Non-Invasive Machine Parameters Measurement in a Storage Ring Based on Bunch-by-Bunch 3D Position Data Correlation Analysis

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Outline

- Introduction & Background
- System Setup & Performance
  - A software package（HOTCAP）
- Application
  - non-invasive machine parameters measurement
- Summary & Future Work

Introduction & Background

- Why bunch-by-bunch?
- Why Non-Invasive?
- How to do?

Why bunch-by-bunch?

For users

- Finer detection , more stable light
- More stable light, better experimental results

It is necessary to minimize the beam instability and the disturbance to the user during the injection process

For beam instrument group

- Job
- Machine study tool
- Easier to do experimental research of wake field and impedance

Better diagnosis

For physicists

- A bunch is the basic unit for physical phenomenon analysis
- If the parameters of a single cluster can be obtained, particle dynamics can be studied.

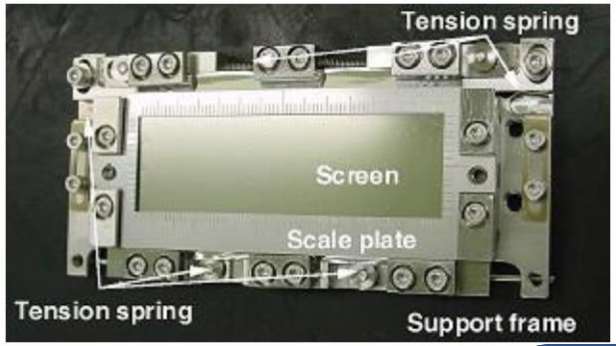
Know bunch status continuously and synchronously.

For machine parameter measurement

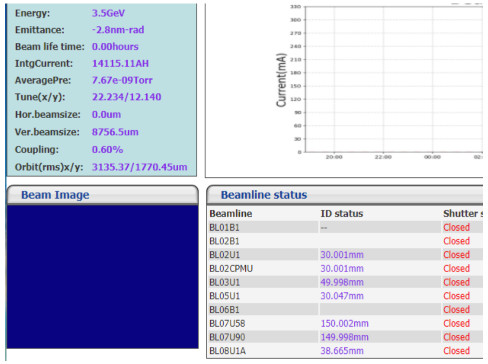
Single bunch measurements should be minimally susceptible to the collective effects, such as reactive tune shifts, etc.

Why Non-Invasive?

~~Invasive devices~~

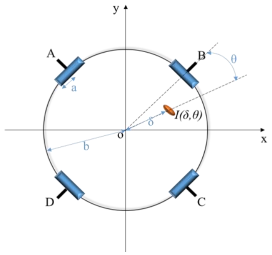


~~Change light source status~~



Non-Invasive measurement is important for user operation time

Non-Invasive devices ✓

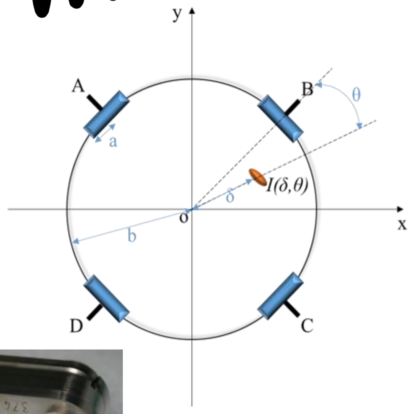


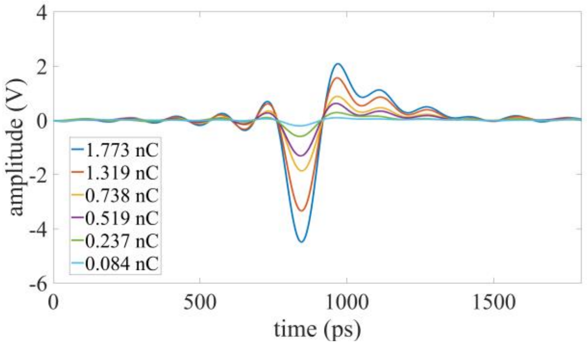
No need to change machine status ✓

For machine parameter measurement

With Non-Invasive measurement, machine parameters can be monitored in real time during user operating.

How to do?





charge quantity → Q; Longitudinal phase → t_0; Bunch → σ

$$I(t) = \frac{Q}{\sqrt{2\pi}\sigma} exp[-\frac{(t-t_0)^2}{2\sigma^2}]$$

Transverse position → $F(\delta,\theta)$

$$V_b(t) = \frac{\pi a^2}{2\pi b}\frac{1}{\beta c}\cdot Z\cdot\frac{t-t_0}{\sigma^2}I(t)\cdot F(\delta,\theta)$$

The signal obtained from the BPM pick-up contains **all** the 3-D information.

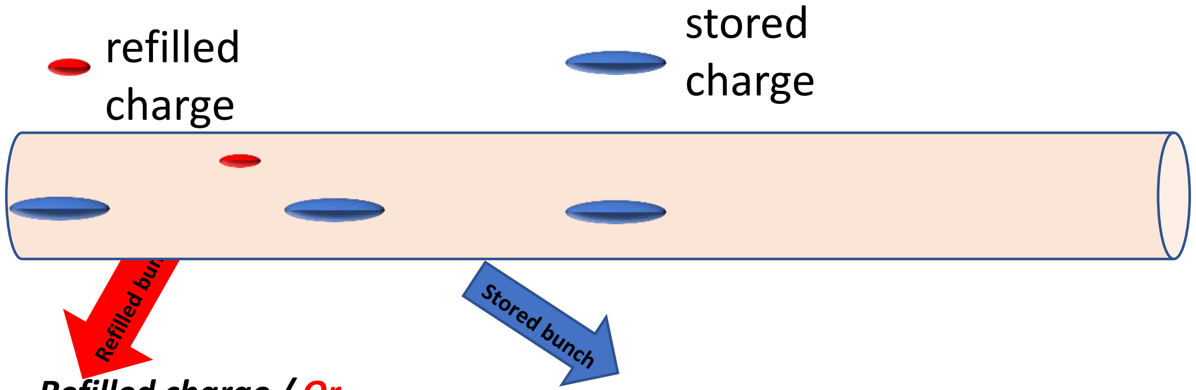
- ☐ **Change machine parameters**

  (Ideal experiment for beam instability study, Require dedicated machine study time)

- √ **Injection transient process**

  (frequently observe in the user operation mode at top-up mode)

- **Betatron Damping oscillation** ← **mismatch of kickers, also injector and storage ring**
- **Synchrotron Damping oscillation** ← **mismatch of injector and storage ring**



- ***Refilled charge / Qr***
- ***Betatron amplitude / Ar***
- ***Synchrotron amplitude / zm***
- ***Synchrotron damping time / τ***
- ***Initial position in phase space / φ0***

- ***Stored charge / Qs***
- ***Transverse tune / νx, νy***
- ***Betatron amplitude / As***
- ***Betatron damping time / Lx***

The injection transient process can be **frequently** observed in the user operation with **top-up mode**.

System Setup & Performance

- A software package（HOTCAP）

High speed Oscilloscope based Three-dimensional bunch Charge And Position measurement system

System Setup

HOTCAP:

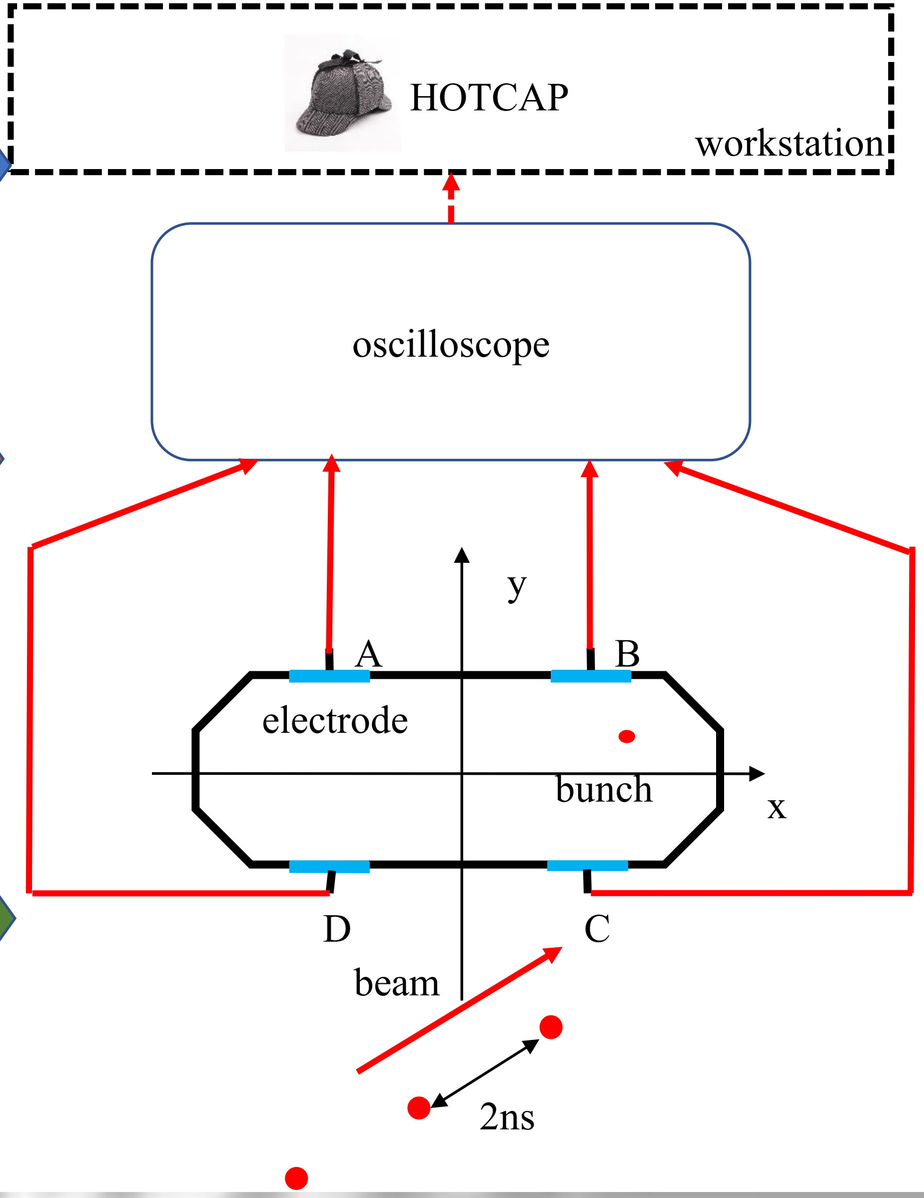
- Code language: Python
- GUI:PYQT5
- compilation efficiency :Numba

Oscilloscope (acquisition device):

- High sampling rate (>10GHz)
- high bandwidth (>4GHz)
- Large storage depth

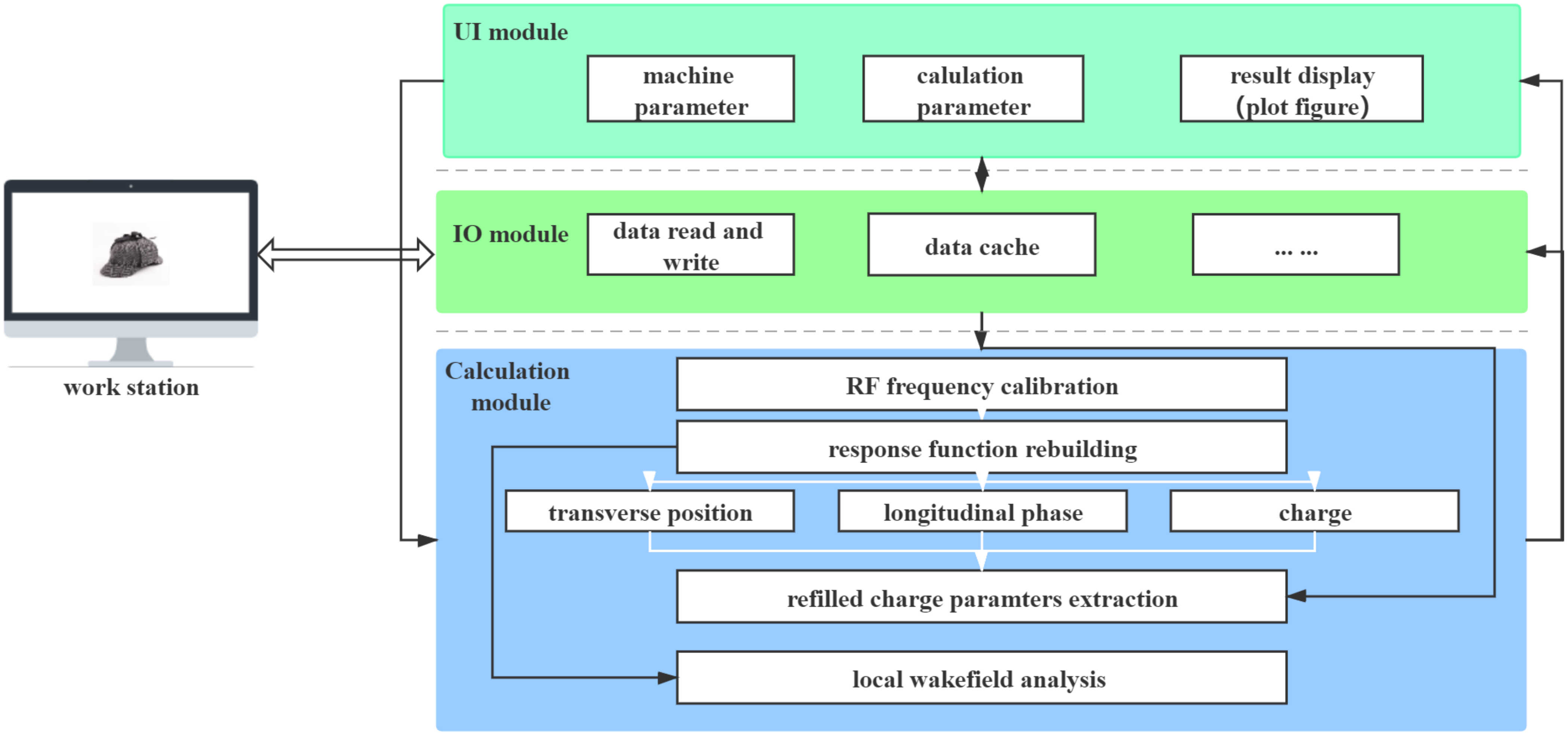
Probe (BPM pick up)

- 2 electrodes or 4 electrodes
- Non-Invasive



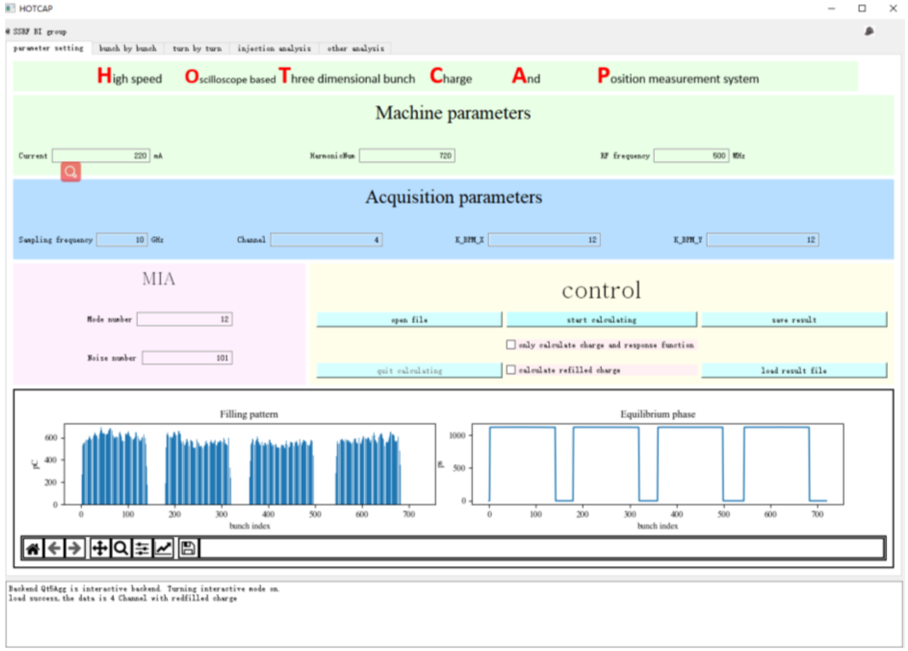
HOTCAP:

A new software package for high speed oscilloscope based three dimensional bunch charge and position measurement.



