Experimental Verification and Analysis of Beam Loading Effect Based on Precise Bunch-by-Bunch 3D Position Measurement

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IBIC 2022

International Beam Instrumentation Conference

Krakow, 11-15 September 2022

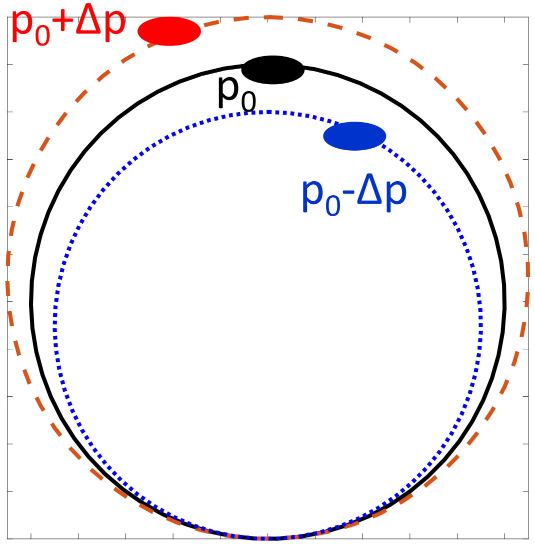
Outline

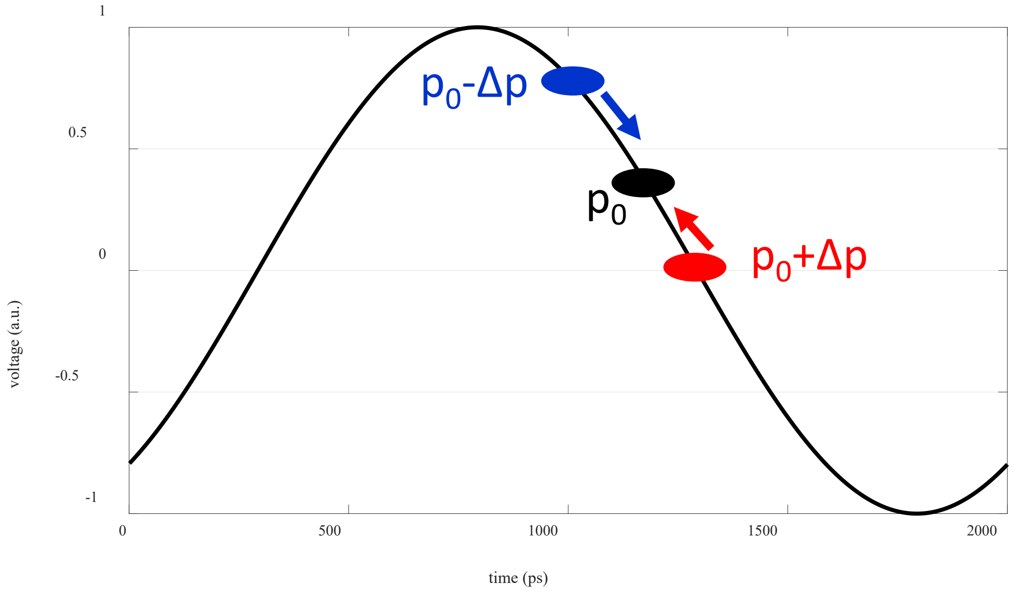
- Motivation: why beam loading effect and why using 3D position tools
- How: what instruments and software tools used
- How: experiment setup and result analyze
  - Accelerating phase shift measurement and analyze
  - Synchrotron tune and damping time measurement and analyze
- Summary

Synchrotron motion and beam loading effect

Synchrotron motion: ideal condition

The synchrotron motion can be modeled as **simple damped harmonic oscillator** under ideal condition.





Longitudinal motion equation:

$$\frac{d^2\Delta s}{dt^2} + 2\alpha_D \frac{d\Delta s}{dt} + \Omega^2 \Delta s = 0$$

Total energy gain per turn:

$$\Delta E_T = qV + U(E)$$

$$V_{RF}(t) = \hat{V}\sin(\omega_{RF} t) = \hat{V}\sin(h\omega_0 t)$$

Dispersion effect in storage ring

- Higher energy, larger orbital radius
- Higher energy bunch arrives later
- Lower energy bunch arrives earlier

Longitudinal focusing come from a time-varying accelerating field provided by an RF system

Synchrotron motion: ideal condition

The synchrotron motion can be modeled as **simple damped harmonic oscillator** under ideal condition.

$$\frac{d^2\Delta s}{dt^2} + 2\alpha_D \frac{d\Delta s}{dt} + \Omega^2 \Delta s = 0$$

$$\alpha_D = -\frac{1}{2T_0}\frac{dU}{dE}\bigg|_{E_0}$$

synchrotron damping time

- Mainly: synchrotron radiation energy loss
- Additional: Landau damping ($\Delta\Omega \uparrow$)

$$\Omega^2 = \alpha \frac{1}{p_0}\frac{q}{T_0}\frac{dV}{ds}\bigg|_{s_0}$$

synchrotron frequency

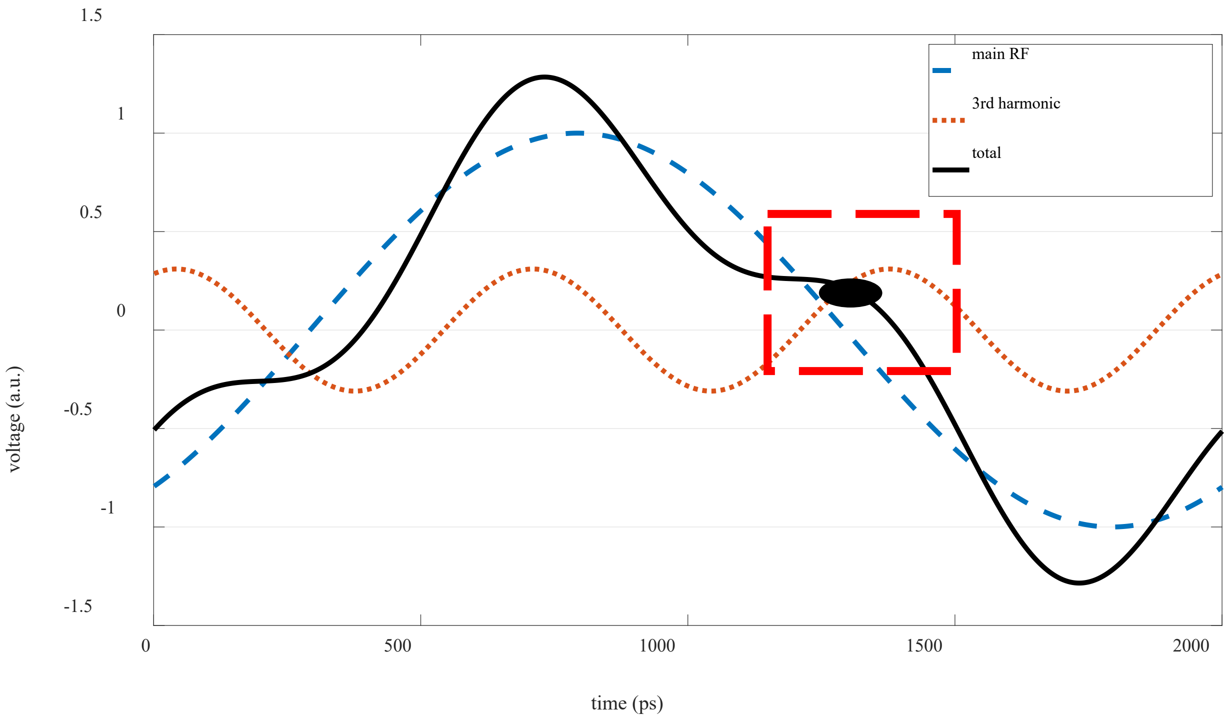
- Mainly: accelerating electric field gradient
- $\frac{dV}{ds} \uparrow$, $\Omega \uparrow$

Synchrotron motion: **practical condition**

Total voltage = main RF cavity voltage + 3rd harmonic cavity voltage

The field distribution near the accelerating phase can be modified by the wake field induced by the harmonic cavity and **the other vacuum components**.

There will be some parameter changes.

