Beam Coupling Impedance Analysis Using Bunch-by-Bunch Measurement

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Outline

- Introduction & Background
- System Setup & Performance
- Application
- Summary & Future Work

Introduction & Background

What is impedance & wakefield ?

impedance & wakefield

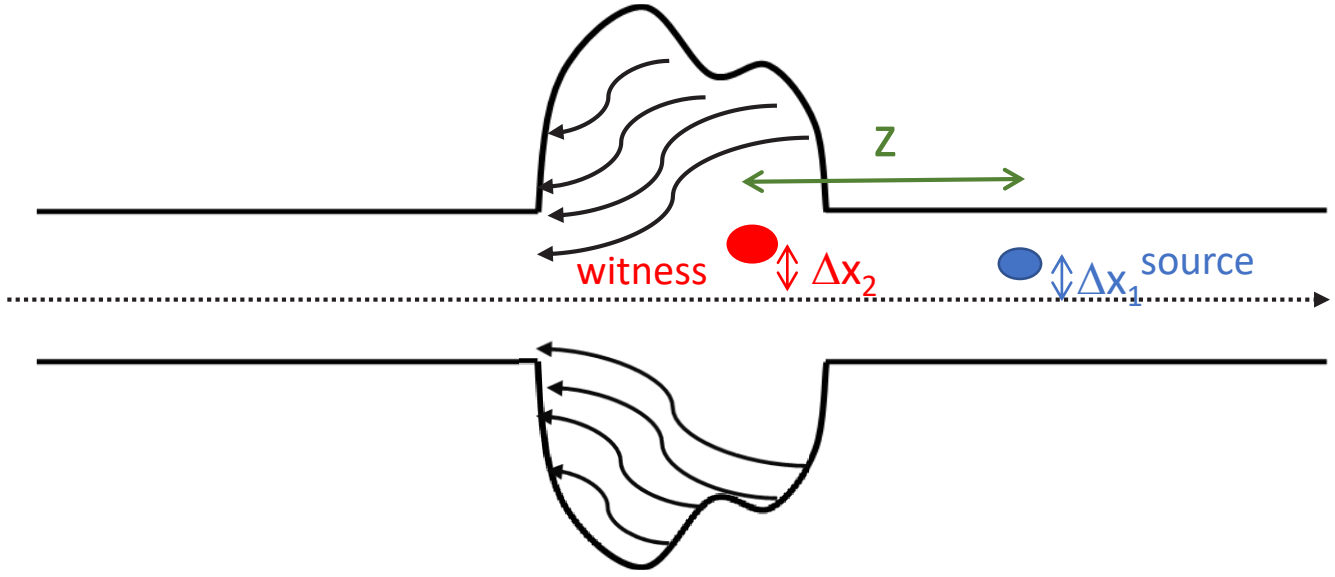
- The electromagnetic fields generated by a particle moving through a vacuum chamber are usually described as wakefields.
- Impedance is the expression of the wakefield in the frequency domain.
- Wakefields generated by the head particles can act back on following particles modifying their dynamics and (potentially) driving **instabilities**.
- A long range wakefield causes coupling **multi-bunch instability.**
- A short range wakefield causes **single bunch instability**.

$$W_x(z) = -\frac{E_0}{q_1 q_2}\frac{\Delta x_2'}{\Delta x_1}$$

The transverse wakefield

$$W_{\parallel}(z) = -\frac{\Delta E_2}{q_1 q_2}$$

The longitudinal wakefield



q_1, q_2: $charge$

How to measure impedance & wakefield ?

Analytical Methods

Wakefield and impendence can be derived directly from Maxwell equations:

- Fundamental methods:

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{B} = 0$$

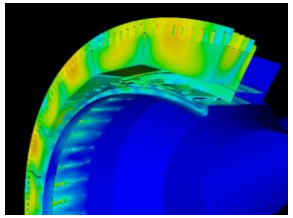
$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu\varepsilon_0 - \frac{\partial \vec{E}}{\partial t}$$

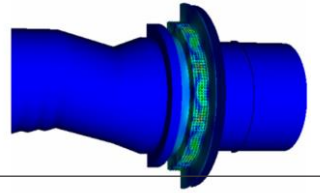
- Only simple model;

Simulation calculation methods

Wakefield and impendence can be calculated by electromagnetic field simulation software with high-performance computing equipment:

- Convenient;
- Applicable for complex structure;



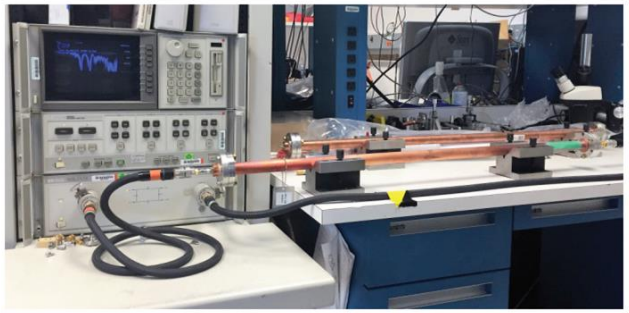


- Takes a long time;
- High requirement for computation equipment;

Emulation Test

Measure the wakefield by emulating the process of the beam passing through the accelerator components:

- Coaxial based simulation measurement scheme is relative mature;
- Close to real situation;

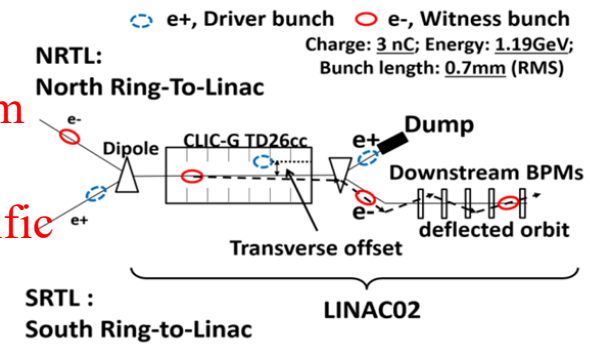


- High requirement for wires and excitation signals

Beam machine study

Measure the wakefield by beam experiments:

- Directly measure
- real situation;



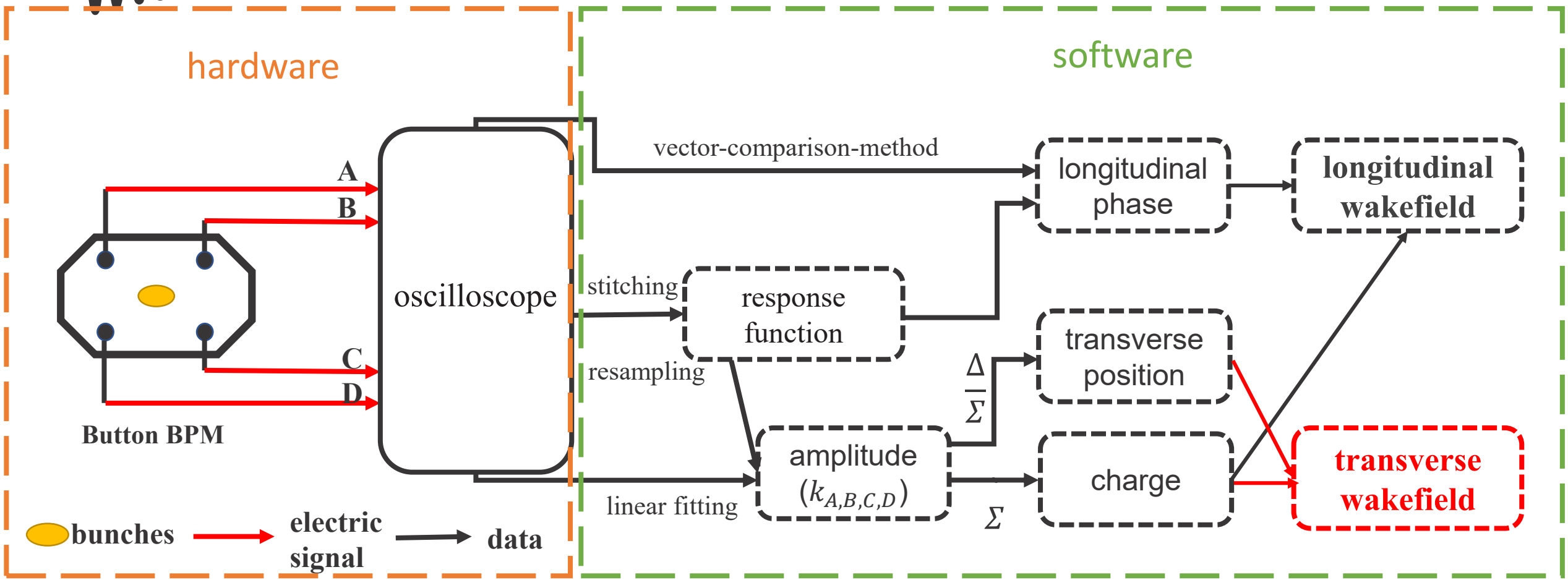
- Design a dedicated beam experiment;
- Usually requires a specific injection mode;

