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?

<table>
<thead>
<tr>
<th>For users</th>
<th>For beam instrument group</th>
<th>For physicists</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Finer detection, more stable light</td>
<td>• Job</td>
<td>• A bunch is the basic unit for physical phenomenon analysis</td>
</tr>
<tr>
<td>• More stable light, better experimental results</td>
<td>• Machine study tool</td>
<td>• If the parameters of a single cluster can be obtained, particle dynamics can be studied.</td>
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</table>

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

Better diagnosis

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?

Non-Invasive measurement is important for user operation time.

Invasive devices

Change light source status

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?

- Refilled charge / \( Q_r \)
- Betatron amplitude / \( A_r \)
- Synchrotron amplitude / \( z_m \)
- Synchrotron damping time / \( \tau \)
- Initial position in phase space / \( \varphi_0 \)
- Stored charge / \( Q_s \)
- Transverse tune / \( \nu_x, \nu_y \)
- Betatron amplitude / \( A_s \)
- Betatron damping time / \( L_x \)

Injection transient process

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

- Betatron Damping oscillation
- Synchrotron Damping oscillation

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

Transverse position

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

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

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

**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

- **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
Calibration 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
  - Longitudinal phase
    - Sliding cross correlation method
  - Transverse position
    - Difference ratio
    - Linear fitting

- The refilled charge signal extracting method

Diagram:
- Data
  - Normalized
  - DC compensation
  - Find signal peak
  - RF coarse adjustment
  - Response function rebuilding
  - RF fine adjustment
  - Longitudinal phase and transverse position (refilled charge)
  - Extract refilled charge signal
  - Refilled?
  - Increase in speed by Numba

Legend:
- 2 channels
- 4 channels
- 2 channels response function rebuilding
- 4 channel response function rebuilding
- Charge filling mode equilibrium phase
- 2 channels amplitude and longitudinal phase
- Transverse position
- 4 channels amplitude and longitudinal phase
- Channel
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

\[ \times 10^4 \]

amplitude (arb.units)

response function obtained by direct splicing
response function after "window smooth"
Longitudinal phase based on sliding cross correlation method

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

$$-1 \leq correlation \leq 1$$

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

The refilled charge signal extracting method

\[ signal(n) = signal_s(n) + signal_r(n) \]

**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.
• 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.

Measurement uncertainty of longitudinal phase

<0.2ps @>0.6nC

Measurement uncertainty of transverse position

<5µm @>0.6nC
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

HLS applied result

<table>
<thead>
<tr>
<th>TABLE 1. Parameters of SSRF and HLS</th>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>energy ($E/GeV$)</td>
</tr>
<tr>
<td>RF frequency ($f_{RF}/MHz$)</td>
</tr>
<tr>
<td>buckets ($h$)</td>
</tr>
<tr>
<td>revolution frequency ($f_o/kHz$)</td>
</tr>
<tr>
<td>bunch length ($\sigma/\text{ps}$)</td>
</tr>
</tbody>
</table>
Application–non-invasive machine parameters measurement

- Momentum compaction factor
- Dispersion function
**BxB beam lifetime measurement**

**System setup**
- Timing System: 64 kHz Sync.
- Multiplexer: 999 kHz
- Signal divider: 1000 Hz
- Beam NCT
- DAQ 14 Bit Digitizer
- NI Controller

**BxB charge measurement@140Hz**
- Beam charge measurement
  - Measurement uncertainty (RMS) = 0.076% ± 0.075 / 548 ± 1.4E-4
  - Resolution < 0.02%

**BxB lifetime measurement**
- Distribution of time (minutes)
- Counts
- Measurement uncertainty = 1 hour

**BxB touschek lifetime fitting**
- Fitting of data
- F10 lifetime (1 hrs)

**Application:**
- Online lifetime measurement
- Lifetime measurement at 140 Hz

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Non-Invasive Momentum compaction factor Measurement

\[ \alpha_c = \frac{\Delta L/L}{\Delta p/p} \]

\[ \Delta f_{\text{rf}} = -\alpha_c \frac{\Delta p}{p} = -\alpha_c \frac{\Delta E}{E} \]

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

Invasive (Interfering with user experiments)

\[ z_d = z_m \sin \left( \sqrt{\Omega^2 - \lambda_t^2} t + \varphi_0 \right) e^{-\lambda_t t} \]

\[ \alpha_c = \frac{2\pi E \nu_s^2}{e h V_{\text{rf}}} \]

need measurement: the synchrotron tune
man-modified: None

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

Longitudinal phase oscillation \(\rightarrow\) 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).

- 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.

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:
- \( \tau \): The period of the particle revolution (longitudinal phase)
- \( \mathcal{X} \): 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.
Non-Invasive Dispersion function Measurement

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

Low pass filtering
Linear fitting
Get dispersion function

\[ x(i) = x_0 + \Delta x(i) + x_\beta(i) + \sum_n x_n(i). \]

- \( x_0 \): the reference orbit.
- \( \Delta x \): the orbit shift
- \( x_\beta \): betatron oscillation.
- \( \sum_n x_n \): noise contributions

The correlation between the normalized shift of the revolution period, \( \Delta \tau/\tau \), and the orbit shift, \( \Delta x \), is linear:

\[ y = -428.4x - 2.614 \times 10^{-8} \]
- 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%**.

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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>
<thead>
<tr>
<th>Position</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
<th>No. 4</th>
<th>No. 5</th>
<th>No. 6</th>
<th>No. 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (m)</td>
<td>0.0688</td>
<td>0.0749</td>
<td>0.0915</td>
<td>0.2511</td>
<td>0.1379</td>
<td>0.1054</td>
<td>0.0780</td>
</tr>
</tbody>
</table>

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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