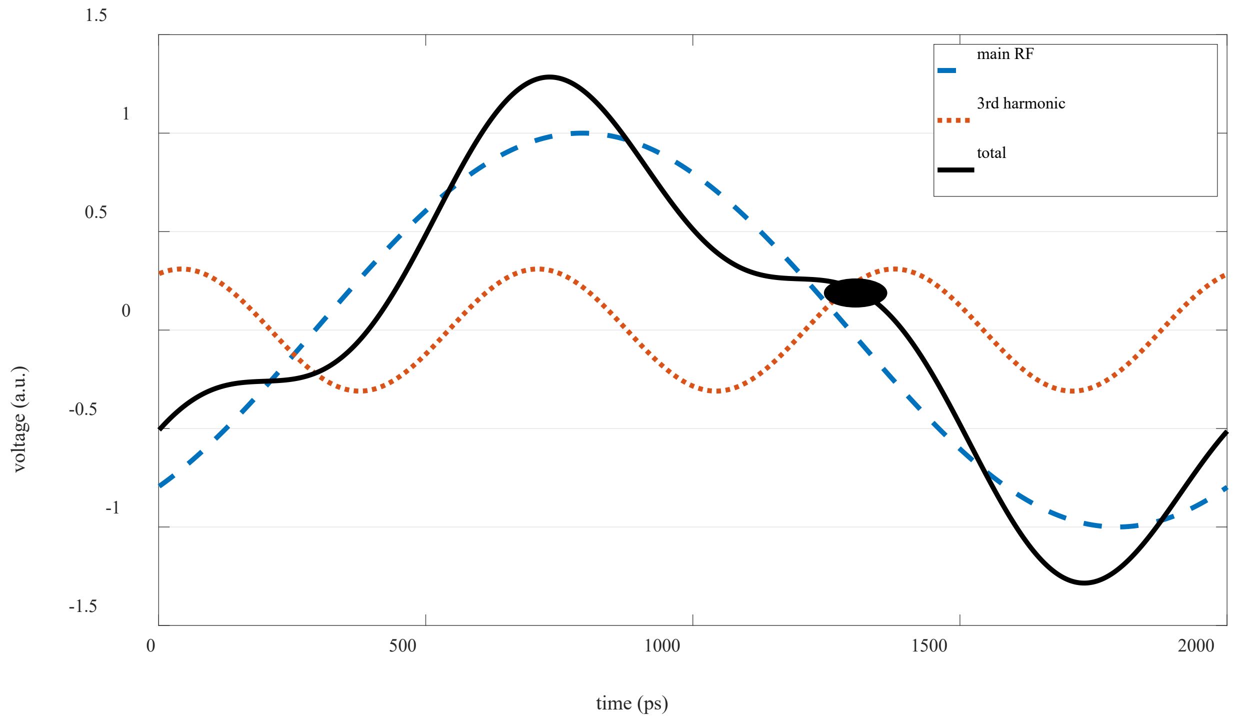


- **Amplitude change:** synchrotron radiation energy loss unchanged → **accelerating phase shift** (ensure equivalent cavity voltage unchanged)
- **Electric field gradient change:** → **synchrotron frequency shift**
- **Increase in synchrotron frequency spread** between bunches: → additional Landau damping → **damping time shift**
- **Potential Well distortion**: → longitudinal distribution (**bunch length**) change

Beam loading effect

- **Uniform fill pattern** (bunches are perfectly symmetrical) → no difference in parameters between bunches
- **Non-uniform fill pattern** (e.g. gaps between bunch trains or differences between bunch charges)→ accelerating field of each bunch inconsistent → characteristic parameters different

The **beam loading effect** mainly comes from non-uniform filling.



- **Influence of beam loading effect**
  - Possible beam quality degradation
  - Increase operational difficulty of related systems: RF system, beam feedback system

Compensation

- **Beam loading effect needs to be observed and analyzed precisely to improve machine performance!**

Beam loading effect: diagnostics tools

Parameters	Design value (typical)	General variation (beam loading effect)	Diagnostic tools		
			streak camera	BYB feedback processor	BYB 3D position measurement system
bunch length	~ 10 ps	10 ps ~ 100 ps	Yes		
sync. phase shift		1 ps ~ 100 ps	Yes		Yes
sync. frequency	~ kHz	kHz ~ 100 Hz		Yes	Yes
sync. damping time	~ ms	~ ms		Yes	Yes

- **Streak camera:** (J.M. Byrd, PRST, 2002 @ALS; G. Penco, PRST, 2006 @ELETTRA)
  - Advantage: bunch length and synchronous phase shift measurement
  - Disadvantage: no charge information, poor synchronous phase resolution
- **BYB feedback processor:** (A. Schälicke, IBIC2013 @BESSY II; M. Honer, IPAC2012 @DELTA)
  - Advantage: synchrotron frequency and synchrotron damping time measurement
  - Disadvantage: require additional perturbation to beam
- **BYB 3D position measurement system:** (X.Y. Xu, PRST, 2021 @SSRF; Y.M. Zhou, NIMA, 2020 @SSRF)
  - Steady-state data: obtain synchronous phase shift between bunches
  - Injection transient data: obtain synchrotron frequency and damping time using refilled charges as probe

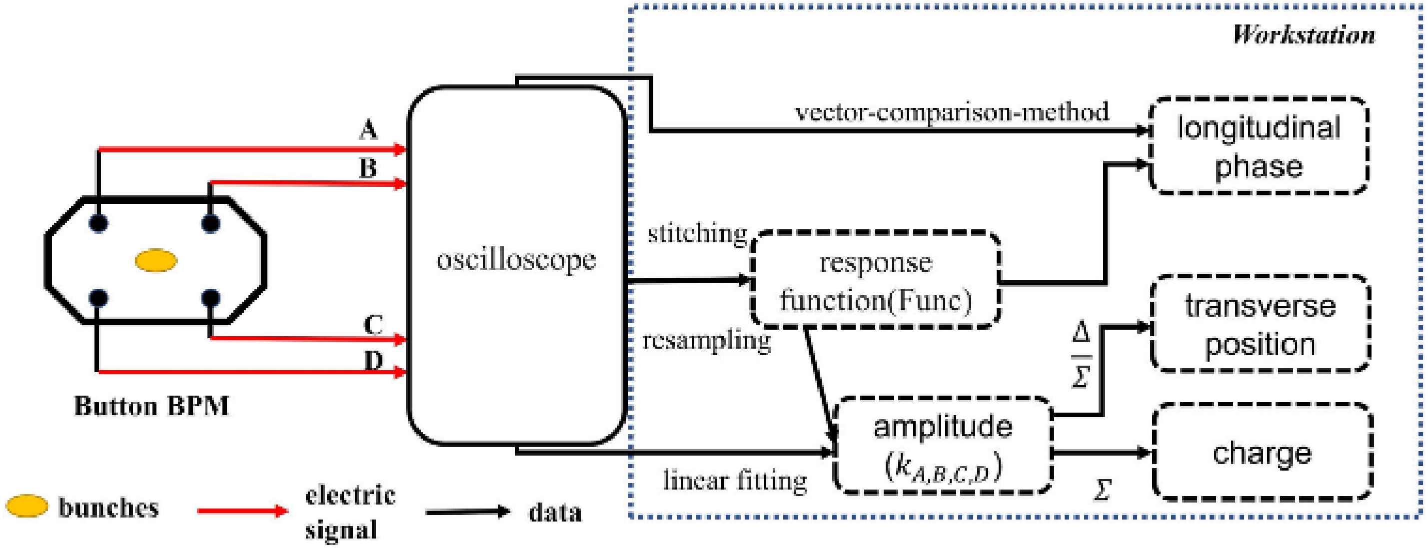
Undisturbed!

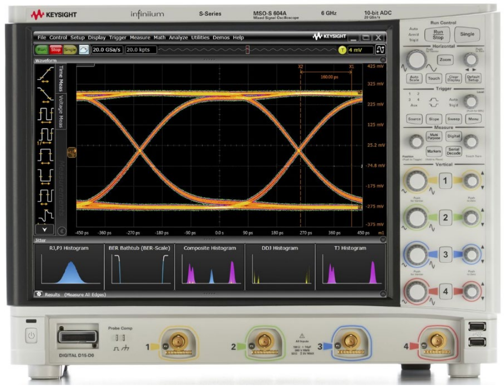
Diagnostics and software tools for observation and analyze

Including:

- Bunch by bunch 3D position measurement tools: HOTCAP
- Longitudinal simulation code: STABLE

HOTCAP: System Framework





Source: → **Hardware:** → **Data processing:**

Button BPM

$$V_b(t) = \frac{-Z}{\beta c} \cdot \frac{t - t_0}{\sigma^2} \cdot I(t) \cdot F(\delta, \theta)$$

Longitudinal phase (t_0); Charge ($I(t)$); Transverse position ($F(\delta, \theta)$)

Keysight MSOS604A	
Sampling rate	10 GS/s
Bandwidth	4.2 GHz
ENOB	10 bit
Memory depth	103 M/channel

Correlation coefficient-based method

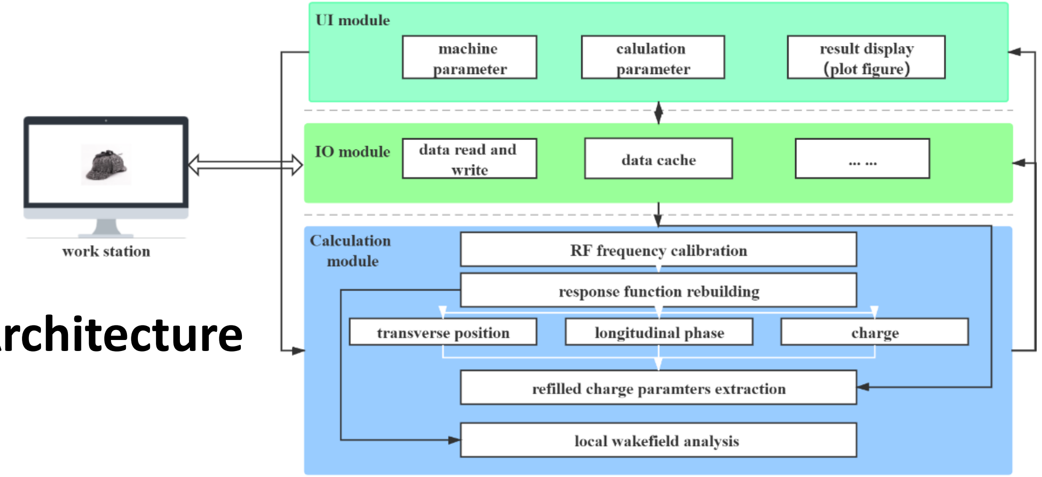
- Construction of ultra-high time-resolved response functions
- 3D position information extraction algorithms