Why analyze wakefield using BxB measurement?

- All bunches in the storage ring as source bunches and witness bunches;
- The transverse oscillation amplitude of bunches is large during the injection process;
- The in-situ real-time analysis, does not affect the normal operation of the synchrotron radiation facility;
- Precise bunch-by-bunch beam monitor
  - Simultaneously measure the three-dimensional position and charge of every bunch;
  - Long measurement time window (milliseconds, thousands of turns);

System Setup & Performance

System setup



- Measurement scheme and algorithm flow.
- Based on bunch-by-bunch three-dimensional position and charge measurement.
- Resolution: longitudinal phase < 0.2 ps, transverse position<10 μm, charge<0.03%.

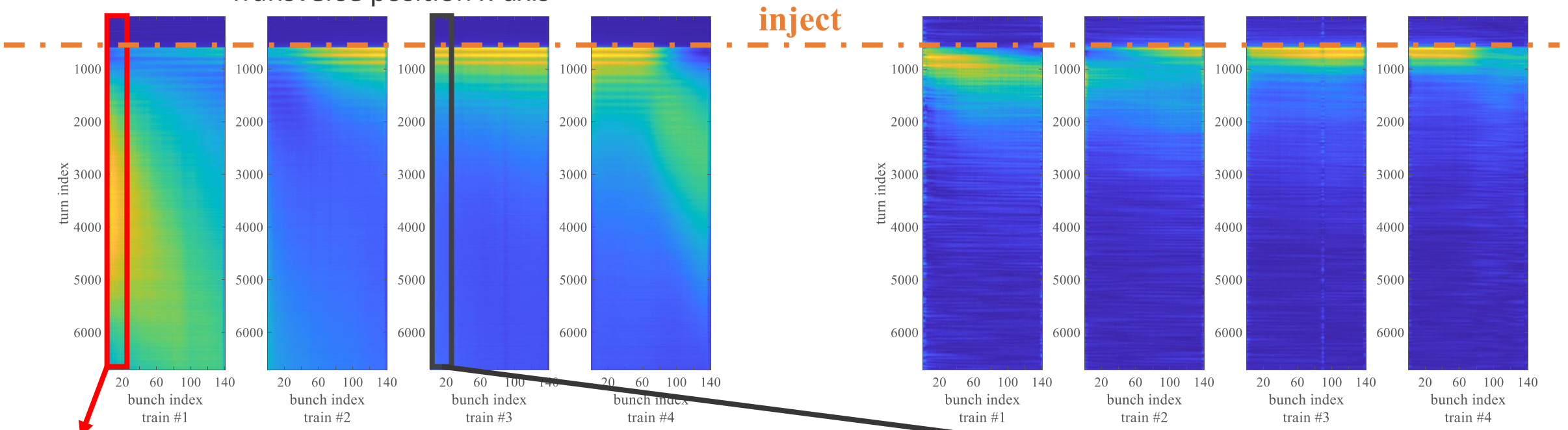
Application–wakefield analysis

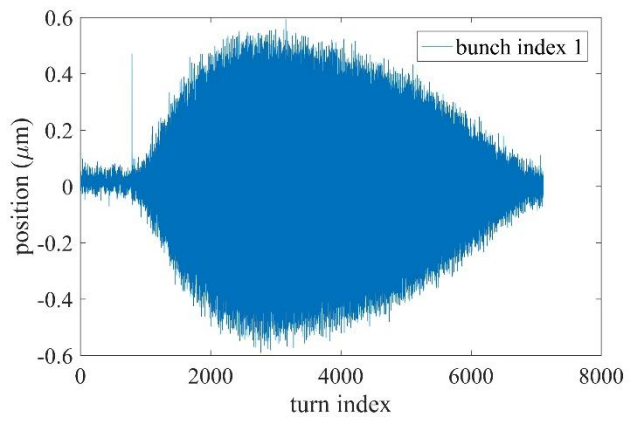
- Inject transient during normal operation of SSRF
- Special beam research in SSRF