UI&IO module

- UI: Qt Designer ,PyQT5
- show figure: matplotlib
  - bunch-by-bunch
  - turn-by-turn
  - refilled charge 3D show
- Operations: ALL can be completed by clicking the mouse



HOTCAP.exe

- Open file: load data (file type“.mat” for Matlab)
  - 2 channels for 2 electrodes: array(BPM1,BPM3)
  - 4 channels for 4 electrodes: array(BPM1,BPM2,BPM3,BPM4)
- Save result: save data (file type“.mat” for Matlab)
  - Bunch charge, longitudinal phase, transverse position
  - Injection status
  - Response function, accurate RF frequency
- Load result:
  - Load the results of previous calculations for display

BunchPhase1	720x7112 double
BunchPhase3	720x7112 double
BunchPhase2	720x7112 double
BunchPhase4	720x7112 double
Correlation_coefficient3	720x7112 double
Correlation_coefficient2	720x7112 double
BunchAmp1	720x7112 double
BunchAmp3	720x7112 double
BunchAmp2	720x7112 double
BunchAmp4	720x7112 double
Correlation_coefficient1	720x7112 double
Correlation_coefficient4	720x7112 double
PhaseBalance	1x720 double
Charge_pc	1x720 double
LUT1	720x20012 double
LUT3	720x20012 double
LUT1_shift	1x720 double
LUT3_shift	1x720 double
T	20.0123
LUT2	720x20012 double
LUT4	720x20012 double
LUT2_shift	1x720 double
LUT4_shift	1x720 double
field1	1x14408882 double
field2	1x14408882 double
field3	1x14408882 double
field4	1x14408882 double
Position_x	720x7112 double
Position_y	720x7112 double
phase1	1x7112 double
amp1	1x7112 double
lut1	1x19999 double
phase2	1x7112 double
amp2	1x7112 double
lut2	1x19999 double
phase3	1x7112 double
amp3	1x7112 double
lut3	1x19999 double
phase4	1x7112 double
amp4	1x7112 double
lut4	1x19999 double
Position_x_refilledcharge	1x7112 double

result   interface

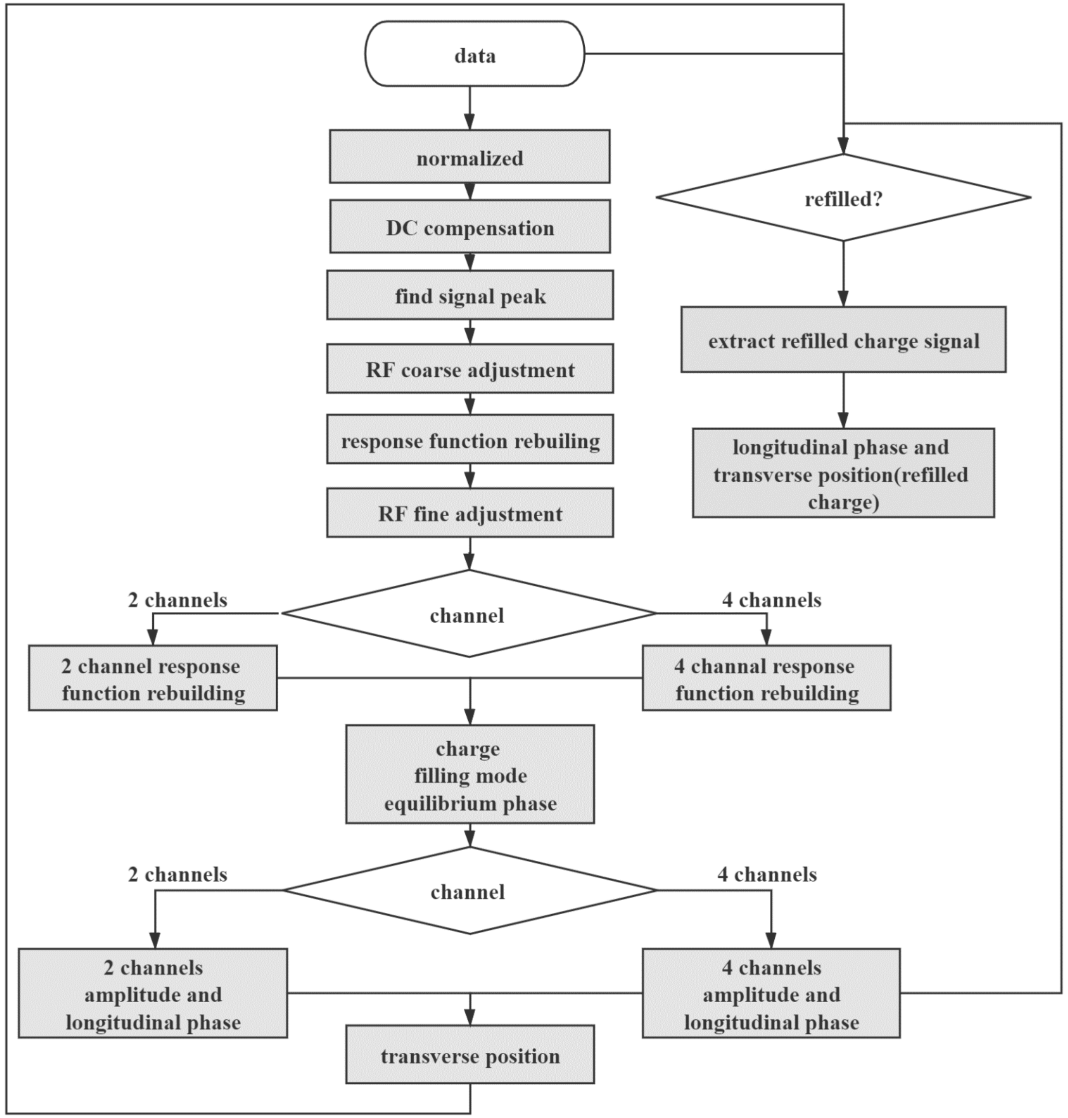
python

MATLAB

Calculation module

- Pre-process
  - Normalization
  - DC compensation
  - signal initial peak finding
  - RF frequency coarse
  - fine adjustment
- The response function reconstruction
  - multi-turn data splicing
  - window smoothing
- The phase and position extracting
  - the longitudinal phase
    - sliding cross correlation method
  - the transverse position
    - difference ratio
    - linear fitting
- The refilled charge signal extracting method