* X.Y Xu, Phys. Rev. Accel. Beams 24 032802 (2021)

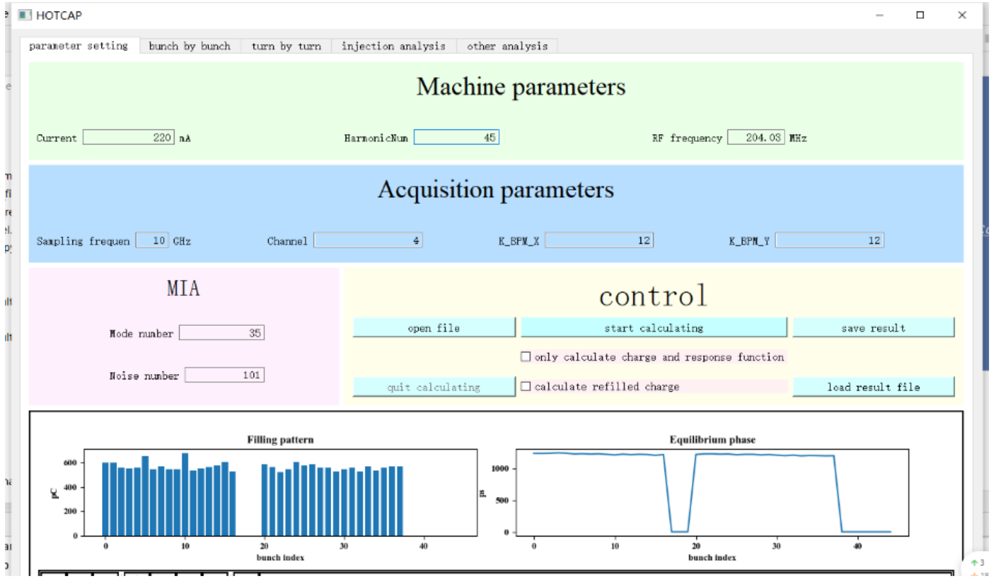
HOTCAP: functionality

High speed **O**scilloscope based **T**hree-dimesion bunch **C**harge **A**nd **P**osition measurement system， **HOTCAP**

- Composition: User Interface (UI) Module, Calculation Module, Input Output (IO) Module
  - Input: Electrode signal by high-speed oscilloscope
  - Output: 3D position results (including stored bunches and refilled charges)
  - Others: Injection analysis, Wakefield analysis…
- Application: SSRF, HLS



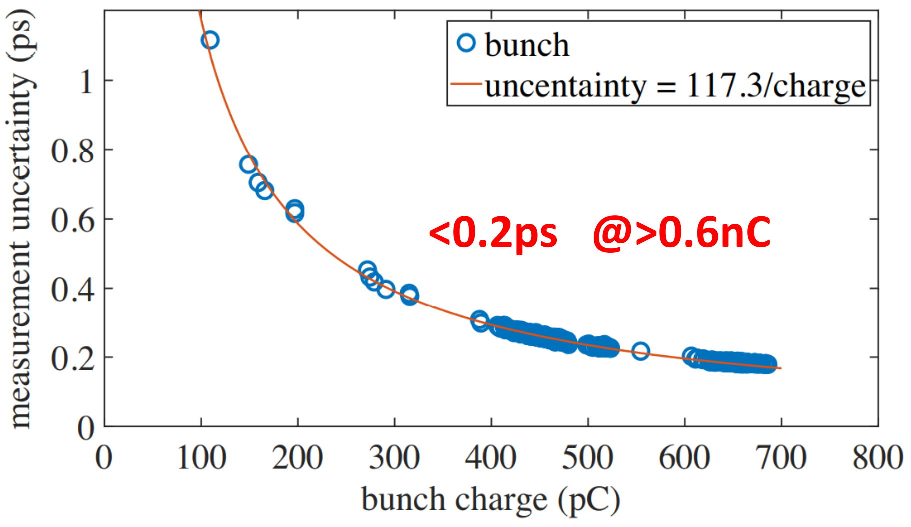
Architecture



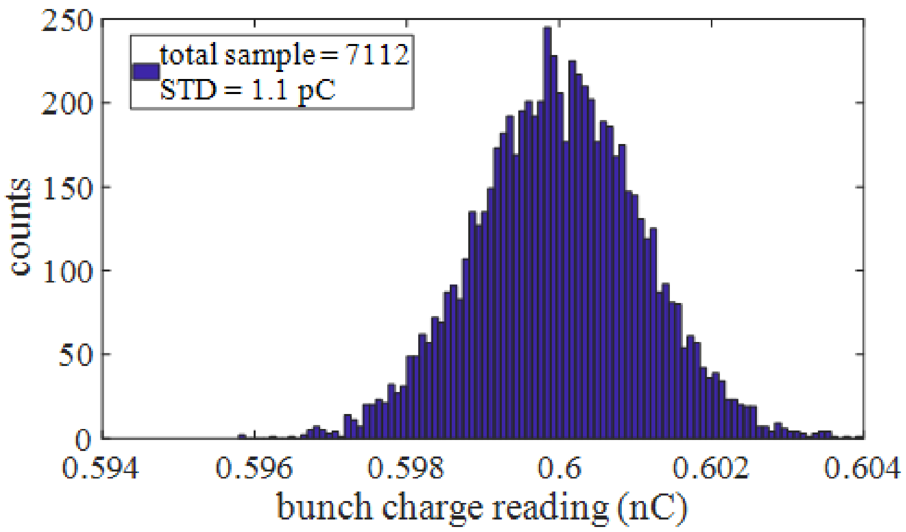
HOTCAP: System performance

- Data collected during user operation, uniform filling
- PCA method to evaluate transverse position and longitudinal phase measurement errors

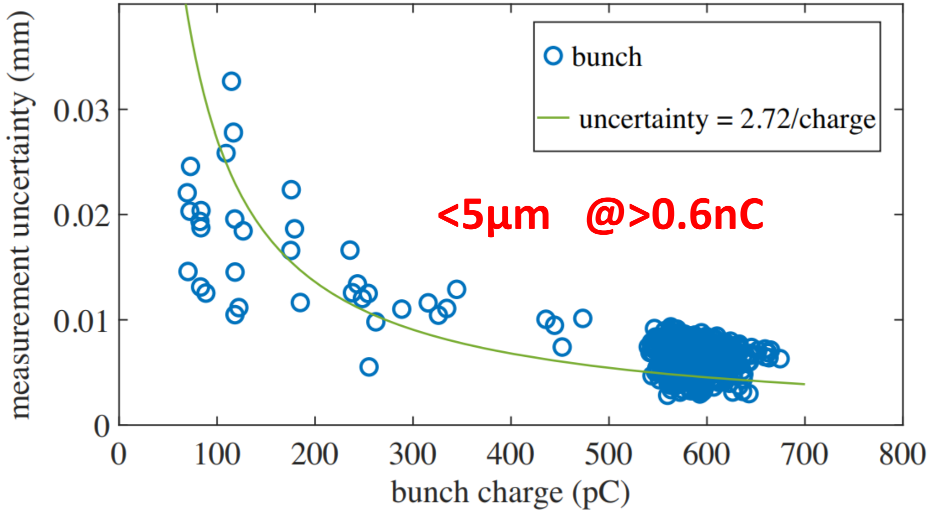
- Charge resolution: 0.2% (averaged charge reached 0.02%)
- **Phase resolution: 0.2ps @ 0.6nC**
- Position resolution: 0.5μm @ 0.6nC



Longitudinal phase measurement uncertainty with charge



Bunch-by-bunch charge resolution



Transverse position measurement uncertainty with charge

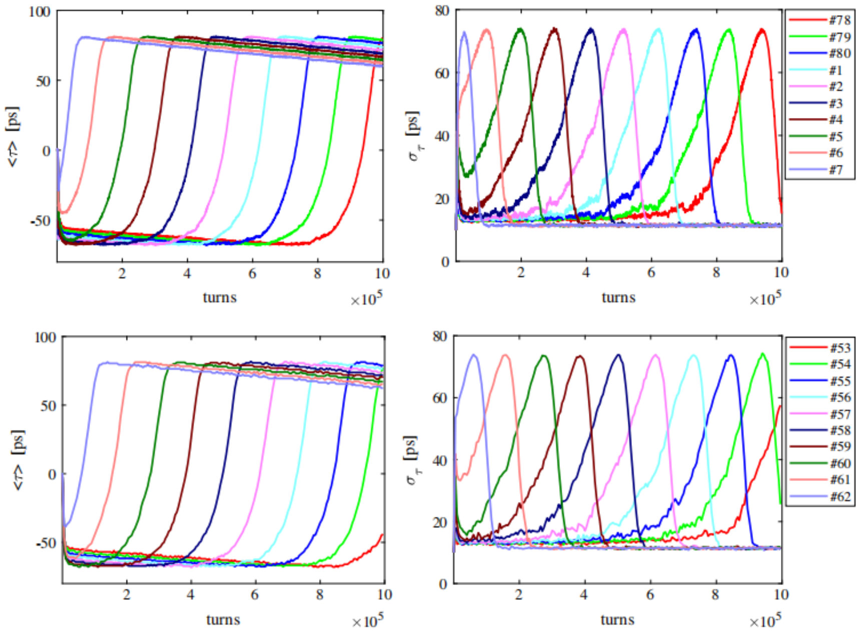
GPU-accelerated tracking code-STABLE

- Presently used for longitudinal beam dynamics study only.
- Arbitrary filling pattern and arbitrary charge configuration, short range wakefield, HOMs, Realistic rf feedback modelling for active rf cavity.
- MATLAB script
- High efficient
- Benchmark well against Elegant-code

