Injection transient study using 6-dimensional bunch-by-bunch diagnostic system at SSRF

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IBIC 2018

International Beam Instrumentation Conference

Shanghai, China, 9-13 September 2018

Outline

- Bunch-by-bunch diagnostic overview
- System Setup & performance
- Application: Injection transient study
- Next Works
- Summary

Bunch-by-bunch study overview

Why bunch-by-bunch diagnostics

For the construction and operation of the machine

Basic requirements for diagnostics:

- Toolkit to monitor beam parameters for machine operation
- Toolkit for machine study
- Complete other measurement requirements demanded by physicists

Not just "follow the orders to be a soldier"

Play a more active role in the accelerator

- The distribution of high energy particles in the three-dimensional space
- The distribution evolution over time

Almost → Derive all other parameters from the above measurements

For bunching beam

Bunch-by-bunch diagnostics

What bunch-by-bunch

In the simplest case

Assume:

- Bunching beam
- Gaussian distribution in the three-dimensional space

Six spatial parameters (x, y, z, σx, σy, σz) + Charge (Q) = an independent bunch

6-dimensional **bunch-by-bunch diagnostic system**

What benefit from bunch-by-bunch diagnostics

Stable beam parameter monitoring during user operation mode

- **Online monitoring** of stable beam parameters of each bunch such as length, size and charge
- Results can be used to optimize the operation mode

Unstable beam parameter monitoring during user operation mode

- **Transient process capture** and **further analysis of instability** (amplitude, size, phase)
- Instability prediction (long-term data)

Machine study tool

- Much easier to do experimental research of **wake field** and **impedance**

Injection transient process study

- Evaluate **injection process performance** and optimize injection system (repeatability, disturbance)
- Evaluate **the injector performance** and optimize the injector parameter
- Obtain **dynamic parameters** of the storage ring, optimize storage ring operating parameters, and alert abnormal status

How bunch-by-bunch diagnostics

Source	Advantages	Disadvantages
SR light	• Most ideal signal • Contains all beam information	• Limited by the **bandwidth** of the signal processing system • Not convenient for **online** extraction of **longitudinal information**
Button	• Easy to capture and condition signal	• Unable to get **transverse size** information

SSRF solutions:

- SR light (x, y, σx, σy) + Button (x, y, z, σz)
- Associate the data by twiss parameters

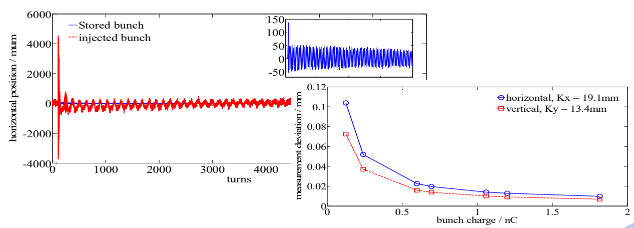
Signal conditioning, acquisition system	6D information extraction methods
• Multi-channel simultaneous sampling (> 4 (x, y)+2 (z)+2 (σz)+4X2 (σx,σy) = 16 channels) • Sampling frequency >= RF (500MHz@SSRF) • Analog bandwidth >=RF/2 (>500MHz@SSRF, reduce overlap between bunches)	• Transverse position: delta/sum (⊿/∑) • Transverse size: Gaussian fitting • Longitudinal phase: zero-crossing detection • Longitudinal length: two-frequency method **More methods are exploring……**

Roadmap

2012-2015	2013-2016	2014-2017	2015-2017	2017-present
Transverse position	**Longitudinal length**	**Transverse size**	**Longitudinal phase**	**6D Synchronous sampling**
Oscilloscope	**Oscilloscope**	**Oscilloscope**	**Oscilloscope**	**DAQ**

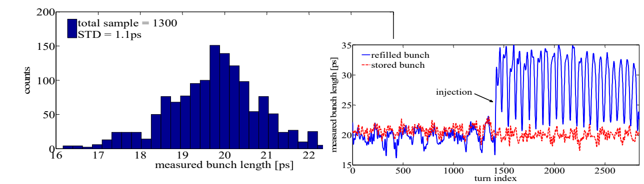
6-dimensional bunch-by-bunch diagnostic system

Transverse position (x,y)



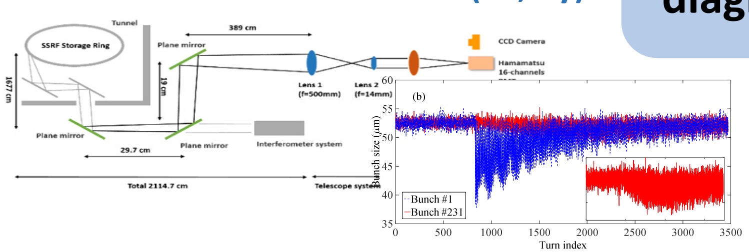
Button pickups + Δ&Σ algorithm
Resolution ≤ 10μm *(Y.B. Leng, IPAC15)*

Longitudinal length (σz)



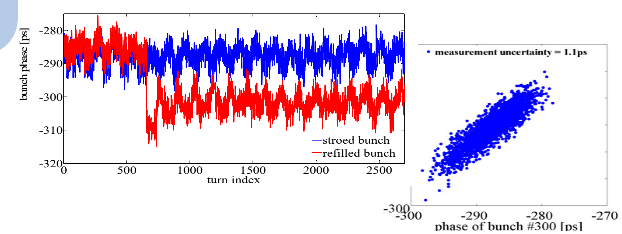
Button pickups + Two-frequency system
Resolution 0.5ps *(L.W. Duan, NST, 2017)*

Transverse size(σx, σy)



SR light + PMT array + Gaussian fitting algorithm
(H.J Chen, NST, 2018)

Longitudinal phase (z)