increase in speed by Numba



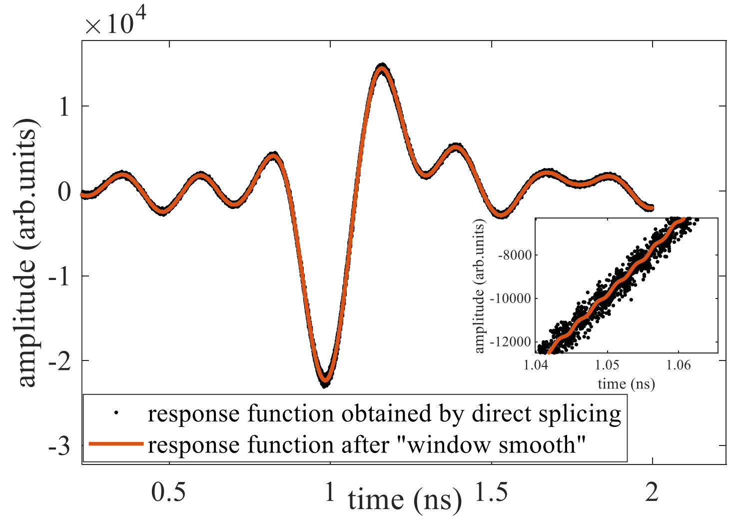
The response function reconstruction

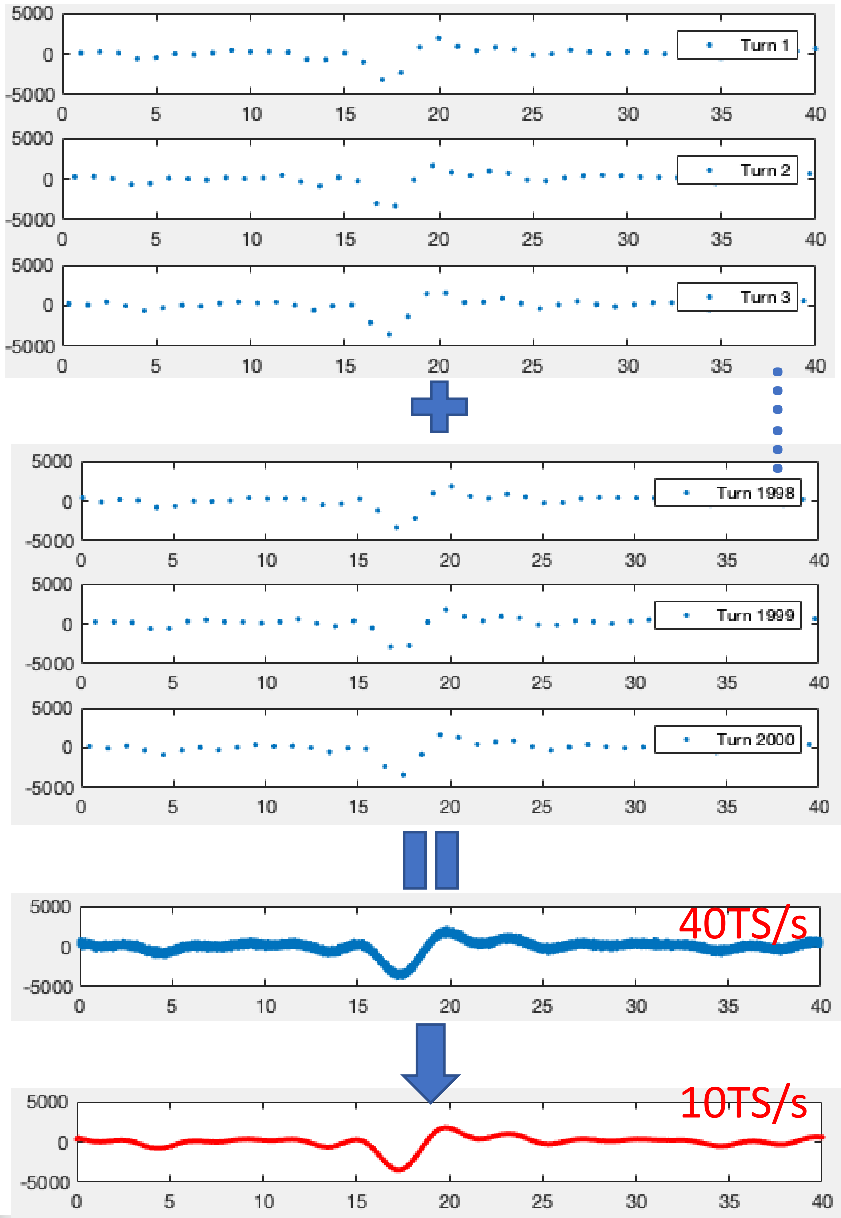
$$f \neq m \cdot f_c$$

f_c :the revolution frequency

f :the sampling frequency of the oscilloscope

1. multi-turn data splicing
2. Window smoothing (low pass filtering)
3. Sampling





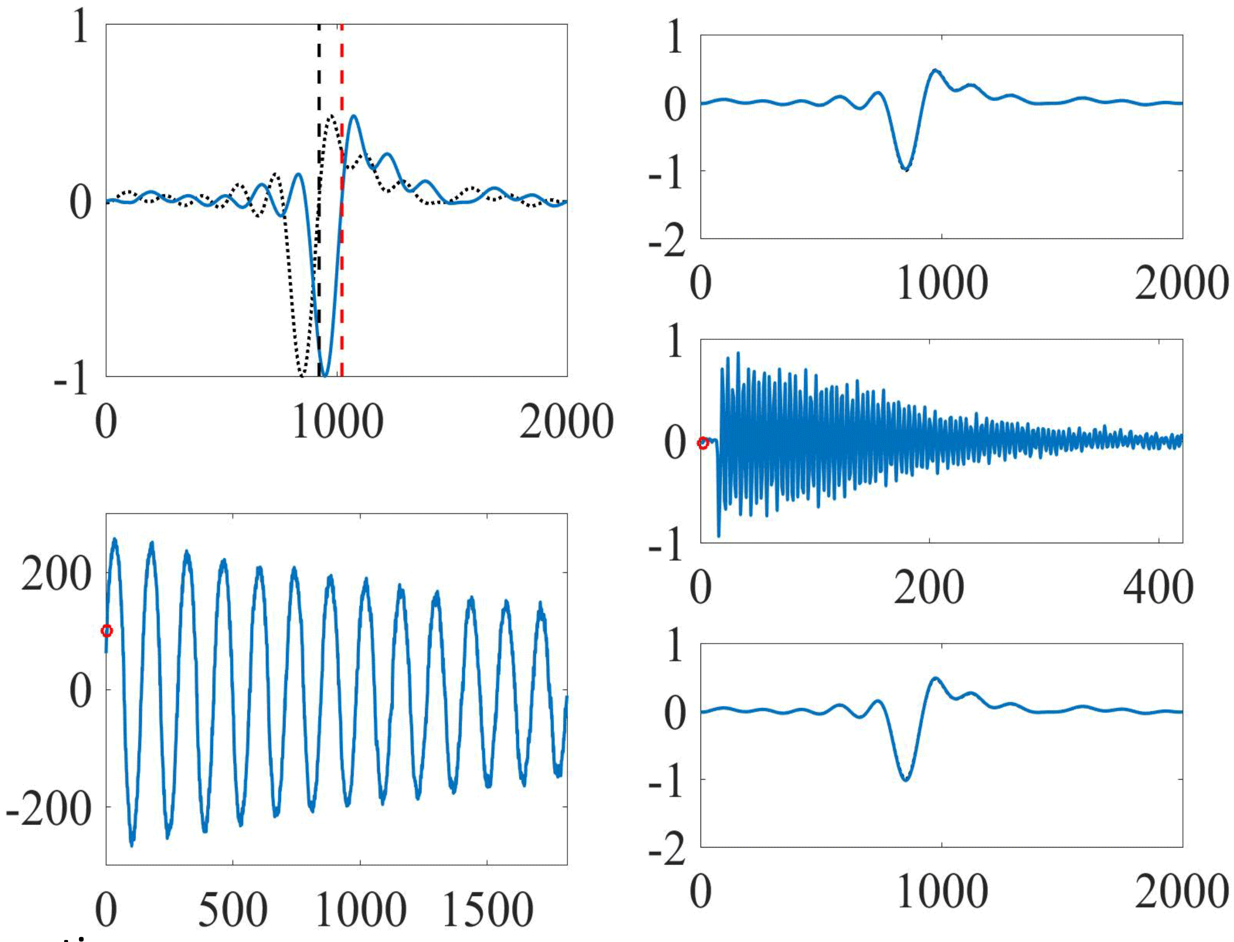
Longitudinal phase based on sliding cross correlation method

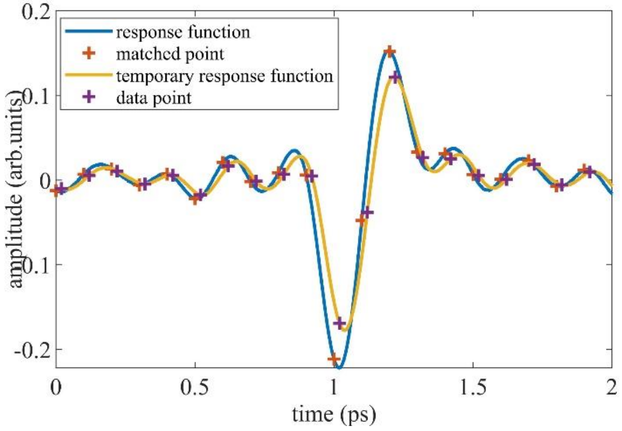
$$correlation\_coefficient = \frac{\{\mathbf{d_N^n}\} \cdot \mathbf{LUT^{n,i}}}{|\{\mathbf{d_N^n}\}| \cdot |\mathbf{LUT^{n,i}}|}$$

$$-1 \le \text{correlation} \le 1$$

perfect negative correlation

perfect positive correlation



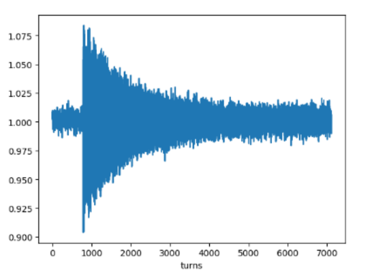


1. Sampling the response function
2. Calculate the correlation coefficient
3. Find **maximum** correlation coefficient
4. Get longitudinal phase

X. Xu, Y. Zhou, and Y. Leng, B. Gao, J. Chen, and S. Cao, Bunch-by-bunch three-dimensional position and charge measurement in a storage ring, Phys. Rev. Accel. Beams 24, 032802 (2021). doi: 10.1103/PhysRevAccelBeams.24.062802

The refilled charge signal extracting method

Transverse position



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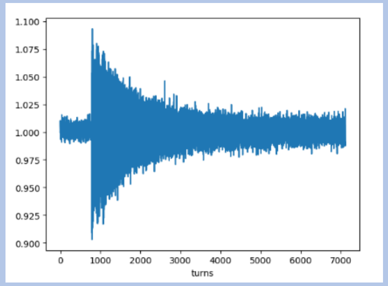
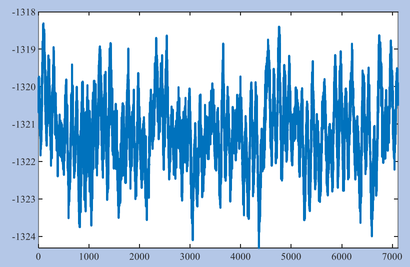