Inject transient

Transverse position x-axis

Transverse position y-axis



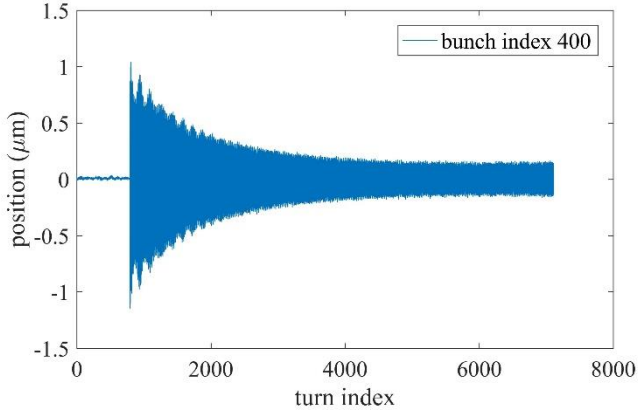


kichers field

- deviate from orbit (very short action time)
- influence on the bunches were not constant

Transverse coupled wakefield

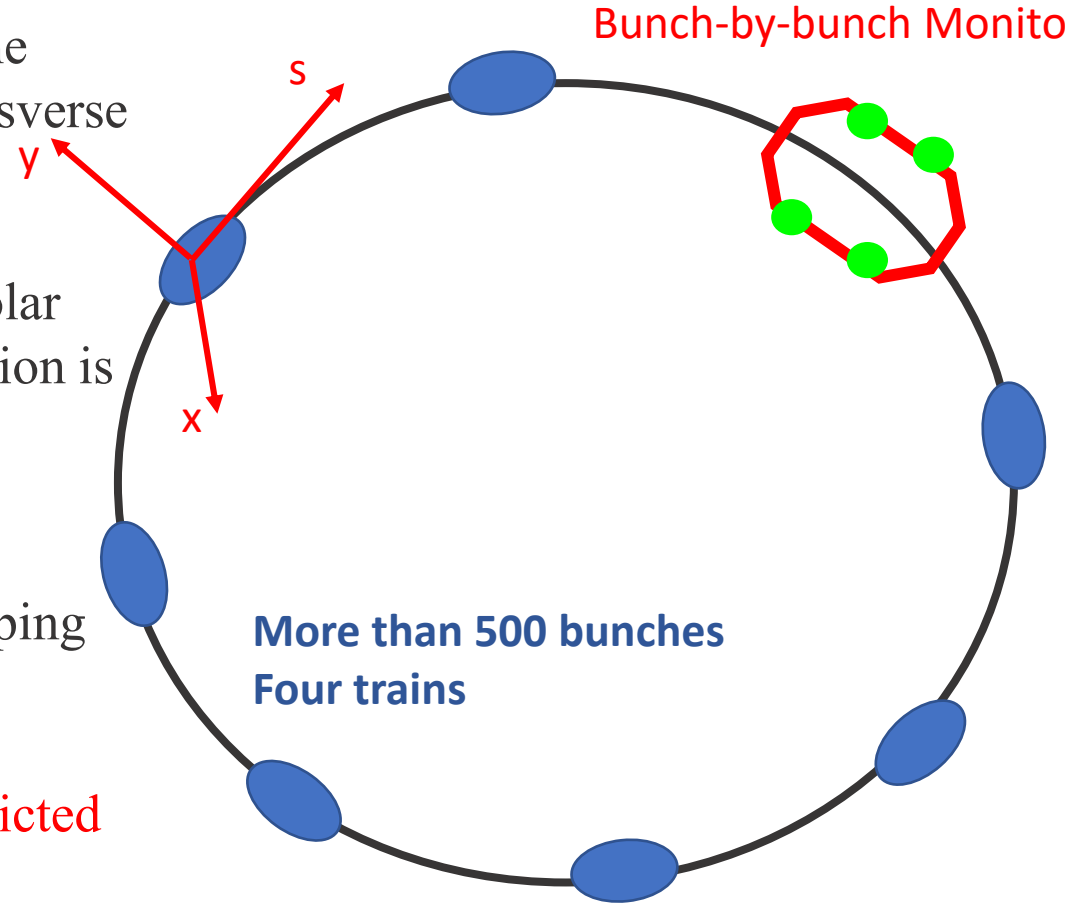
- Transmission of oscillation between bunches
- Influence on oscillation evolution



