FFT: extract Q_x and Q_y independently at every BPM; robust but limited by the FFT bin spacing.

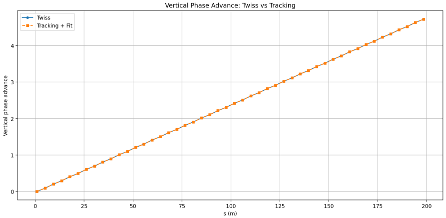


Fit: obtain sub-bin Q_x and Q_y estimates consistently across all BPMs, together with the fitted phase at each BPM.

Reconstruct phase advance from multi-BPM fits



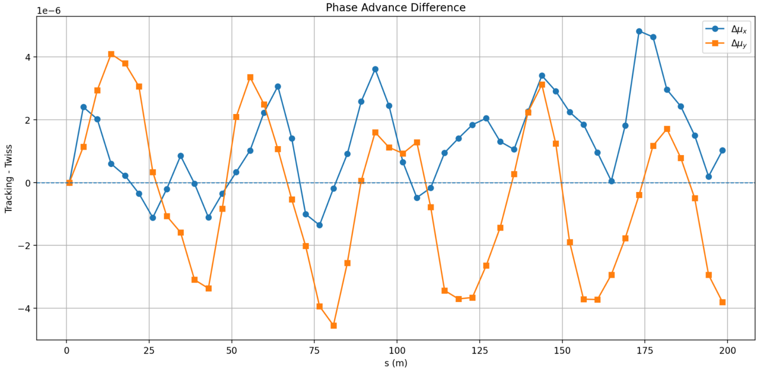
Horizontal phase advance



Vertical phase advance

From the fitted phase ϕ at each BPM, use $\mu = \phi/(2\pi)$ and adjust by integers to obtain a monotonically increasing accumulated phase. The reconstruction closely follows the SciBmad Twiss result.

Multi-BPM phase-advance benchmark



- Difference shown as tracking/fit minus Twiss.
- Agreement is at the few-10^{-6} level in this SciBmad simulation.
- This validates the phase-reconstruction procedure before applying it to future multi-BPM experimental data.

Summary

1. **Booster Modeling & Benchmarking**
   Developed and benchmarked a SciBmad model of the Booster, providing a foundation for optics calculations, tracking studies, and operational applications.

2. **2025 Tune Measurement**
   Applied frequency- and time-domain analysis to experimental turn-by-turn data to extract tune information and study coherent beam-motion decoherence.

3. **Tune Measurement Simulation**
   Reproduced the tune-measurement procedure with SciBmad tracking and used the model to investigate beam response, decoherence, and the kicker–BPM optics.

4. **2026 Tune Measurement**
   Extended the analysis to noisier 2026 data, using kicker-OFF/ON comparisons and frequency-domain filtering to isolate the coherent tune signal.

5. **Multi-BPM Analysis**
   Developed a multi-BPM framework for more robust tune extraction and phase-advance reconstruction, and validated the method against SciBmad Twiss calculations.

Thank You