* T. He and Z. Bai, Phys. Rev. Accel.Beams 24 104401 (2021)

Table. Calculation efficiency test

Machine	Bunch number	Particles per bunch	Time [s]
ALS-U	284	1×10^3	79
ALS-U	284	5×10^3	154
ALS-U	284	1×10^4	249
HALF	720	1×10^3	108
HALF	720	5×10^3	295
HALF	720	1×10^4	529



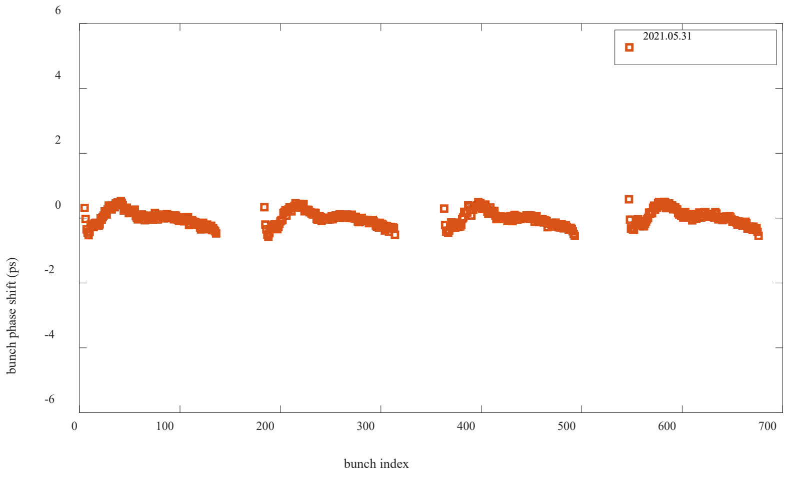
STABLE

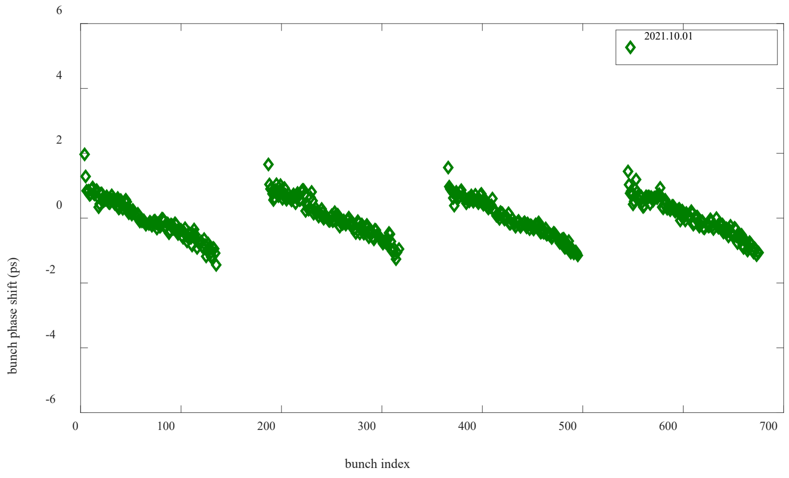
ELEGANT

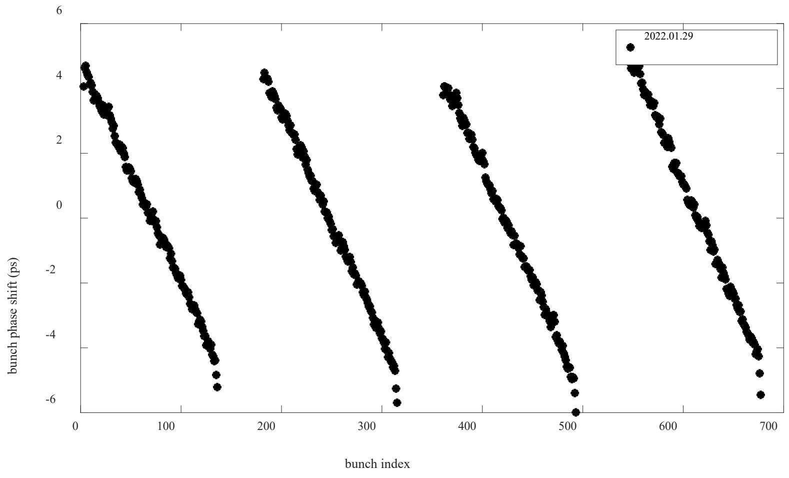
Synchronous phase shift measurement and analyze

Phase shift modulation by beam impedance

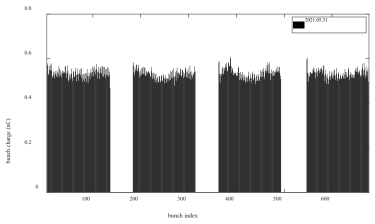
- **Bunch equilibrium acceleration phase** modulation → derived from the correction of the beam wake field (impedance)
  → an important measurement parameter for evaluating the beam loading effect
- HOTCAP system to record equilibrium acceleration phase in bunch train during different stages of **user operation** in the SSRF
- For approximately uniform fill patterns：
  - **Before** the harmonic cavity installation → impedance sources: Main cavity + IDs → phase shift ~ 1ps
  - **After** the harmonic cavity (passive) installation → impedance sources: Main cavity + IDs + Harmonic cavity → phase shift ~ linear distribution



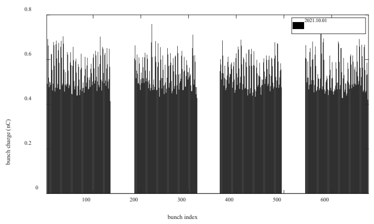




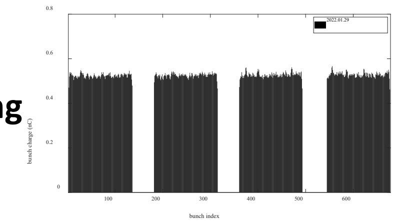
Main cavity + IDs
No harmonic cavity
Phase shift ~ 1ps



Main cavity + IDs
Harmonic cavity installed
Phase shift ~ 3ps



Main cavity + IDs
Harmonic cavity working
Phase shift ~ 10ps

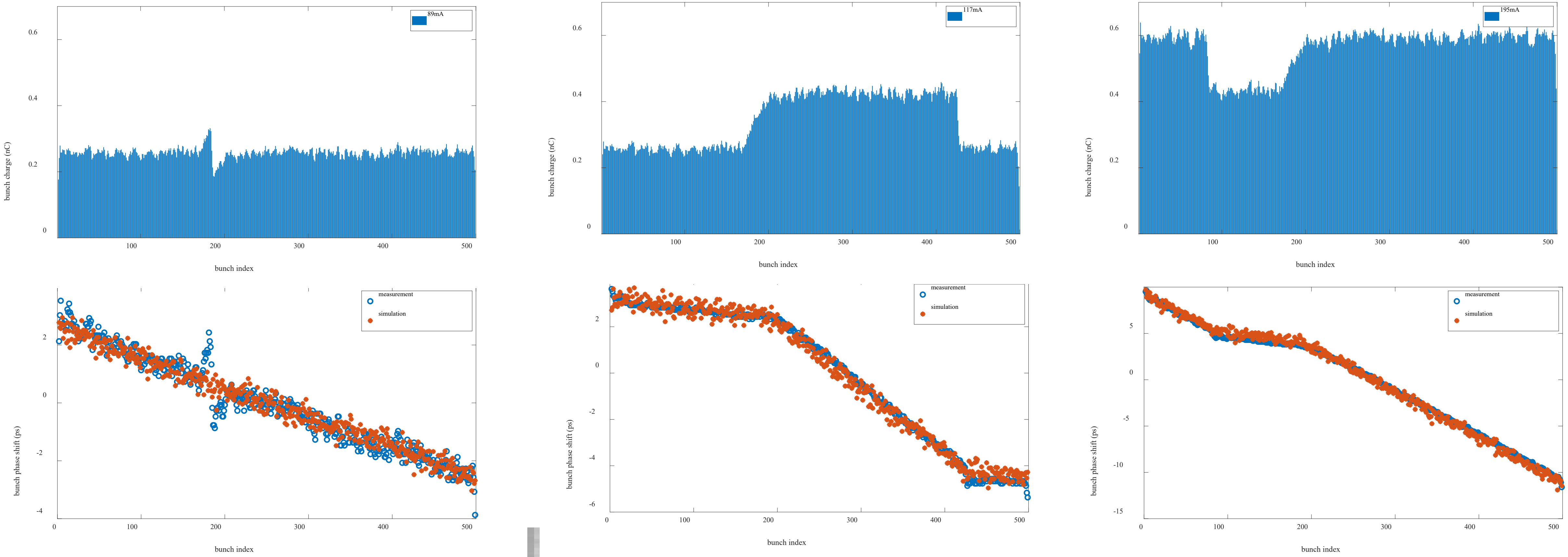


Phase shift modulation by filling patterns

- **Phase shift at the head and tail of the train**
  - a **common value** used to evaluate the strength of beam loading effect
- **Phase distribution in the train** under different filling patterns
  - HOTCAP: measurement (**blue circle**)
  - STABLE: simulation (**red star**)