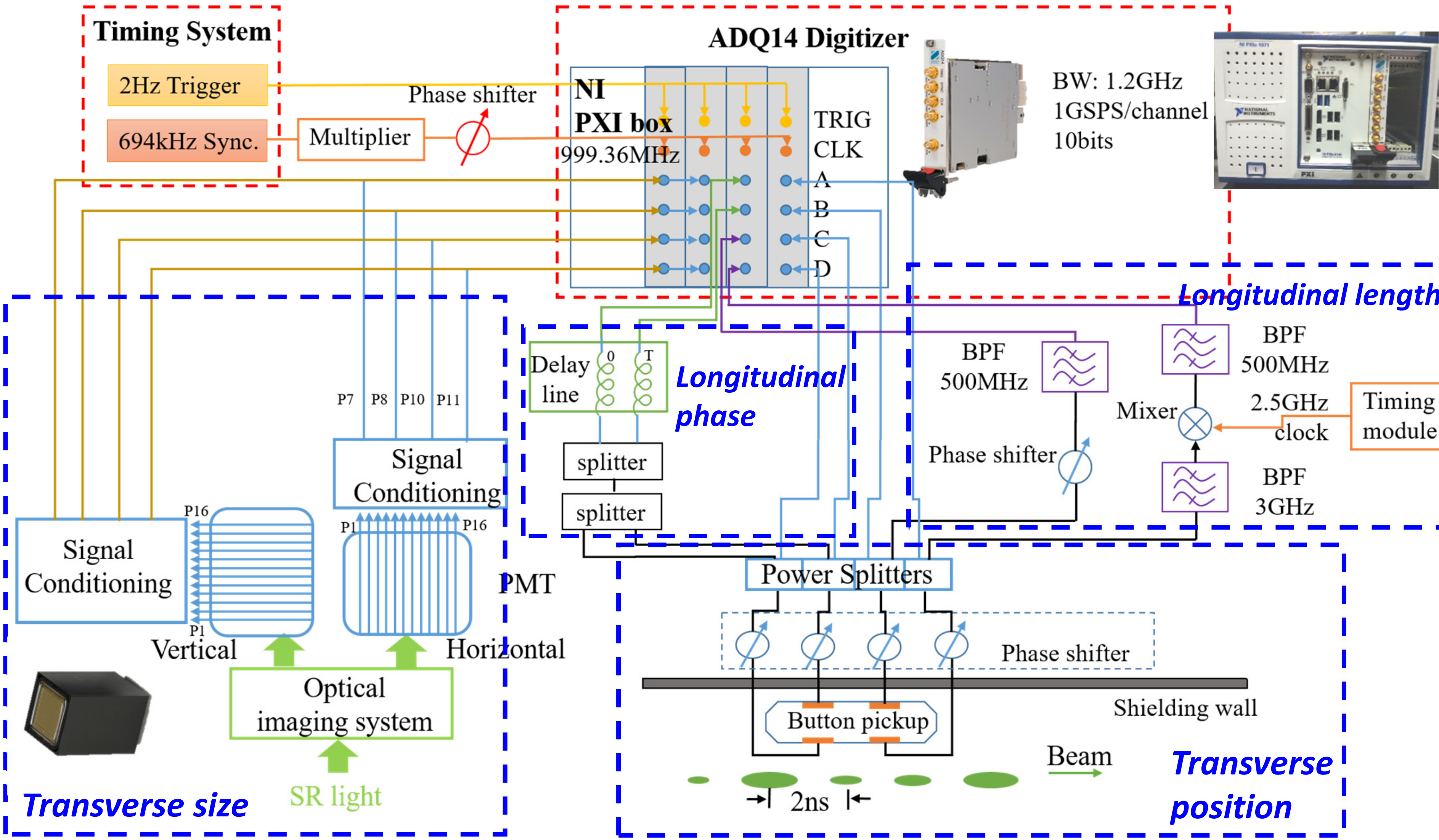


Button pickups + Zero-crossing detection
Resolution ≤ 2ps *(Y.M. Zhou, IPAC17)*

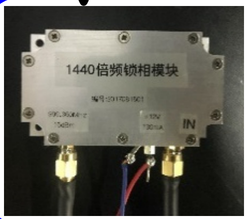
System setup & performance

6D Bunch-by-Bunch diagnostic system

- Synchronization: relies on the same clock and trigger

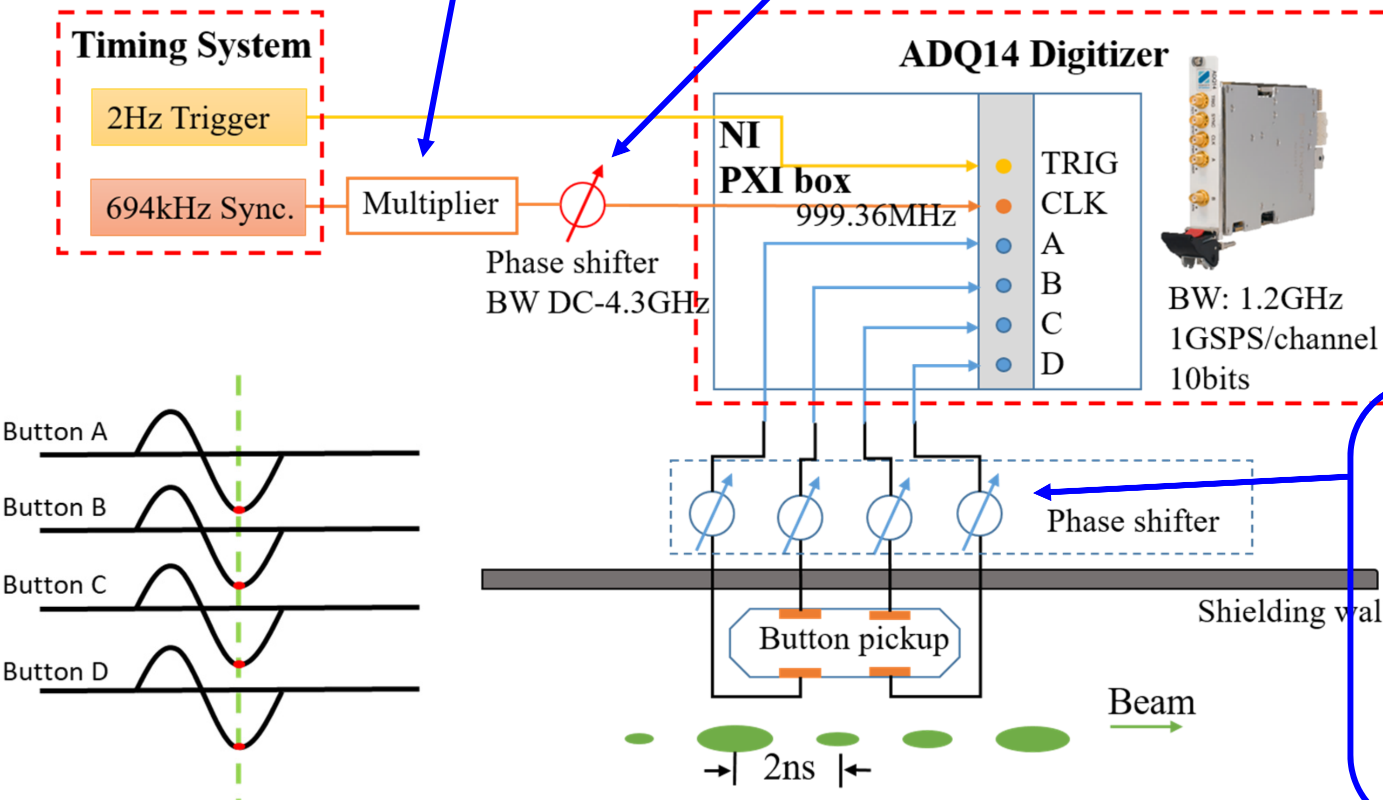


Beam transverse position subsystem



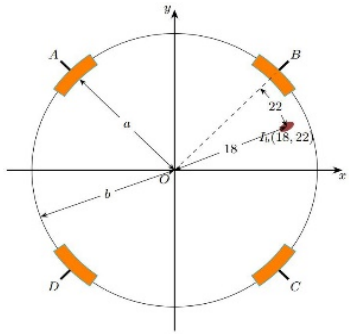
Multiplier module:
The clock signal is multiplied to 1GHz,
To facilitate the use of ADQ

Phase shifter2:
BW DC-4.3GHz
Phase adjustment of the clock signal
To ensure the **peak of signal sampled**



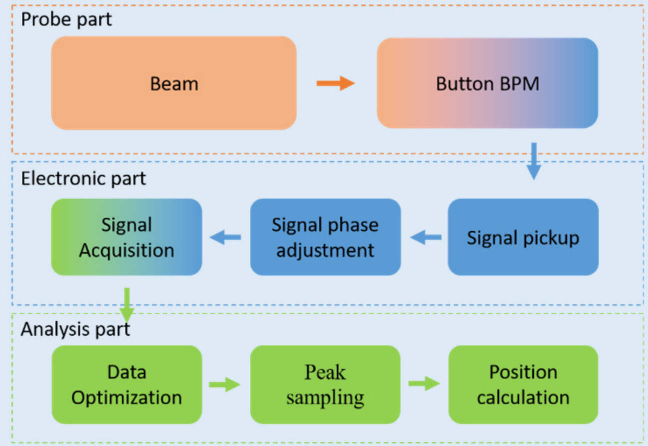