Bunch index N

Bunch index N+1orN-1

Longitudinal phase



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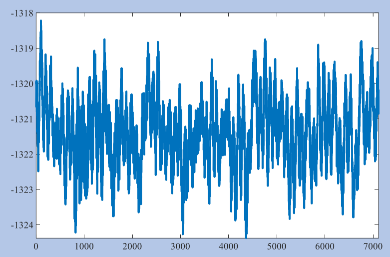
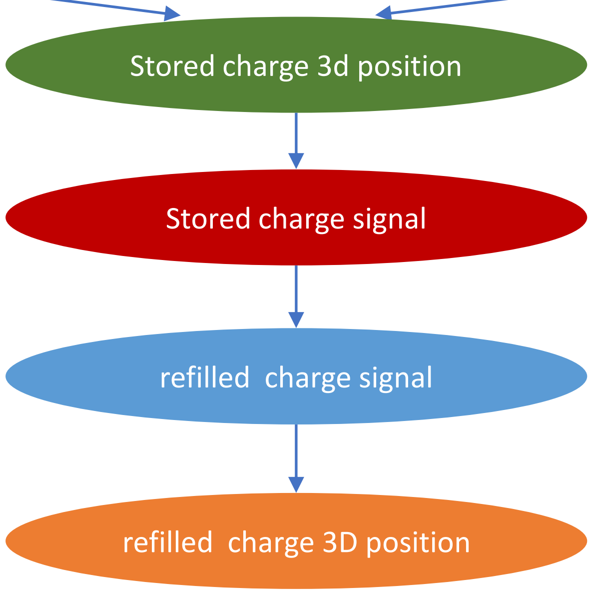


Bunch index N

Bunch index N+1orN-1

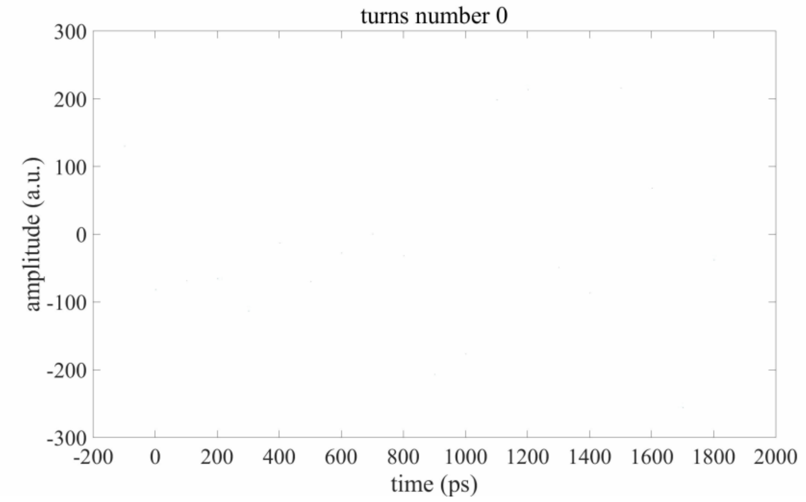


$$signal(n) = signal_s(n) + signal_r(n)$$

signal(n):

acquired data is the sum of the refilled charge signal and the stored charge signal

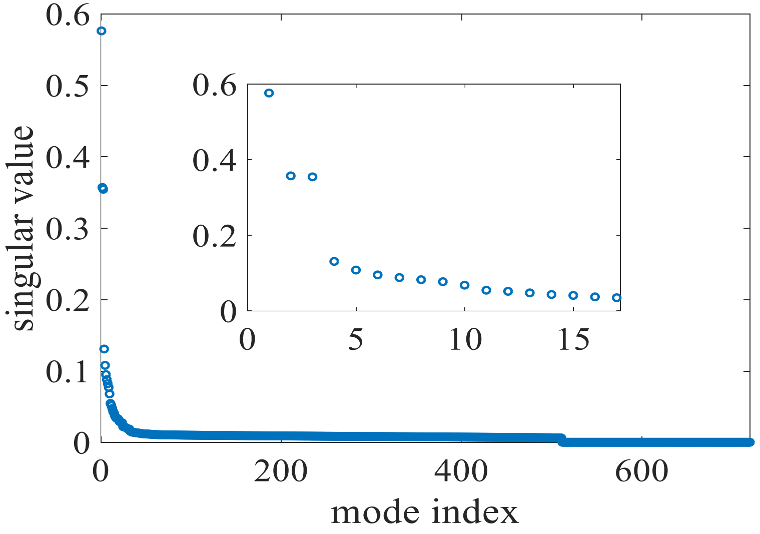
In order to obtain the refilled charge signal, the stored charge signal needs to be subtracted from the acquired signal.



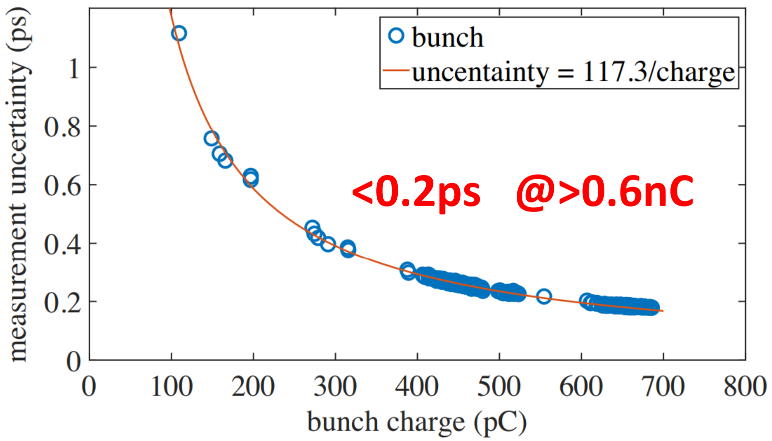
Extracted refilled charge signal

Performance of HOTCAP

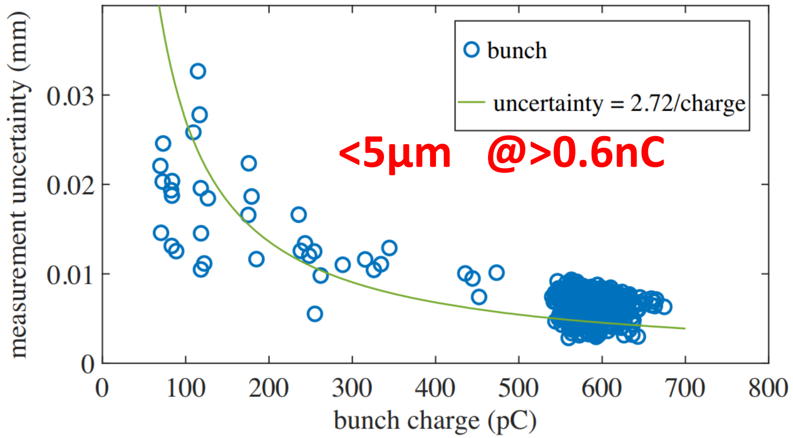
- The measurement uncertainty of transverse position and longitudinal phase measurement was evaluated by PCA method
- The first three main oscillation modes are beam motion, mainly derived from synchronous oscillation /Beta oscillation
- The standard deviation of the noise floor signal after separation is defined as the uncertainty.



pattern separation with PCA



Measurement uncertainty of longitudinal phase



Measurement uncertainty of transverse position

Software generality

HOTCAP works with most synchrotron radiation storage rings.

It has been applied to Shanghai Synchrotron Radiation Facility (SSRF) and Hefei Light Source(HLS).

The robustness of the software package needs to be further verified and optimized under special acquisition equipment and machine conditions.