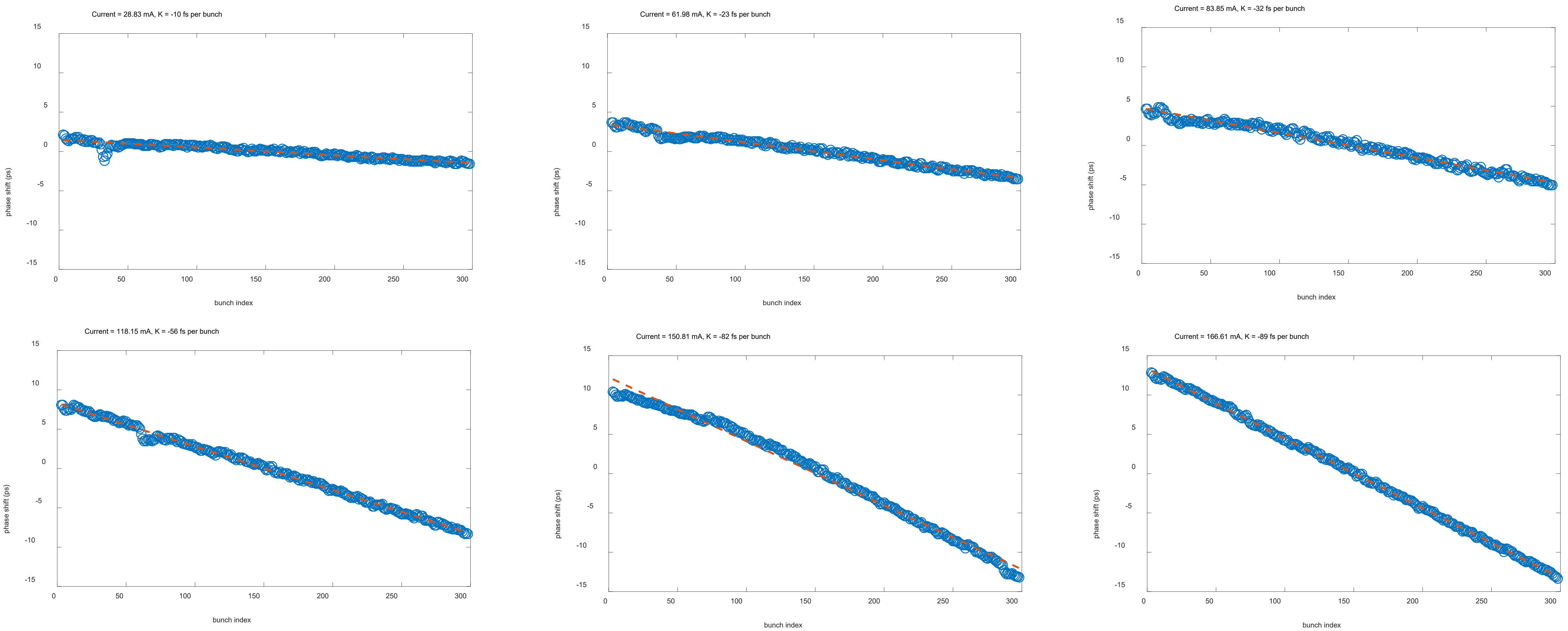
Perfect agreement

- **The slope (K_φ) of phase distribution under uniform filling**
  - a **more accurate parameter** to evaluate the strength of beam loading effect
- Phase distribution is related to the bunch filling pattern
  - the same total current + different charge distribution → different phase shift at the head and tail of the train



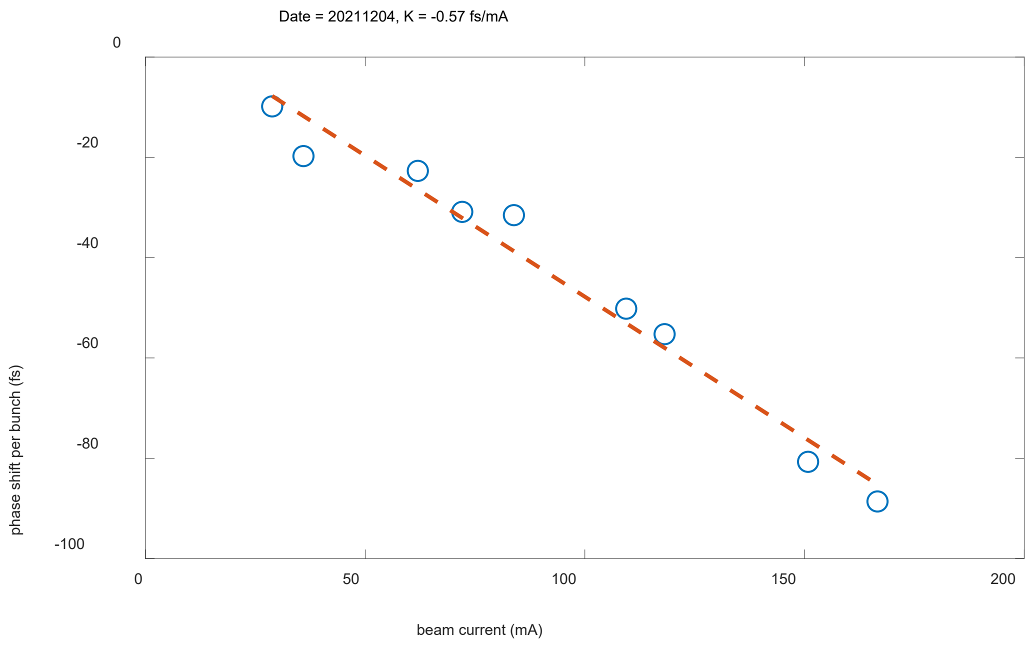
Phase shift modulation by total current

- Beam accumulation process → Equilibrium phase distributions in the bunch train under different beam currents
- Phase distribution → a linear decreasing distribution → the slope (K) is linearly and positively related to the total current
- **The change rate ($K_{\varphi l}$)** of the phase slope K determined by **harmonic cavity parameters**

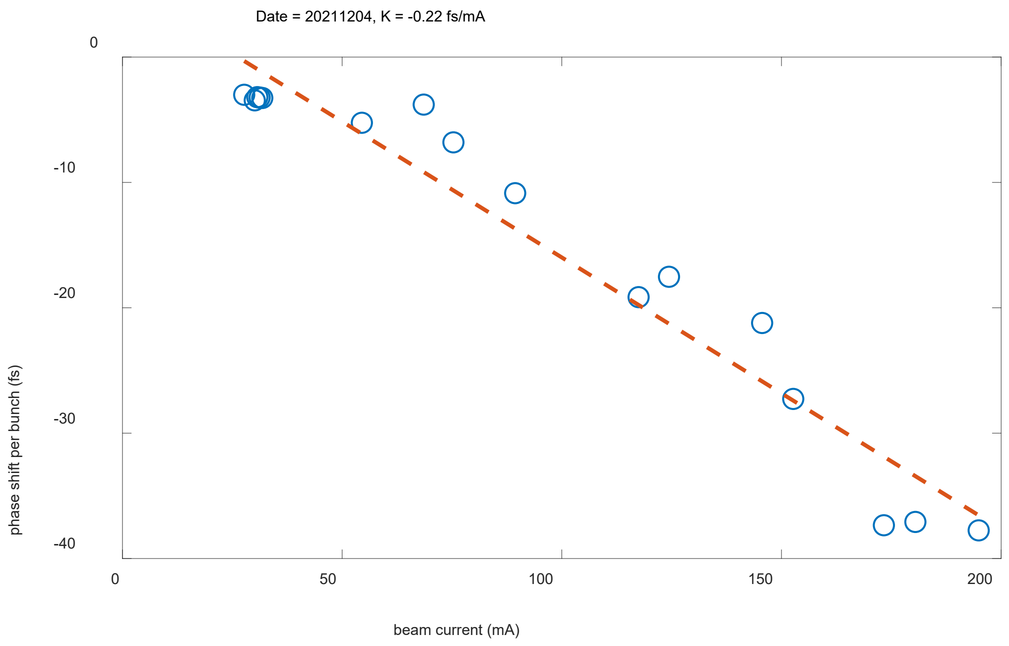


Beam loading effect evaluation

- The change rate ($K_{\varphi l}$) of the phase slope for different bunch filling pattern under the same harmonic cavity parameters
- Larger bunch filling gaps → larger change rate ($K_{\varphi l}$) → larger beam loading effect
- consistent with the theoretical expectation