Phase shifter1:
Ensure **phase coherence** of the pickup signals

Transverse position data processing (x,y)



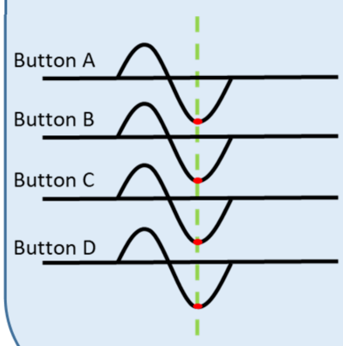
Cross section of button-type BPM

Methods:



Algorithm:

Delta/sum algorithm (⊿/∑)



$$x = k_x \cdot \frac{(V_A(t)+V_D(t))-(V_B(t)+V_C(t))}{V_A(t)+V_D(t)+V_B(t)+V_C(t)}$$

$$y = k_y \cdot \frac{(V_A(t)+V_B(t))-(V_C(t)+V_D(t))}{V_A(t)+V_D(t)+V_B(t)+V_C(t)}$$

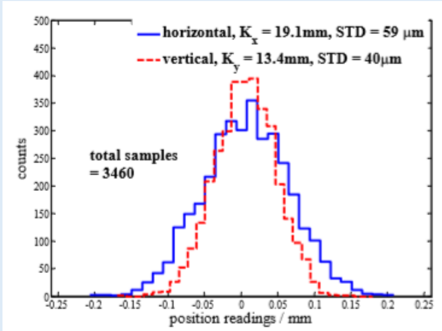
Constant:

$$k_x = 19.1$$

$$k_y = 13.4$$

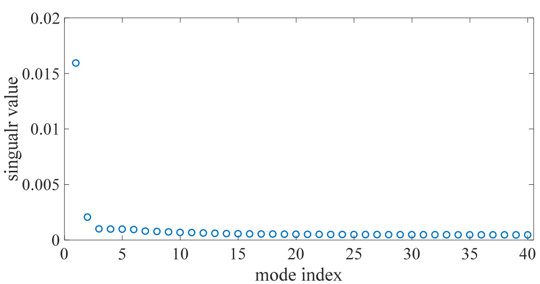
Limitations:

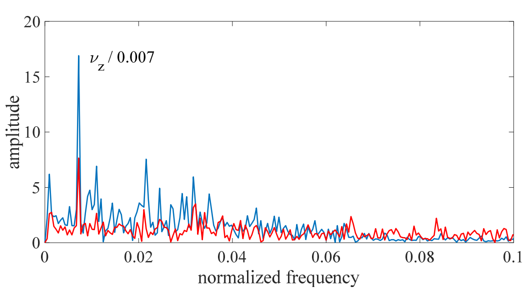
- System error introduced by sampling phase drift