SSRF applied result

TABLE 1. Parameters of SSRF and HLS

Parameter	SSRF	HLS
energy (E/GeV)	3.5	0.8
RF frequency (f_{RF}/MHz)	499.654	204.030
buckets (h)	720	45
revolution frequency (f_o/kHz)	694	4534
bunch length (σ/ps)	18	50

HLS applied result

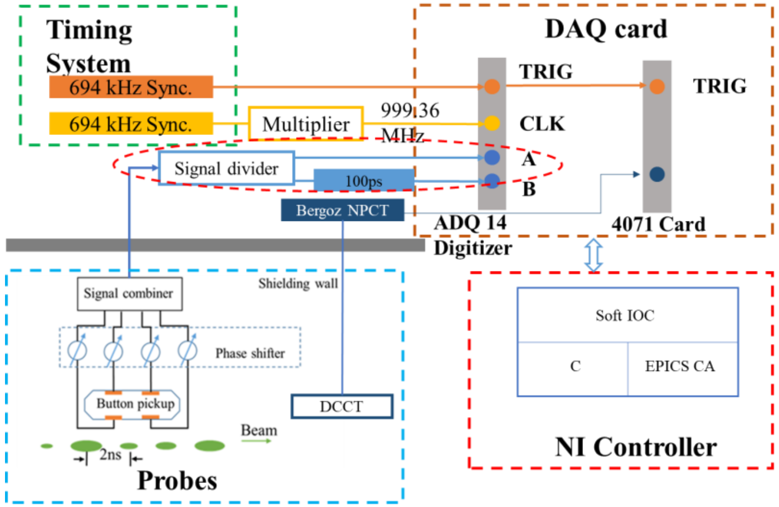
https://github.com/xuxingyi/HOTCAP

Application–non-invasive machine parameters measurement

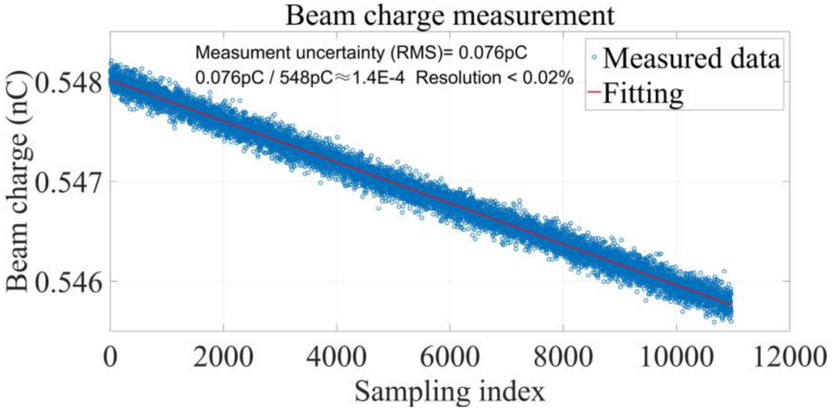
- Momentum compaction factor
- Dispersion function

BxB beam lifetime measurement

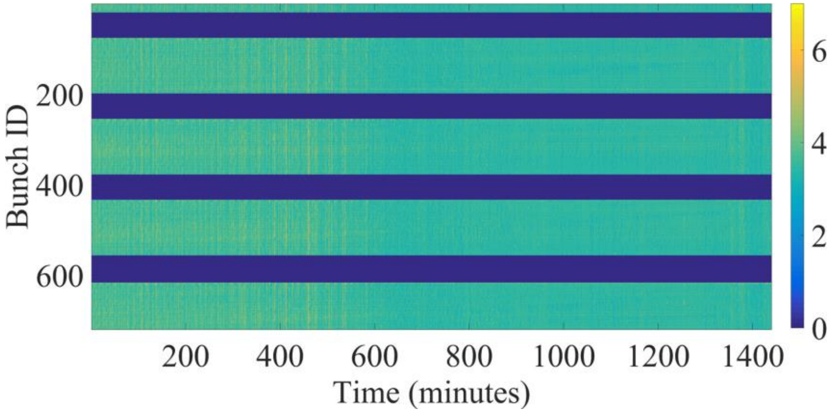
System setup



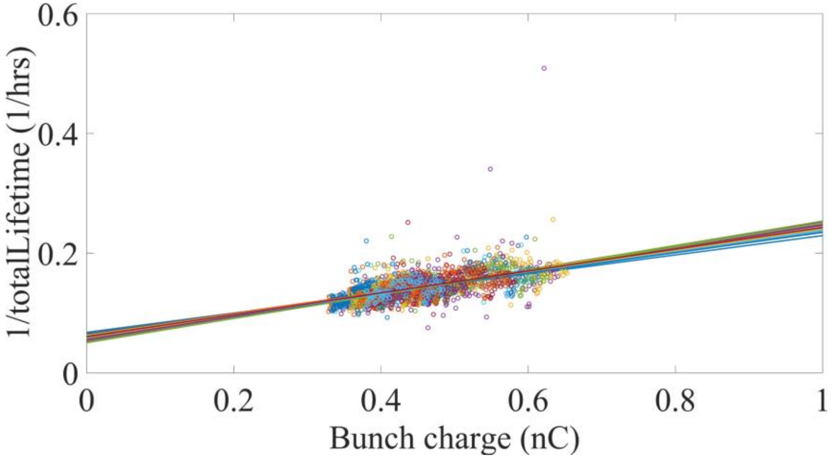
BxB charge measurement@140Hz



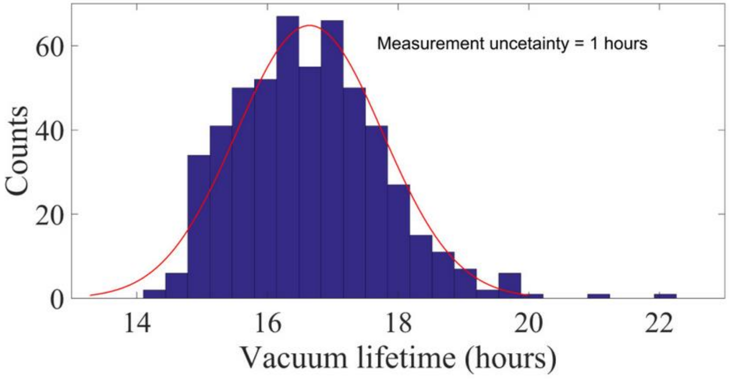
BxB lifetime measurement



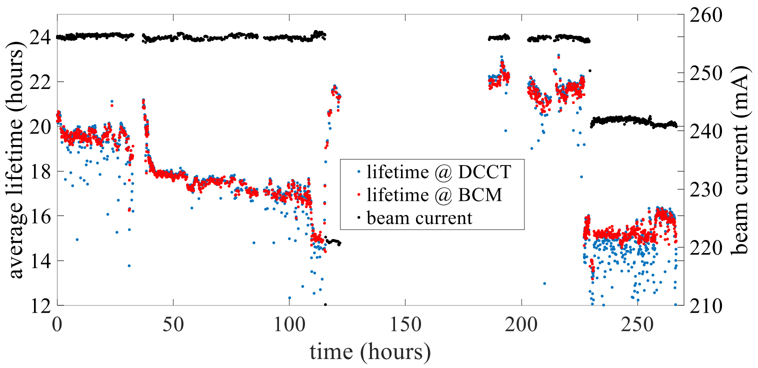
BxB touschek lifetime fitting



BxB lifetime measurement uncertainty: 1 hours



Application: Online lifetime measurement



B. Gao, F.Z. Chen, Y.B. Leng, and Y.M. Zhou, "Online Touschek Beam Lifetime Measurement Based on the Precise Bunch-By-Bunch Beam Charge Monitor", in Proc. IBIC'19, Malmö, Sweden, Sep. 2019, pp. 36-40. doi:10.18429/JACoW-IBIC2019-MOCO01

Non-Invasive Momentum compaction factor Measurement

$$\alpha_c = \frac{\Delta L/L}{\Delta p/p}.$$

$$\frac{\Delta f_{\rm rf}}{f_{\rm rf}} = -\alpha_c \frac{\Delta p}{p} = -\alpha_c \frac{\Delta E}{E}.$$

need measurement: RF frequency, beam energy
man-modified: RF frequency

Invasive (Interfering with user experiments)

$$z_d = z_m \sin\left(\sqrt{\Omega^2 - \lambda_s^2}\, t + \varphi_0\right) e^{-\lambda_s t}.$$

$$\alpha_c = \frac{2\pi E \nu_s^2}{e h V_{\rm rf}}.$$

need measurement: the synchrotron tune
man-modified: None

"top-up" operation mode: frequent injection
transverse injection: transient phase instability

Longitudinal phase oscillation → **the synchrotron tune**

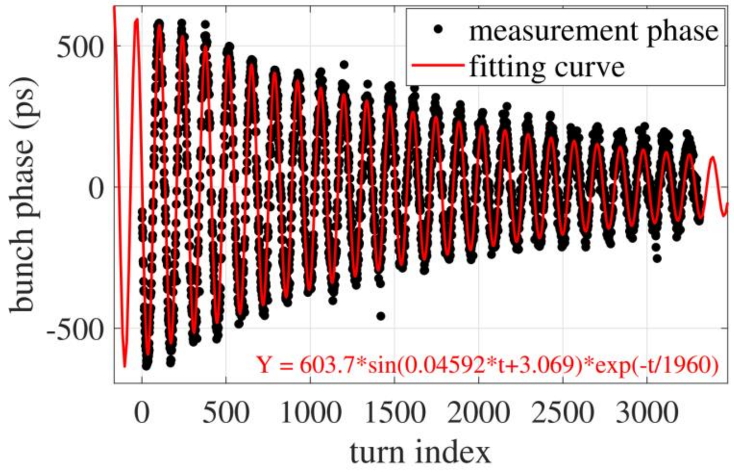
refilled charge   stored charge

We plan to measure the synchrotron tune during the frequent injection process in the "top-up" operation mode.