Modeling

Transverse Equivalent Coupled Wakefield for the Whole Storage Ring

- **Transverse equivalent dipolar wakefield**: The influence of the transverse oscillation amplitude of the source bunch on the transverse oscillation amplitude of the witness bunch.
- **Simplified model**: The betatron oscillation phase and quadrupolar wakefield is not considered. Equivalent dipolar wakefield function is consistent for every source.
- **Target:** Predict the evolution trend of the transverse oscillation amplitude of each bunch under the combined action of the damping term and the wakefield.
- **Verification:** costfunction ——the difference between the predicted trend and the measured trend.



Modeling results

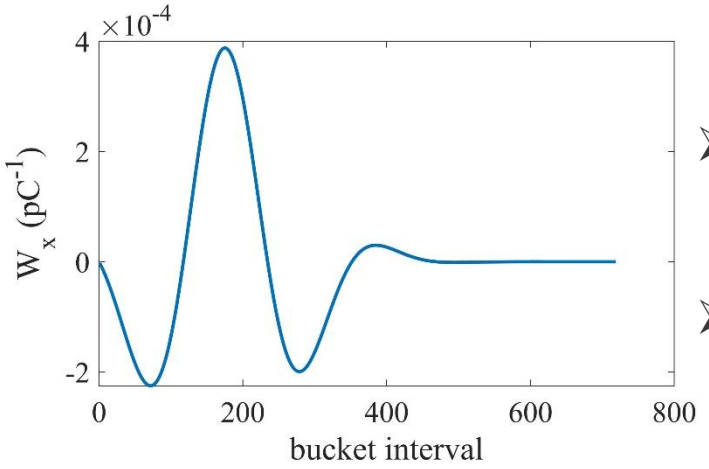
The iterative multi-turns transverse oscillation amplitude evolution trend speculate

- **Coupled wakefield drive**: All bunches will produce a kick for the transverse oscillations of all bunches (including themselves) in each turn.

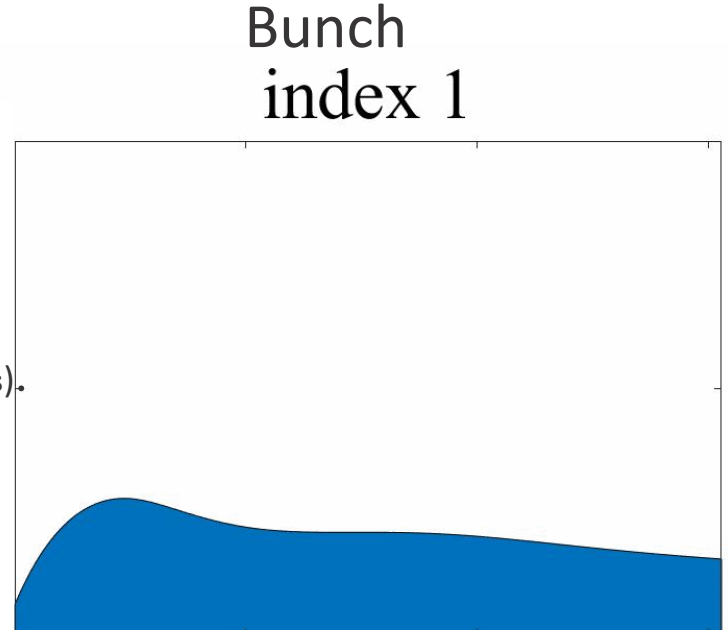
$$W_x(\mathrm{i}-j)=\frac{\Delta x_j}{q_i q_j}\cdot x_i$$

- **Damping term:** Landau Damping, Synchrotron Radiation Damping , Transverse feedback damping, etc.
  The damping coefficient is considered to be a constant value.

- Find which equivalent wakefield can satisfy the real process(**non-uniqueness**).