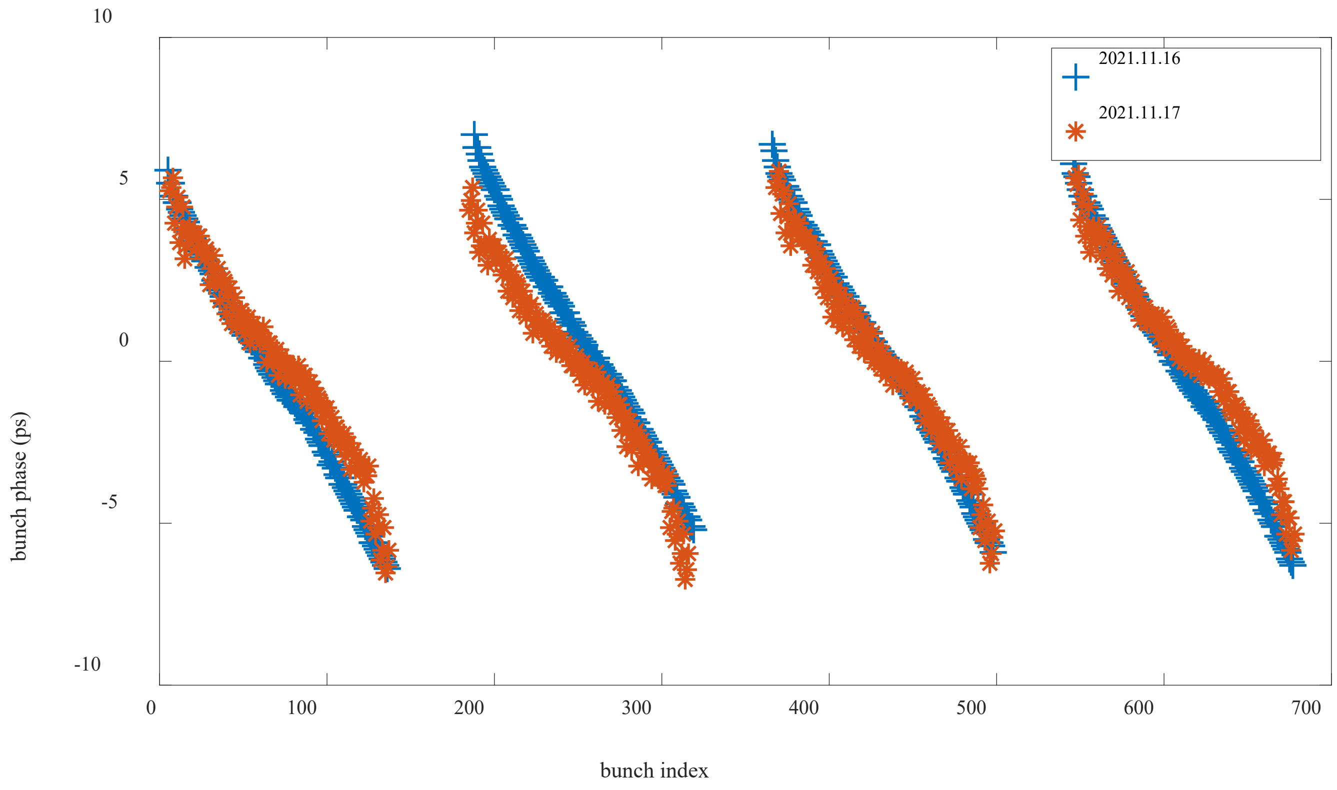
300 bunches filled, gap = 420 buckets

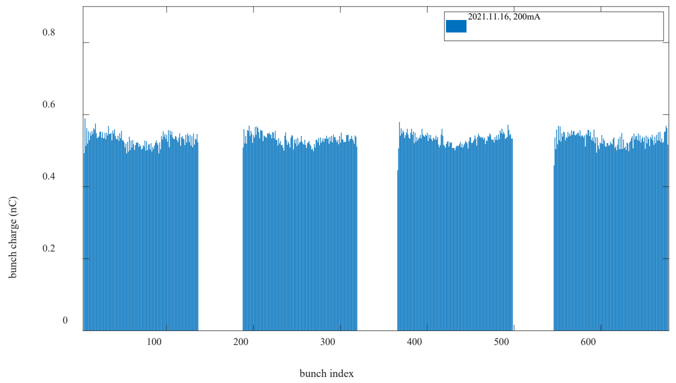


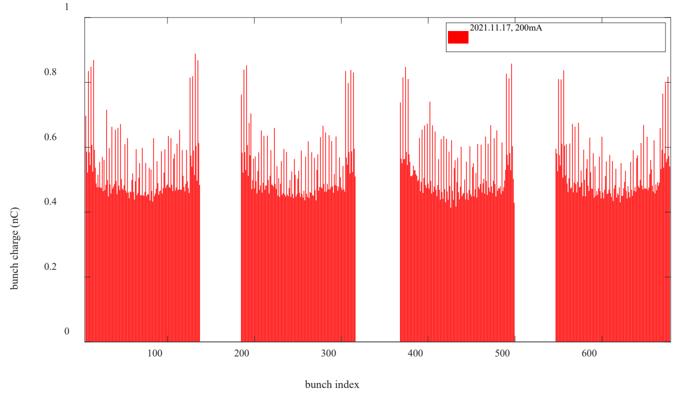
500 bunches filled, gap = 220 buckets

Beam loading effect: Compensation

- **Beam Loading Effect Compensation**: increasing the bunch charge at the head and tail of the beam trains
- The difference of the phase distribution in the beam trains under the two filling patterns is in the **sub-ps order** (HOTCAP: powerful enough to distinguish)
- With compensation filling, the phase shift slope in the bunch trains becomes smaller, the beam loading effect becomes weak





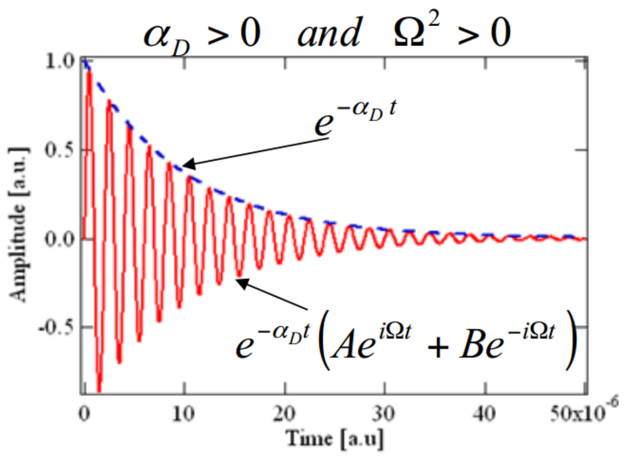


Synchrotron frequency and damping time measurement and analyze

Experiment setup

- Data Acquisition: **injection transient process** of the top-up operation
- Injection data → strip out the refilled charge → analyze the longitudinal damping oscillation process → extract longitudinal damping time and synchrotron tune

$$\frac{d^2\Delta s}{dt^2} + 2\alpha_D \frac{d\Delta s}{dt} + \Omega^2 \Delta s = 0$$



$$\alpha_D = -\frac{1}{2T_0}\frac{dU}{dE}\bigg|_{E_0}$$

$$\Omega^2 = \alpha \frac{1}{p_0}\frac{q}{T_0}\frac{dV}{ds}\bigg|_{s_0}$$

longitudinal damping time

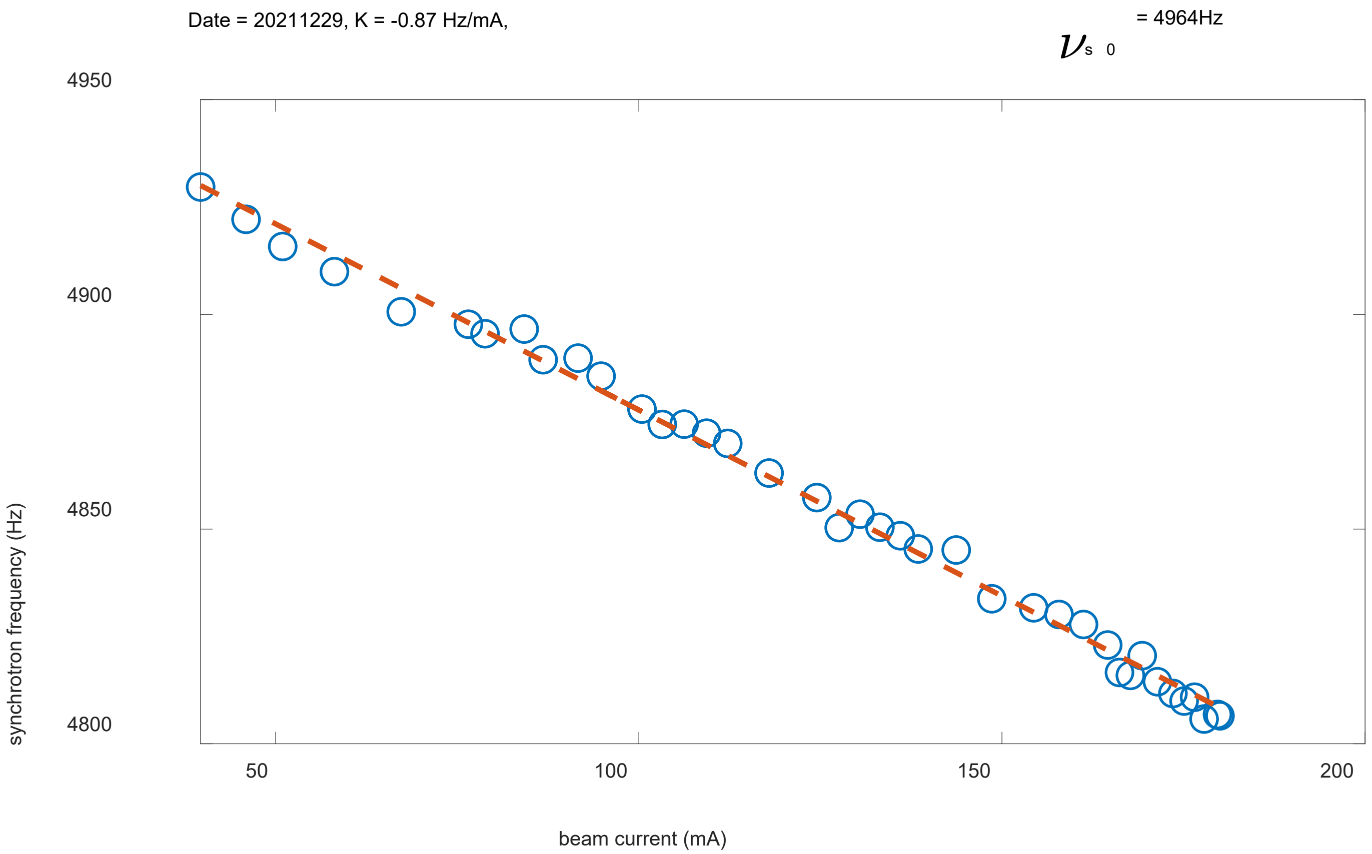
Analyze longitudinal damping time vs beam current
→ Evaluate Landau damping contribution
→ Evaluate longitudinal potential well distortion