Non-Invasive

Non-Invasive Momentum compaction factor Measurement

- no special requirements for the beam status (daily operation of the synchrotron radiation facility). Non -invasive
- high refresh rate depends on the refilling frequency of the top-up mode .
- In the "top-off" mode (infrequent injection), the refresh rate is typically rather low. But, it still work.
- Uncertainty: [4.077 × 10−4; 4.080 × 10−4] with 95% confidence bounds.



$$\alpha_c = \frac{2\pi E \nu_s^2}{ehV_{\mathrm{rf}}}.$$

TABLE I. Parameters of SSRF.

Parameter	Value
Energy (E)	3.5 GeV
Current (I_0)	220 mA
rf frequency (f_{rf})	499.654 MHz
rf cavity voltage (V_{rf})	4.5 MV
Buckets (h)	720
Revolution frequency (f_o)	694 kHz
Bunch length (σ)	18 ps

TABLE II. Beam parameters of the storage ring.

Parameter	Value
Stored charge (Q_s)	582 pC
Refilled charge (Q_r)	21.0 pC
Oscillation amplitude (z_m)	603.7 ± 7 ps
Refilled charge arrived time (φ_0)	3.07 ± 0.01 rad
Synchrotron damping time (T_τ)	2.82 ± 0.05 ms
Synchrotron tune (ν_s)	0.007308 ± 0.000002

Similarly Also May Obtain:

- Oscillation amplitude
- Oscillation damping time
- Oscillation initial phase

Y.M. Zhou, B. Gao, Y.B. Leng, and N. Zhang, "Injection Transient Study Using 6-Dimensional Bunch-by-bunch Diagnostic System at SSRF", in Proc. IBIC'18, Shanghai, China, Sep. 2018, pp. 542-547. doi:10.18429/JACoW-IBIC2018-THOB01

Non-Invasive Dispersion function Measurement

$$\Delta x = \eta(s)\frac{\Delta p}{p}.$$

$$\frac{\Delta\tau}{\tau} = \left(\frac{1}{\gamma^2} - \alpha_c\right)\frac{\Delta p}{p} = \eta_c\frac{\Delta p}{p}.$$

$$\eta(s) = -\alpha_c\frac{\Delta x}{\Delta\tau/\tau}.$$

need measurement:

τ : The period of the particle revolution **(longitudinal phase)**

x : horizontal beam orbit **(horizontal bunch position)**

man-modified: None

need measurement: RF frequency, beam energy

man-modified: orbit/RF frequency

Invasive (Interfering with user experiments)

With the HOTCAP package's high-precision 3d bunch-by-bunch measurement technology, **no manual** changes to machine parameters are required, and **extremely small oscillations under stable light supply** are sufficient to measure the dispersion function.

HOTCAP

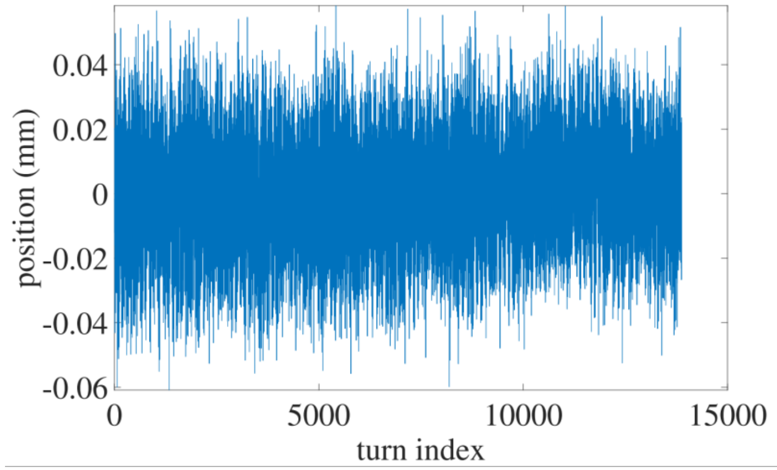
3-dimensional observation

+

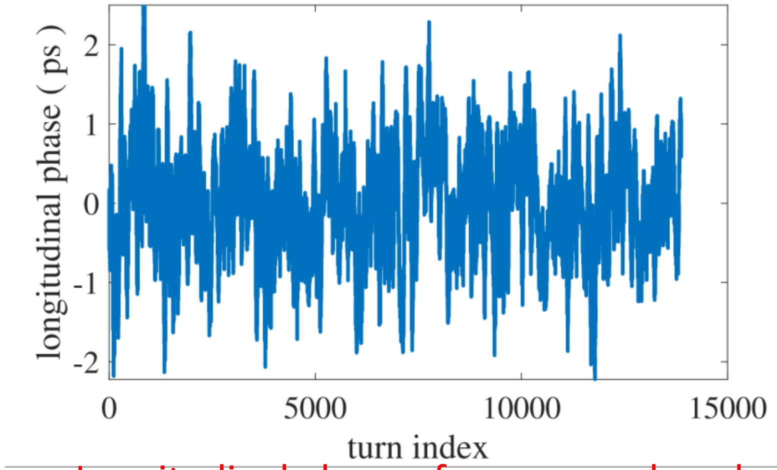
Correlation Analyze

Non-Invasive

Non-Invasive Dispersion function Measurement



horizontal position of a common bunch

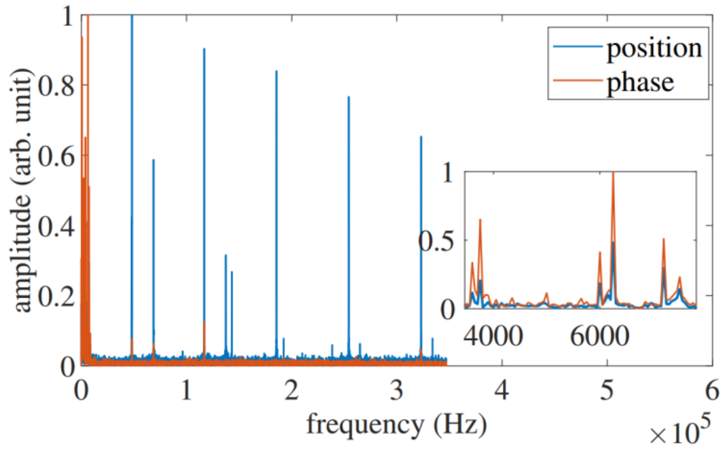


Longitudinal phase of a common bunch

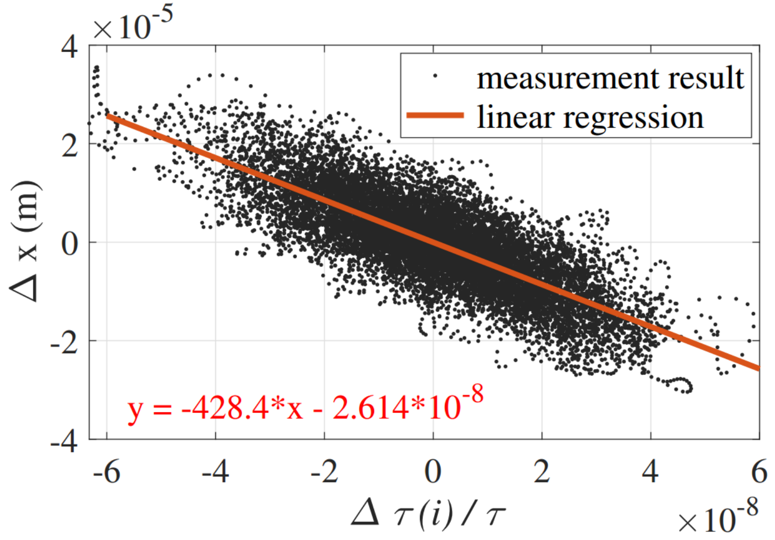
$$x(i) = x_o + \Delta x(i) + x_\beta(i) + \sum_n x_n(i).$$

x_o: the reference orbit.
Δx : the orbit shift
x_β: betatron oscillation.
$\sum_n x_n$:noise contributions