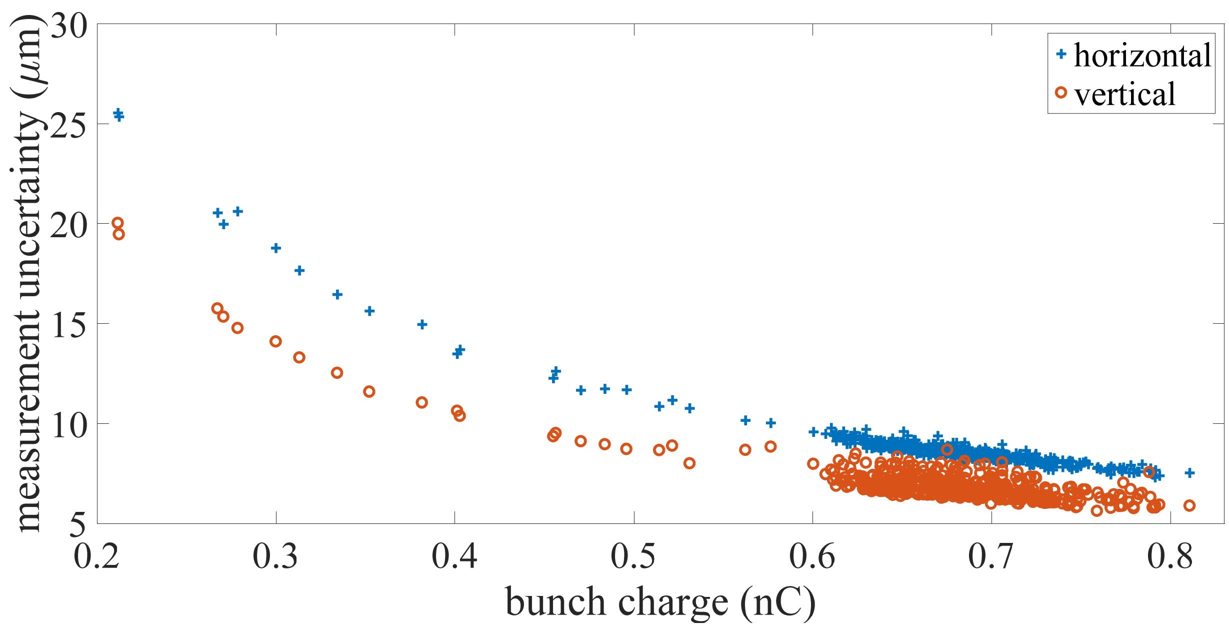


Performance evaluation (x, y)

- Data collected during daily operation, 230mA, uniform filling
- PCA method used to evaluate measurement uncertainty of transverse position
- Two modes above noise floor stand for synchrotron oscillation coupled by dispersion
- Amplitude of noise floor identified the system resolution
- **Position resolution better than 10um with 0.6 nC bunch charge**

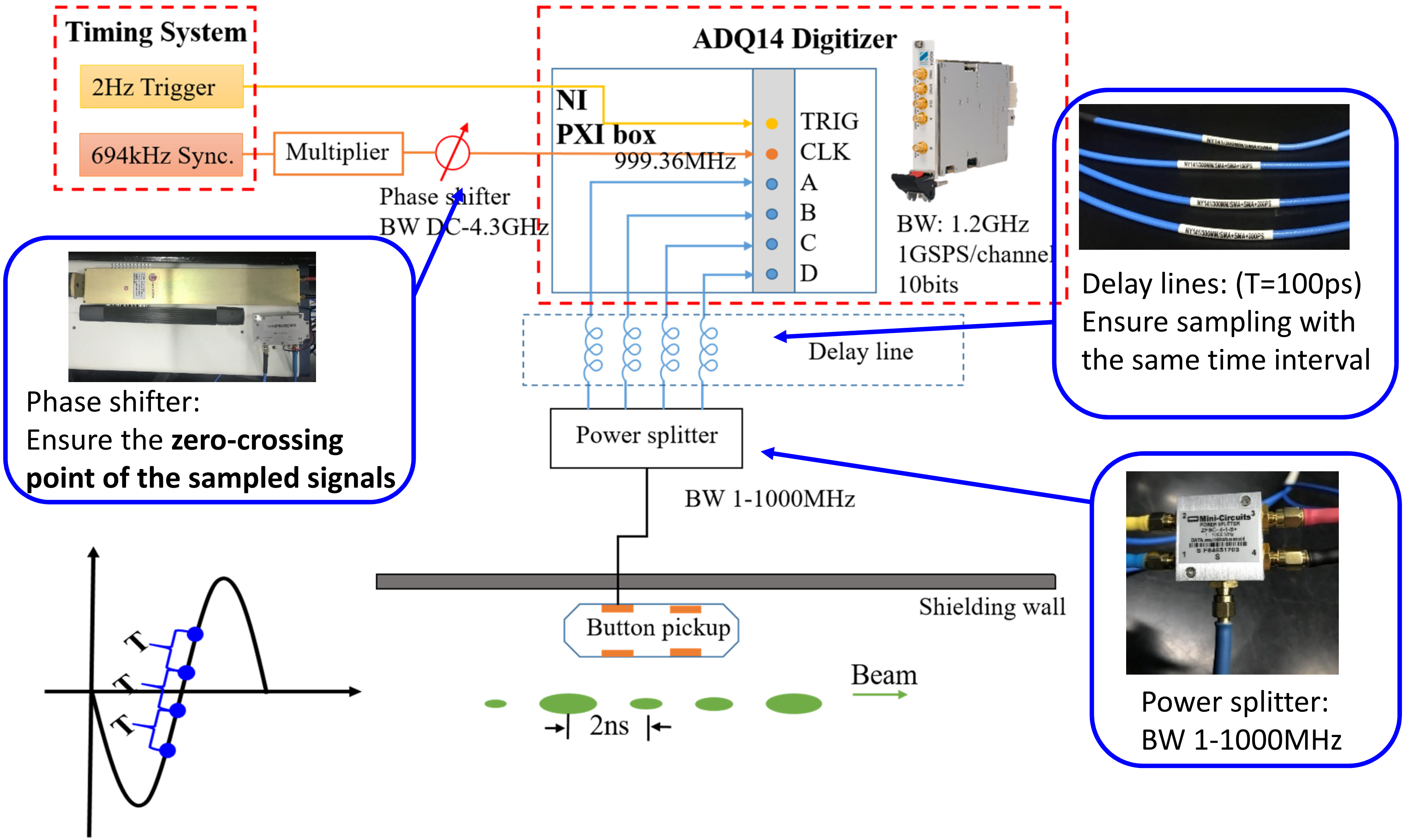




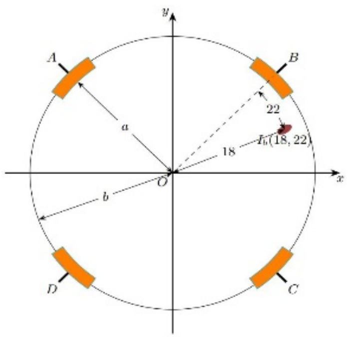


Measurement uncertainty of transverse position

Beam longitudinal phase subsystem

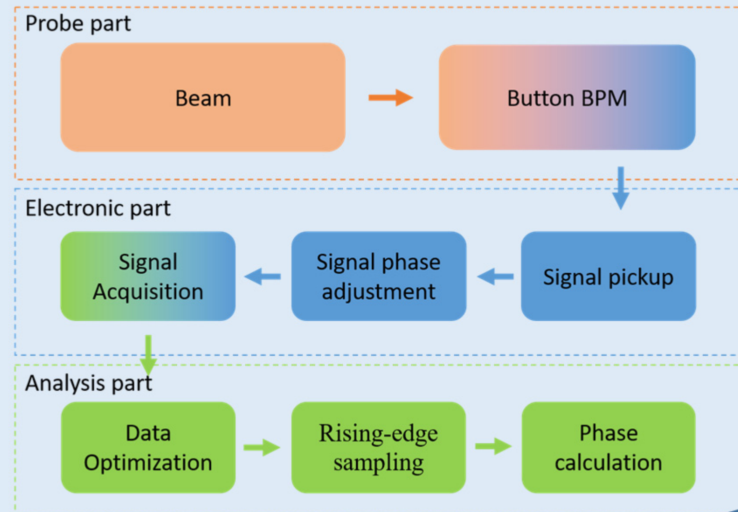


Longitudinal phase data processing (z)