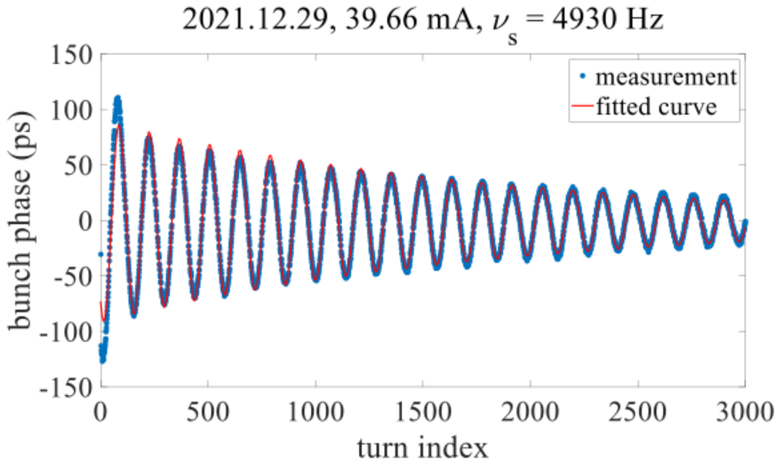
synchrotron frequency

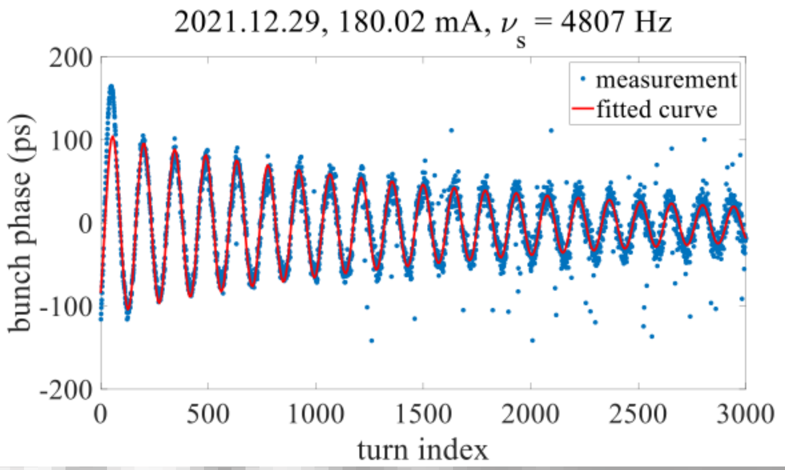
Analyze synchrotron tune vs beam current
→ Evaluate longitudinal acceleration electric field distortion

Synchrotron frequency shift w/o harmonic cavity

- the harmonic cavity **detuned** far from working frequency
- the synchrotron frequency is linearly related to the beam current, and the change rate is **-0.87Hz/mA**
- synchrotron frequency differences can be distinguished at the **order of Hz**