- Low pass filtering
- Linear fitting
- Get dispersion function



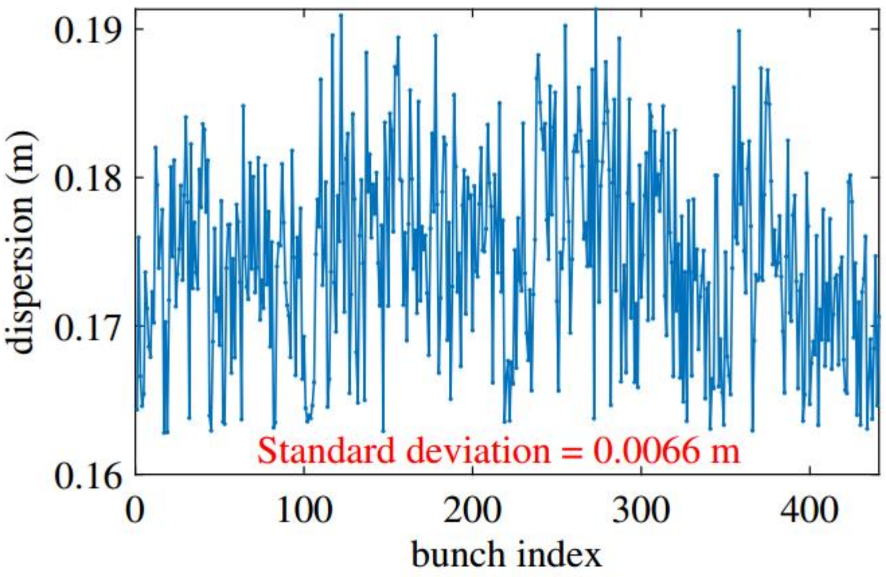
The spectral analysis results : the turn-by-turn horizontal position and longitudinal phase of a common bunch.

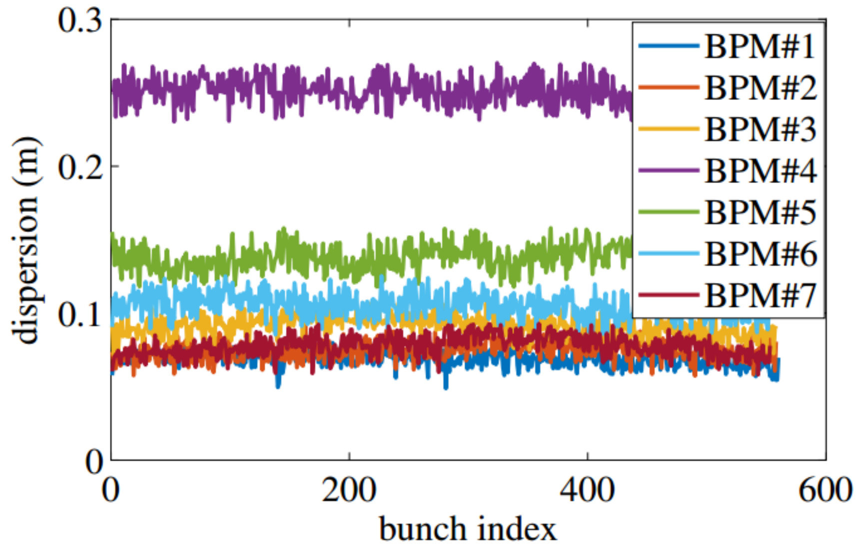


The correlation between the normalized shift of the revolution period, Δτ/τ, and the obit shift, Δx, is linear

Non-Invasive Dispersion function Measurement Performance Evaluation

- Using one standard deviation as definition of the uncertainty of a single independent measurement
- uncertainty value of 0.0066m for the dispersion function measurement (about **3.8%**).
- The processing gain is the square root of bunch number. the relative measurement uncertainty : about **0.2%**.





X. Xu, Y. Zhou, and Y. Leng, New noninvasive measurement method of optics parameters in a storage ring using bunch-by-bunch 3D beam position measurement data, Phys. Rev. Accel. Beams 24, 062802 (2021). doi: 10.1103/PhysRevAccelBeams.24.062802

PROOF EXPERIMENT

I. There are 7 BPMs in each cell. (20 cells at SSRF)
II. Seven sets of data from seven BPMs are recorded respectively.
III. the measured results are in good agreement with the design value.

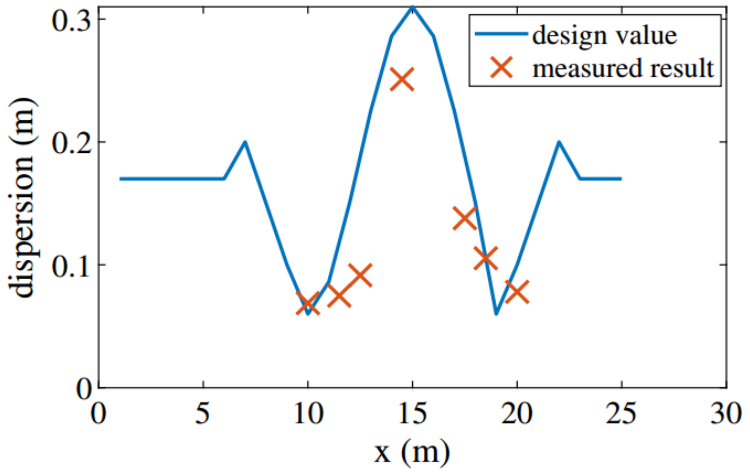
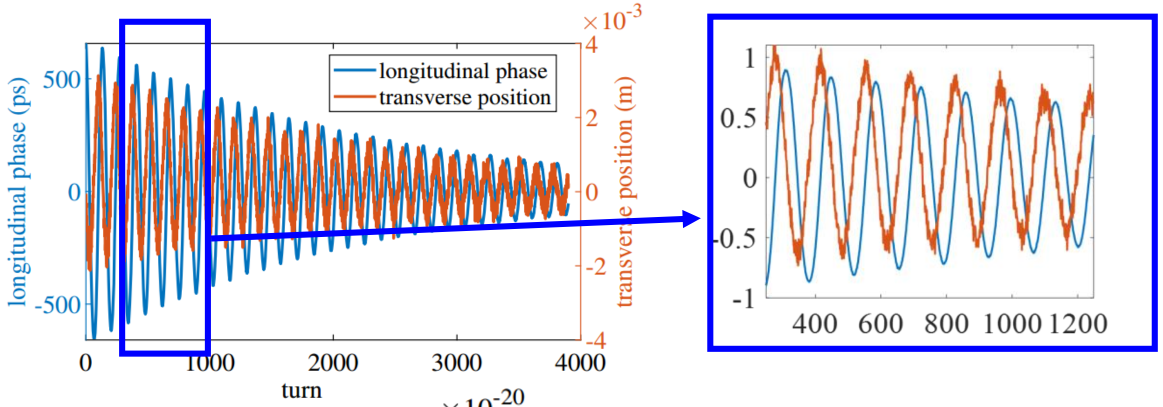
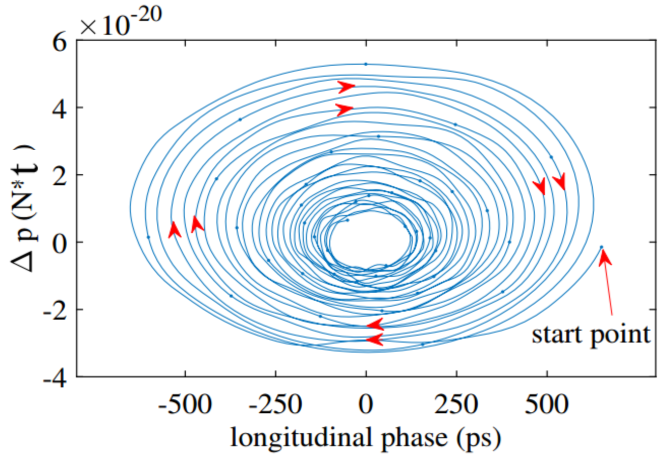


TABLE III. Dispersion value distribution in a cell.

Position	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Value (m)	0.0688	0.0749	0.0915	0.2511	0.1379	0.1054	0.0780

I. Injection transient with empty storage ring
II. The transverse position is coupled to the longitudinal phase
III. The results are consistent with those of refilled charge extraction





Bunch-by-Bunch 3D Position Data Correlation Analysis is a valid way to characterize machine optics in a non-invasive manner.

Summary

- Non-invasive method is suitable for key optics parameter measurement during daily operation without additional machine research time.

- A general software package (HOTCAP) was developed to process the bunch signals and extract bunch parameters. (https://github.com/xuxingyi/HOTCAP)

- This software package does not require special acquisition equipment and does not have strict requirements on the state of the accelerator, the software package can be widely used in the bunch-by-bunch measurement of almost all ring accelerators.

- Simultaneous measurement of the parameters of each bunch is helpful to diagnose the beam state and obtain the machine state by correlation analysis.

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SINAP

Thanks for your attention

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