Cross section of button-type BPM

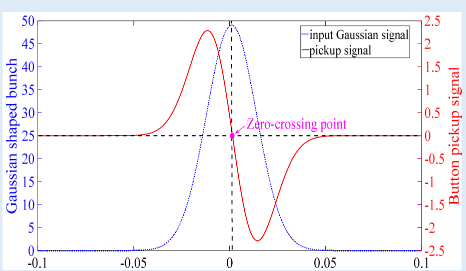
Methods:



Algorithm:

Phase difference

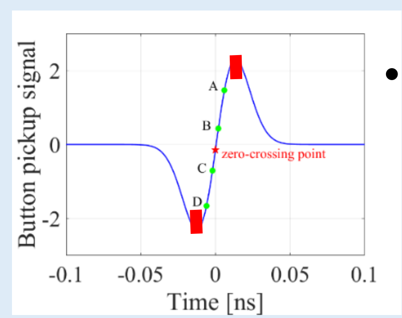
Zero-crossing detection algorithm



$$I(t) = \frac{Q_0}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(t - t_0)^2}{2\sigma^2}\right)$$

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

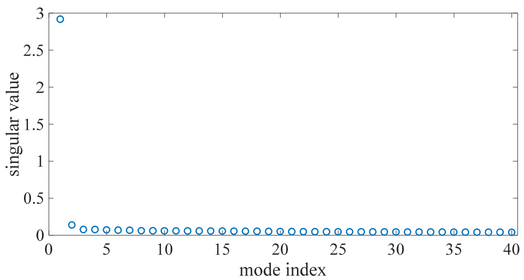
Limitations:

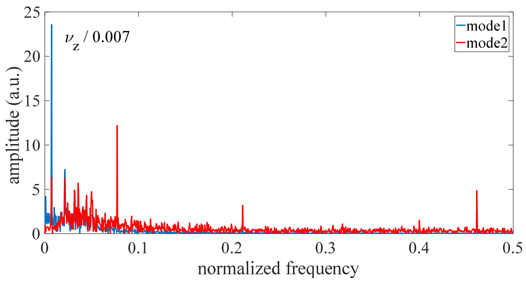


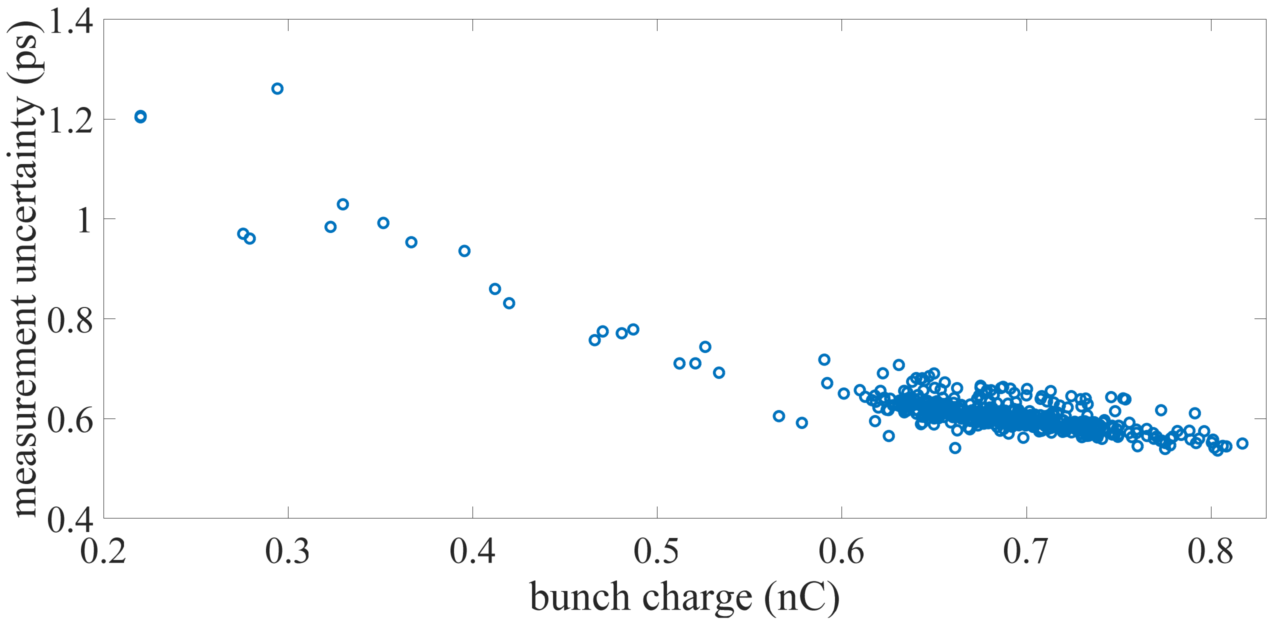
- Algorithm is not applicable when the longitudinal offset is too large

Performance evaluation (z)

- Data collected during daily operation, 230mA, uniform filling
- PCA method used to evaluate measurement uncertainty of longitudinal phase
- Two modes above noise floor stand for synchrotron oscillation
- Amplitude of noise floor identified the system resolution
- **Phase resolution better than 0.8ps with 0.6 nC bunch charge**