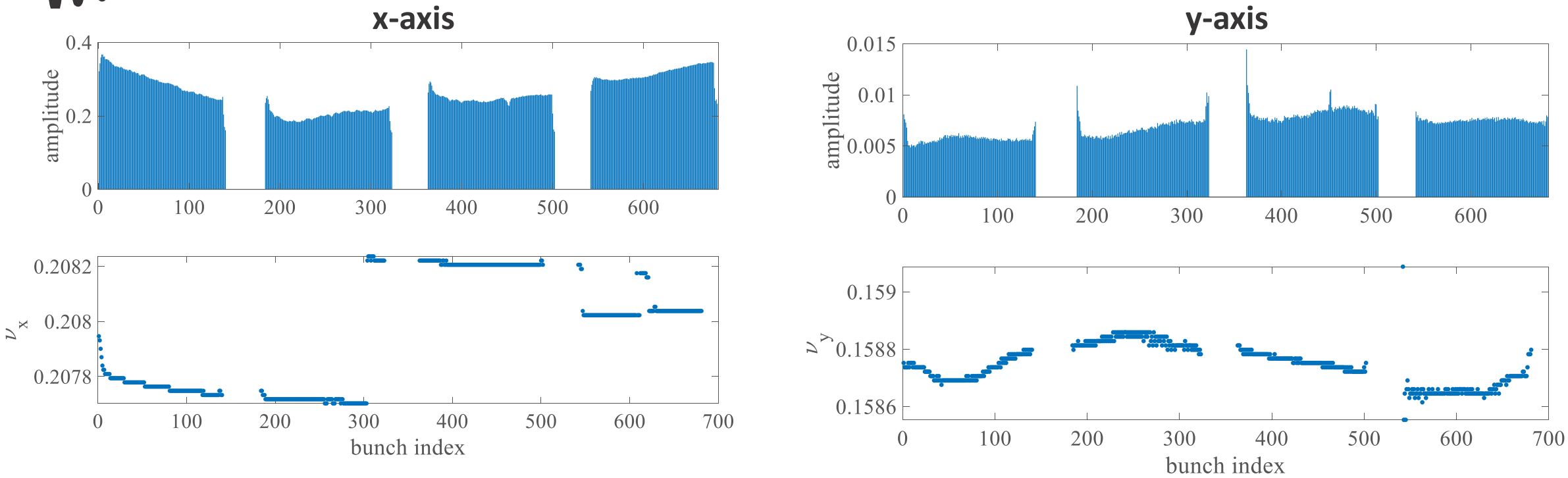


- Bunches that are 180 buckets away have the most obvious influence.
- the transmission of oscillating energy



The predicted trend of transverse oscillation amplitude(x).

The tune difference between bunches



The distribution of amplitude and tune of the transverse oscillation with the bunch index

$$\Omega_\mu - \omega_\beta \approx -i \frac{4\pi}{Z_0 c} \frac{c^2}{2\gamma_0} \frac{I}{I_A} \sum_{p=-\infty}^{\infty} \frac{\beta_\perp Z_\perp}{C_0} \left[(pM + \mu)\omega_0 + \omega_\beta \right]$$

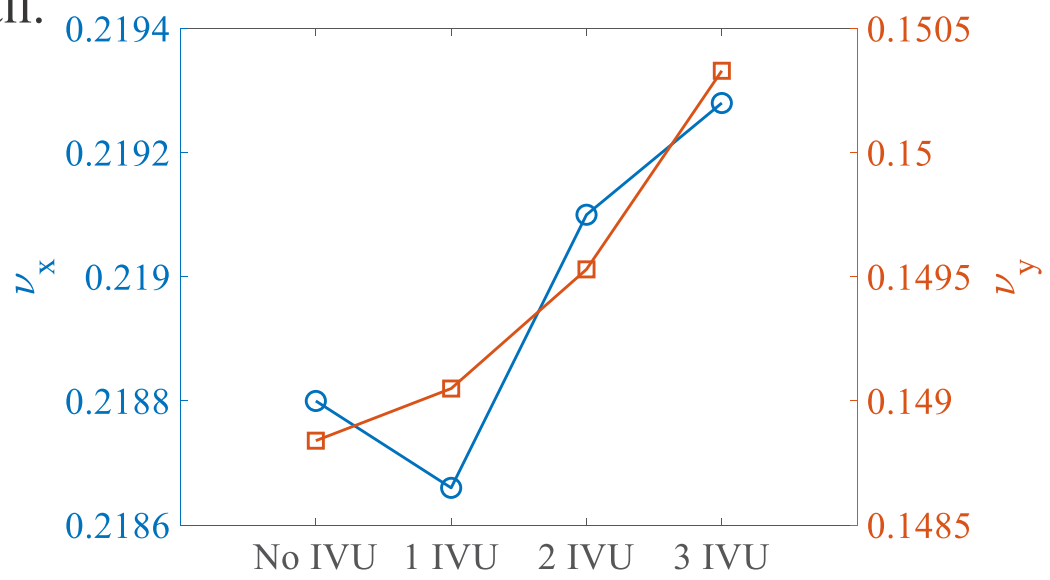
- The frequency shift of betatron oscillation has been observed.
- The frequency of different bunches is dependent on bunch index.
- Transverse quadrupolar wake function