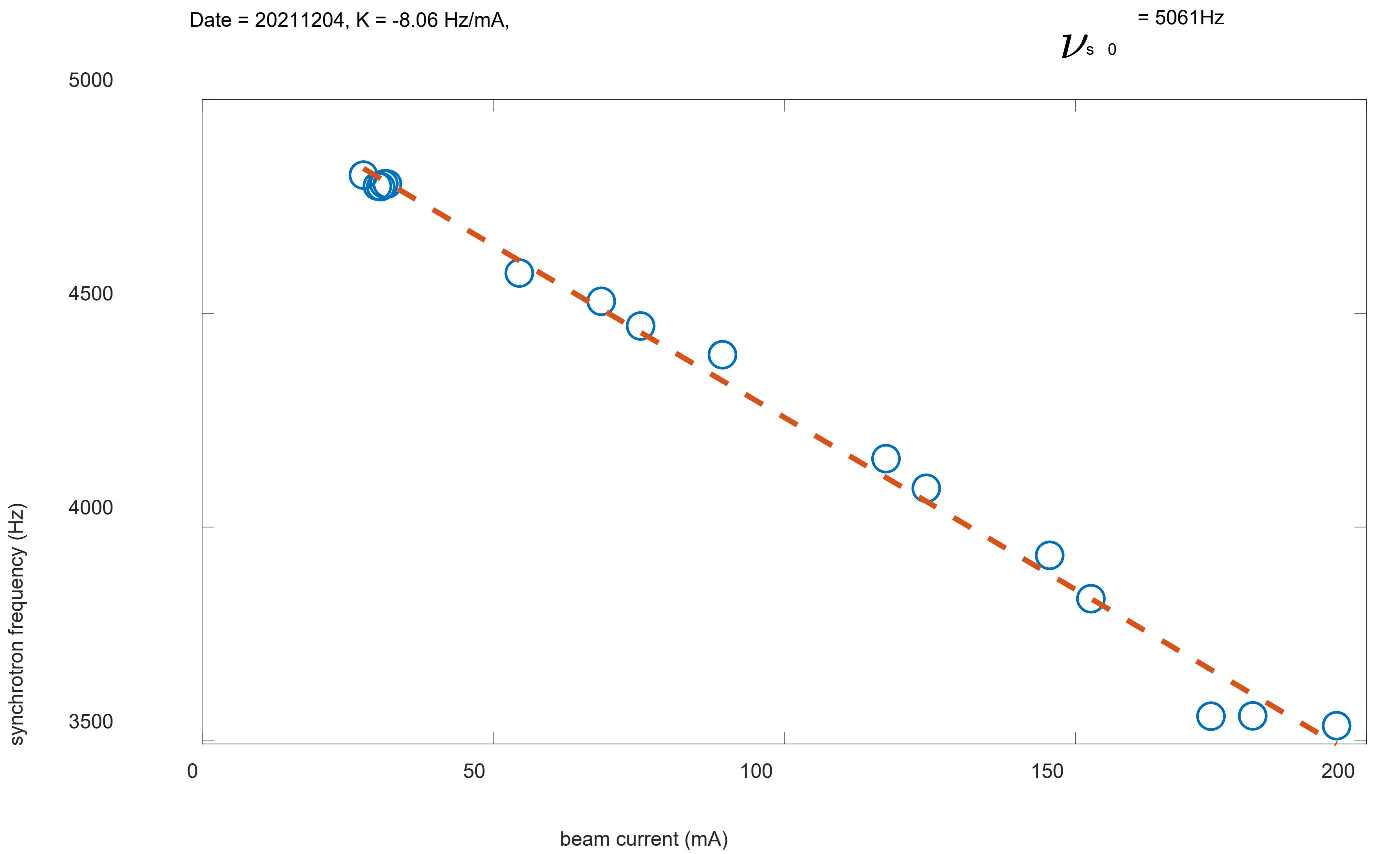


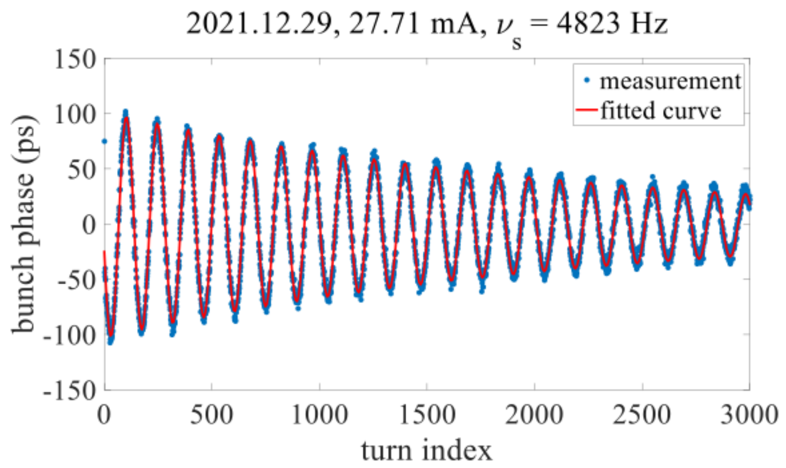


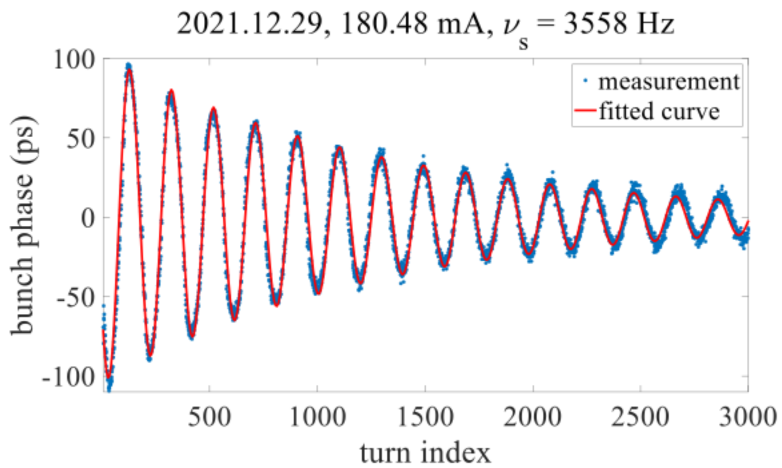


Synchrotron frequency shift with harmonic cavity

- the harmonic cavity **working**
- the synchrotron frequency is linearly related to the beam current, and the change rate is **-8.06Hz/mA (~ × 10)**
- Judgement : the harmonic cavity is still **far from the best working condition (under-stretch for beam)**

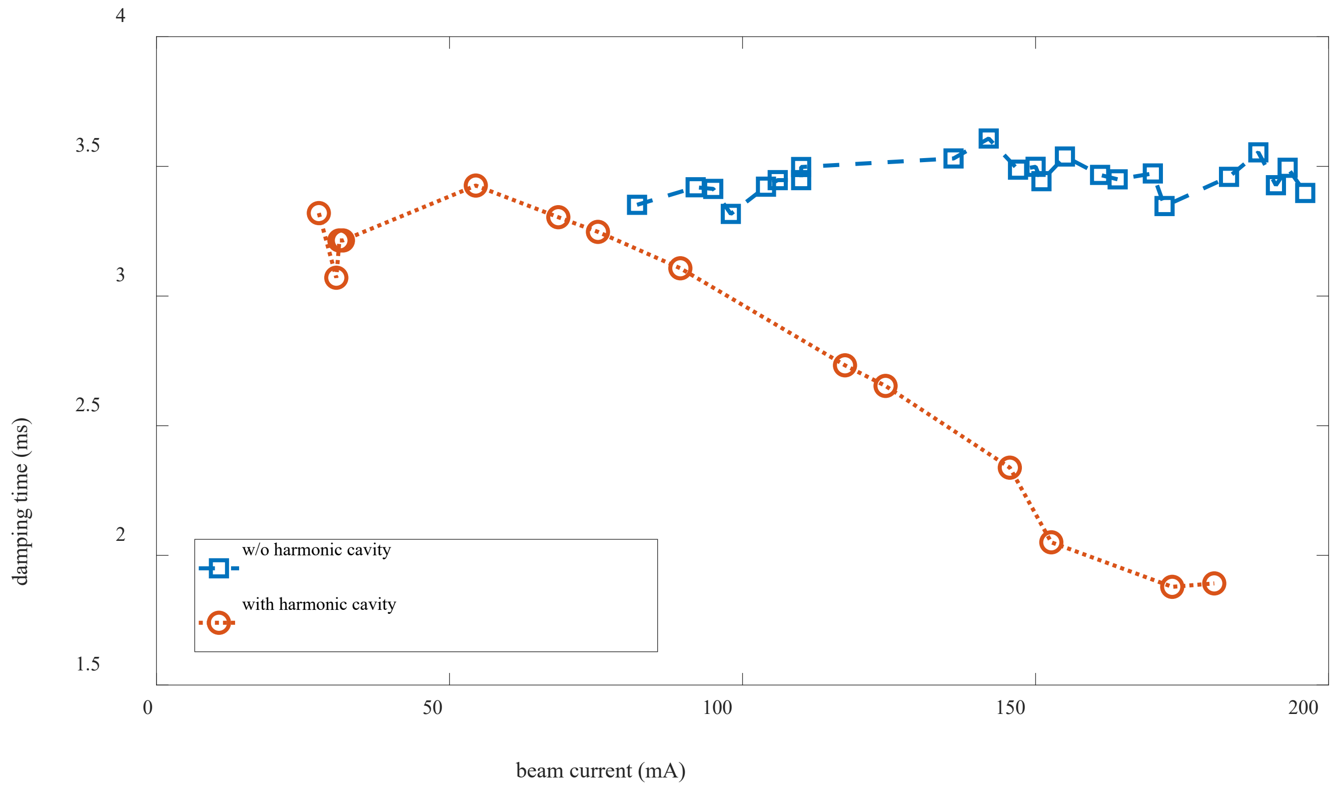


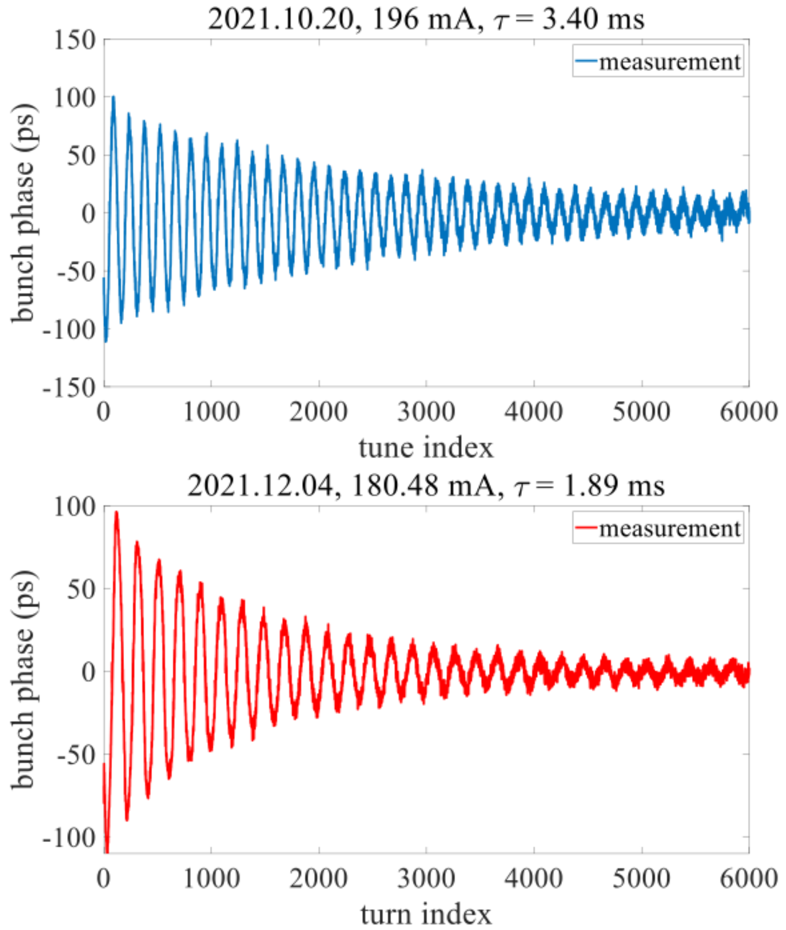




Damping time

- the harmonic cavity **detuned:** the longitudinal damping time is independent of the beam current
- the harmonic cavity **working:** the longitudinal damping time is linearly related to the beam current
- potential well distortion due to harmonic cavity→ synchrotron frequency spread increased → Landau damping
- The change rate of damping time can be used to evaluate the performance of the harmonic cavity.





Summary

Summary

- **Evaluation method of beam loading effect:**
  - Bunch-by-bunch longitudinal parameters precise measurements
- **Commonly used measurement tool: streak camera**
  - ☺ Ability to measure longitudinal distribution and central position for each bunch
  - ☹ Unable to observe long time (ms) event with high time resolution (ps)
  - ☹ No bunch-by-bunch charge information
- **New measurement tool: bunch-by-bunch 3D position measurement system (HOTCAP)**
  - ☺ Analyze steady-state parameters (equilibrium acceleration phase) and dynamic parameters (synchrotron tune, longitudinal damping time)
  - ☺ Analysis results can be checked with each other
- **Experimental measurements of the beam loading effect:**
  - Measurements before and after the third harmonic cavity installation at SSRF
  - Measurement results match perfectly with the simulation results
- **Future plans:**
  - Better model and fit the steady-state parameters and dynamic parameters
  - Directly derive the parameters (e.g. detuning frequency, harmonic cavity voltage)

Acknowledge

- Thanks for the invitation from the 2022 International Beam Instrumentation Conference (IBIC 2022)
- Thanks for the help from the Beam Physics Group and Beam Operation Group of SSRF in beam experiments

Thanks for your attention

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