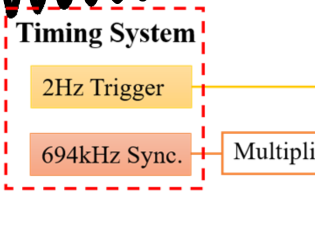


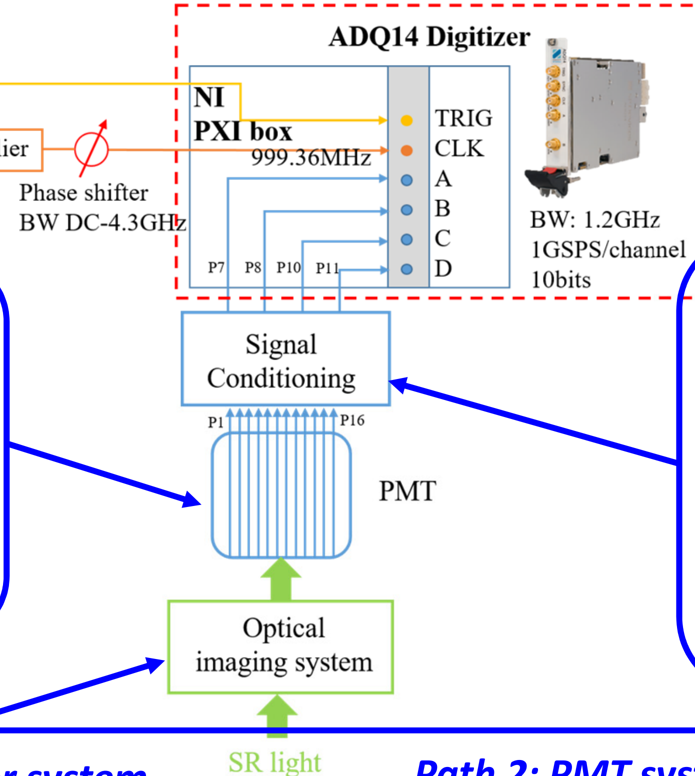


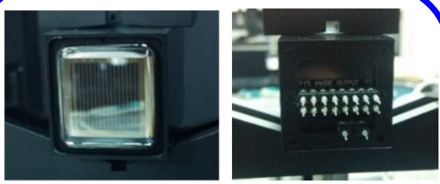


Measurement uncertainty of longitudinal phase

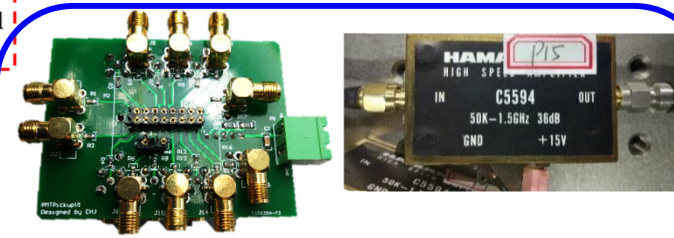
Beam transverse size subsystem







PMT array detector:
16 channels
Hamamatsu H10515B

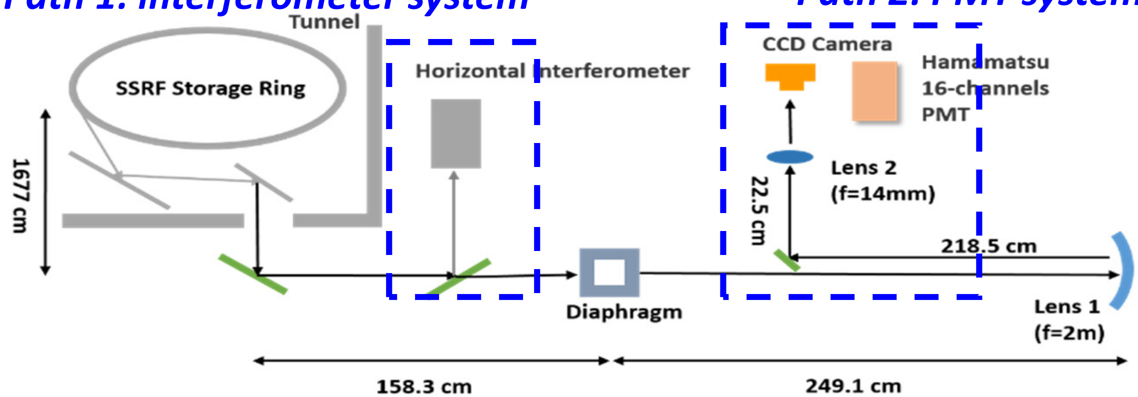


Signal Front-end
Pickup board:
Convert plug pins
to SMA connector

Amplifier:
BW 50k-1.5GHz
Gain 36dB

Path 1: interferometer system

Path 2: PMT system



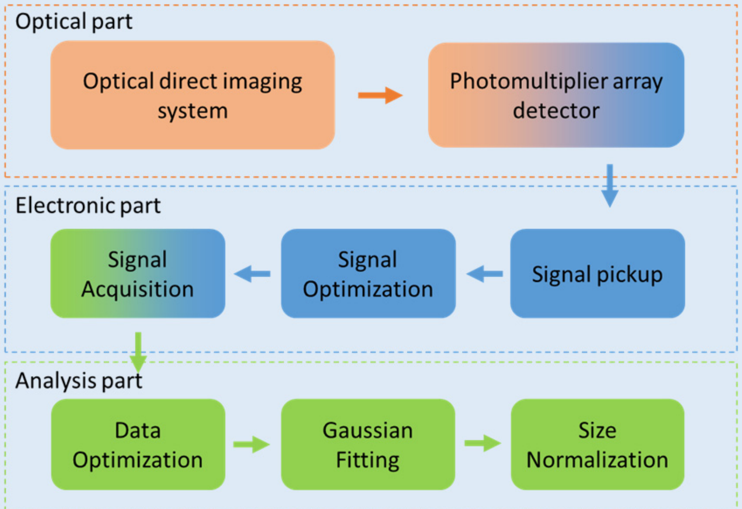
Optical imaging system:

Path1 for system PSF calibration
Path2 for bunch-by-bunch size measurement

- Focus on **horizontal size** measurement
- Be mirror deformed in the vertical direction.