Application–wakefield analysis

- Inject transient during normal operation of SSRF
- Special beam research in SSRF

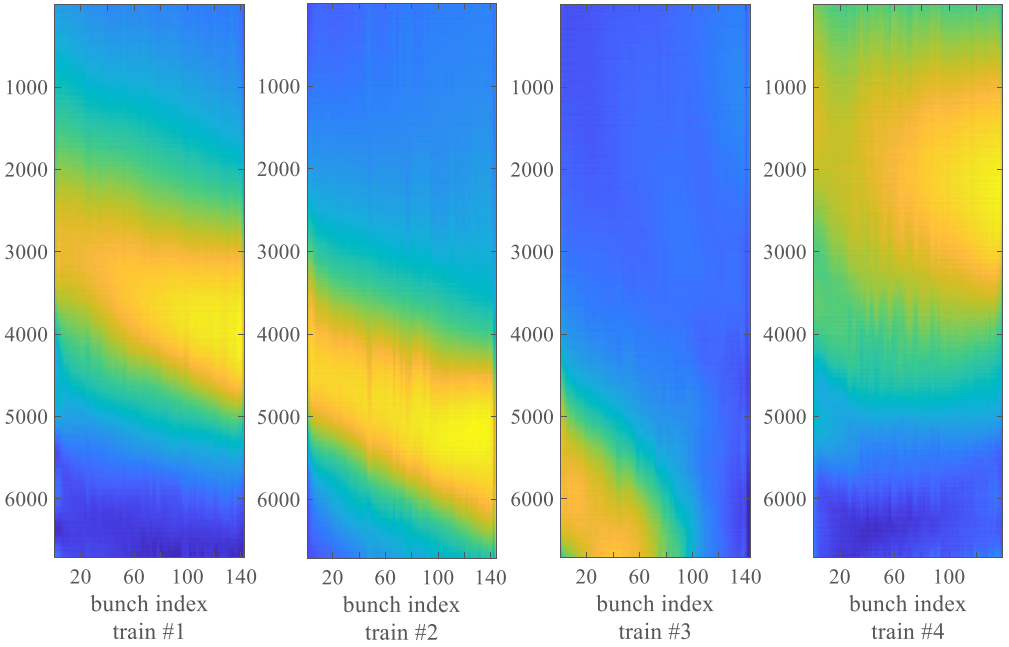
Special beam research in SSRF

- The transverse feedback system off, the damping term very small.
- Long-term large transverse oscillation
- Change Insert vacuum undulator(IVU) status
- The average tune difference
  - transverse quadrupolar wakefield
  - the integrated field error of the undulator



	Transverse feedback system	H18 IVU25 gap	H19 gap	H08EPU gap	Tune x-axis	Tune y-axis
1	off	open	open	open	0.21880	0.14884
2	off	close	open	open	0.21866	0.14905
3	off	close	close	open	0.21910	0.14953
4	off	close	close	close	0.21928	0.15033