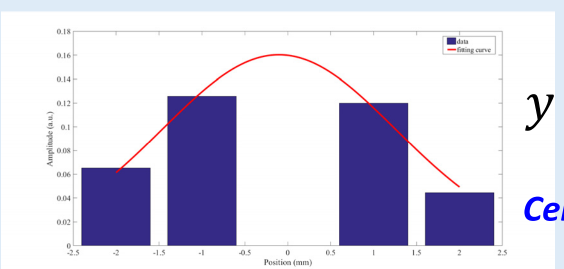
Transverse size data processing (σx,σy)

Methods:



Algorithm:

Gaussian fitting method



Bunch position

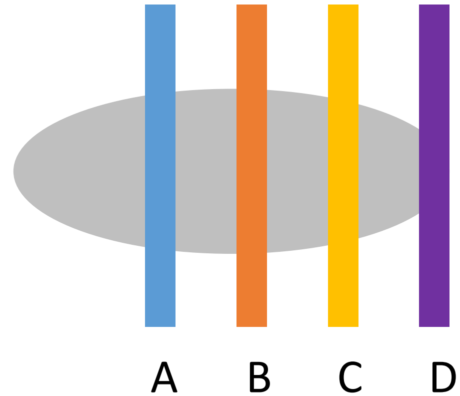
$$y = a \cdot e^{-\frac{(x-b)^2}{2c^2}}$$

Center intensity

Bunch size

New calculation algorithm - Fast

Delta/sum algorithm (∆/∑)



Centroid = ((A+B) – (C+D)) / ∑

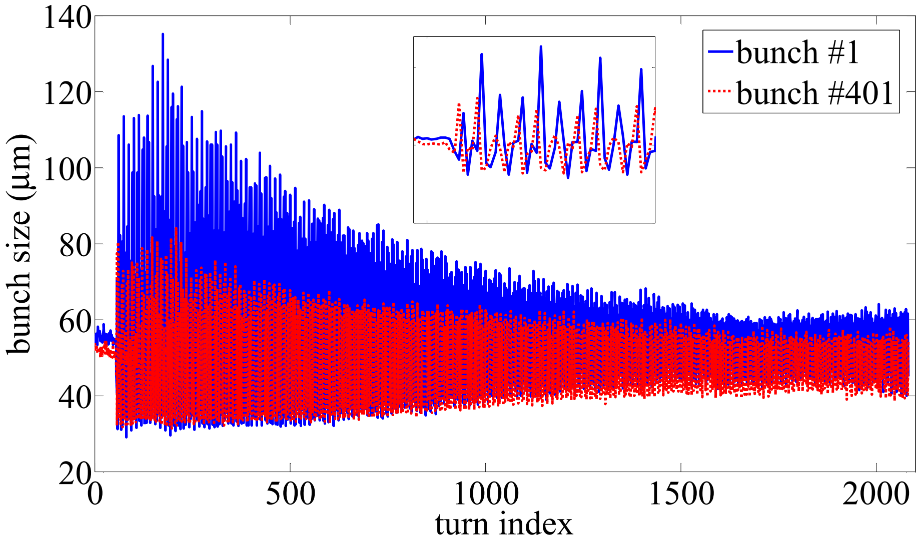
Size = ((B+C) – (A+D)) / ∑

A good upgrade direction & need to be verified next step

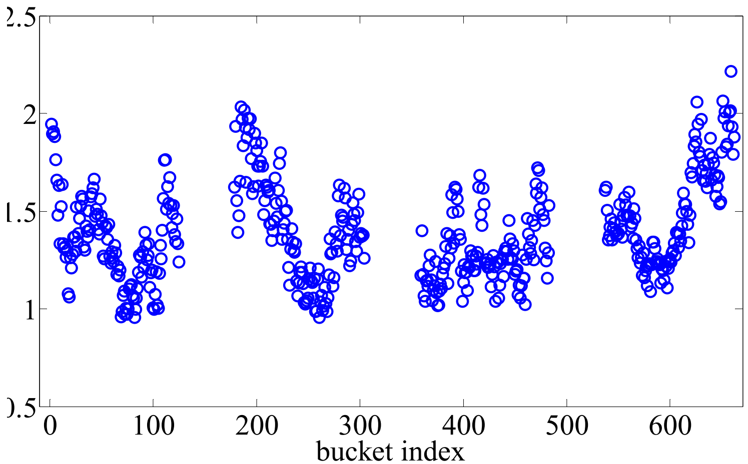
Limitations:

- Only four sampling points are not suitable for non-Gaussian distribution.

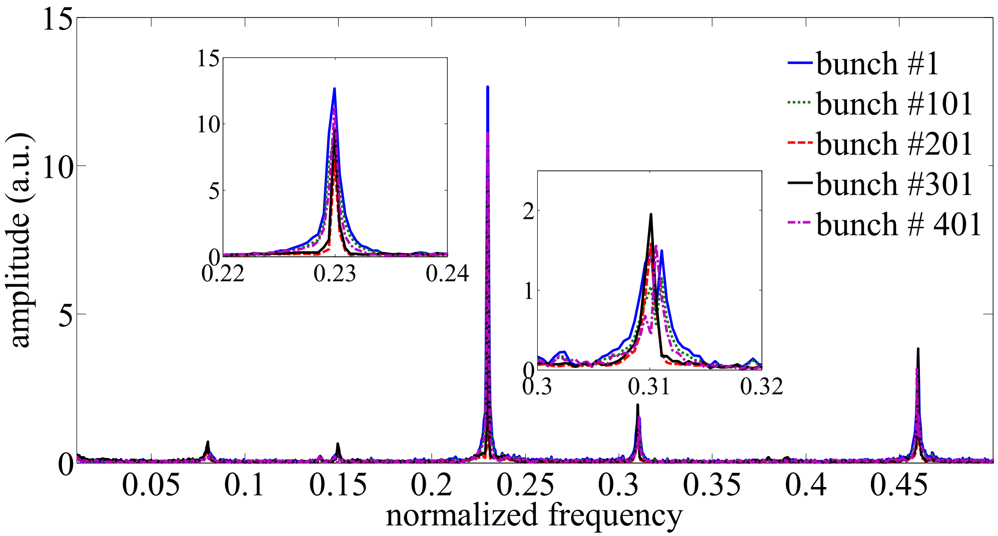
Performance evaluation (σx,σy)