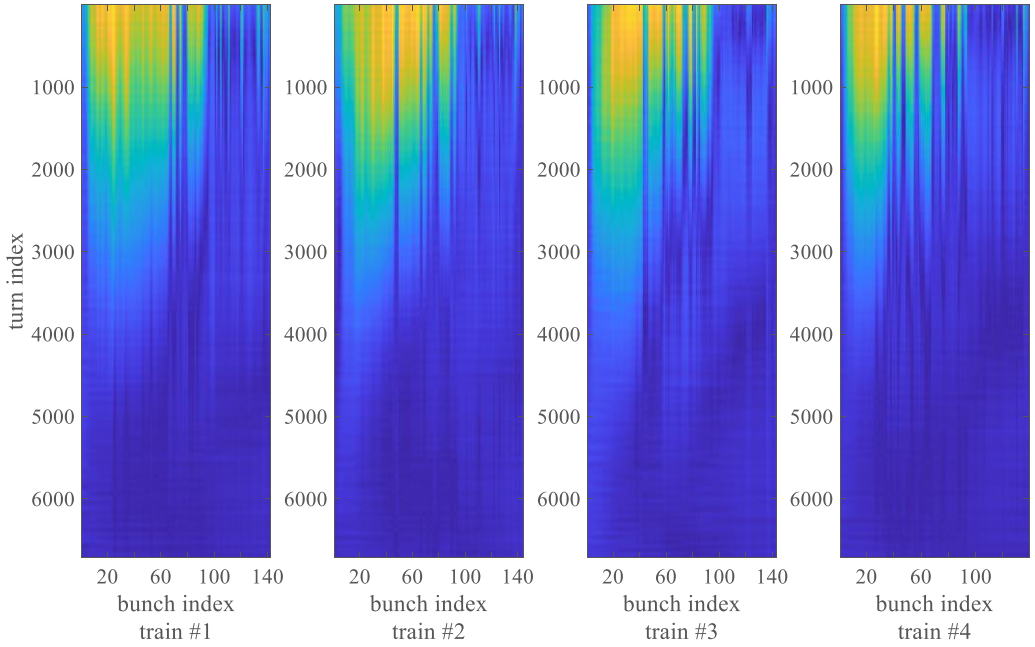
Transverse position x-axis



The horizontal (x-axis) transverse oscillation amplitude evolves with time, similar to a traveling wave, and the maximum amplitude envelope propagates along the bunch index direction with time.

The wakefield is characterized by multi-bunch instability

Transverse position y-axis



The vertical (y-axis) transverse oscillation amplitude evolves with time, which is similar to a standing wave, and the maximum amplitude envelope changes with the time for each bunch.

The wakefield is characterized by single bunch instability or a particularly long wakefield, which spans many turns.

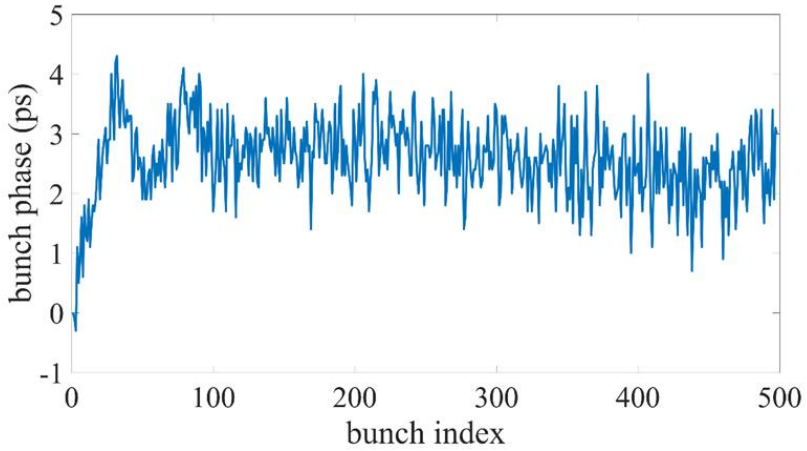
Summary & Future Work

Summary

- ✓ The long-term transverse oscillation driven by the coupled wakefield was clearly observed, thanks to the bunch-by-bunch three-dimensional position and charge measurement system;
- ✓ Realized beam coupling wakefield analysis during user operation;
- ✓ a simplified model was established to describe the evolution of the transverse oscillation amplitude of bunches over time under the action of the coupled wakefield; A rough coupled wakefield function was obtained;
- ✓ The frequency shift of betatron oscillation was observed, which is the basis for analyzing the quadrupolar wakefield.

Future Work

- The current model needs to be further verified and further improved.
- Improve the accuracy of position measurement, try to get quantitative coupled quadrupole wakefield from the tune shift.
- Extract the longitudinal coupling wakefield function from the bunch-by-bunch longitudinal balance phase.



longitudinal balance phase

Thanks for your attention

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