Transverse size oscillation of different bunches



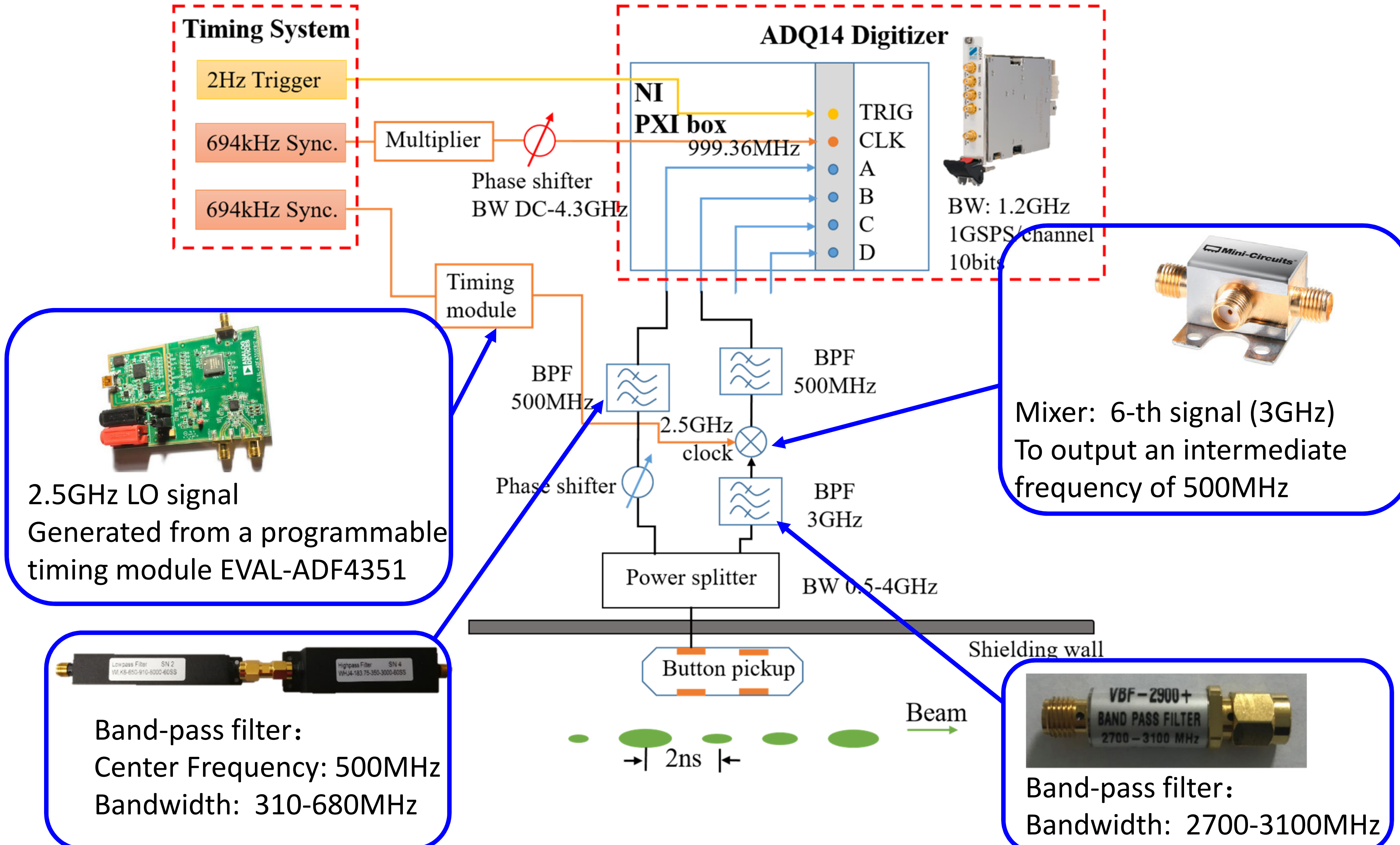
Standard deviation of 500 samples



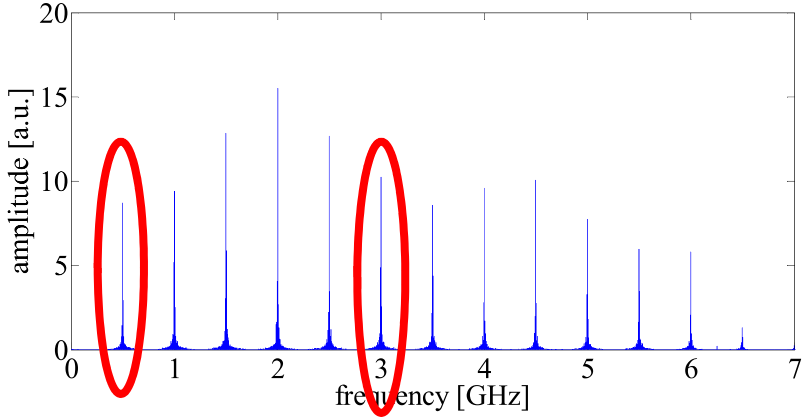
Spectrum of different bunches

- **Good enough to capture transverse size oscillation of different bunches during injection**
- **Spectrum showed size variation contributed by multi sources**
- **Standard deviation of 500 samples (measuring constant bunch size) < 2um**

Beam longitudinal length subsystem



Longitudinal length data processing (σz)

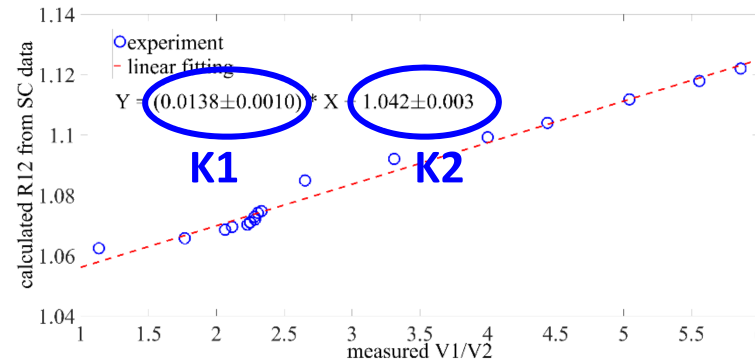


Beam Spectrum at storage ring of SSRF

Methods:

- Enough signal amplitude
- RF component limitation

Choose
m1=1 and ***m2=6***
(about ***500 MHz*** and ***3 GHz***)
as working frequencies



Two-frequency system coefficient
calibration by Steak Camera

Algorithm:

Two-frequency method

Due to two channels
transfer function difference and ***limited bandwidth***

No theoretical analytic solution for ***K1*** and ***K2***
The two coefficients can be calibrated by Streak Camera

$$\sigma=\sqrt{\frac{2}{m_2{}^2\omega_0{}^2-m_1{}^2\omega_0{}^2}\ln\left(K_1\frac{V_1}{V_2}+K_2\right)}$$

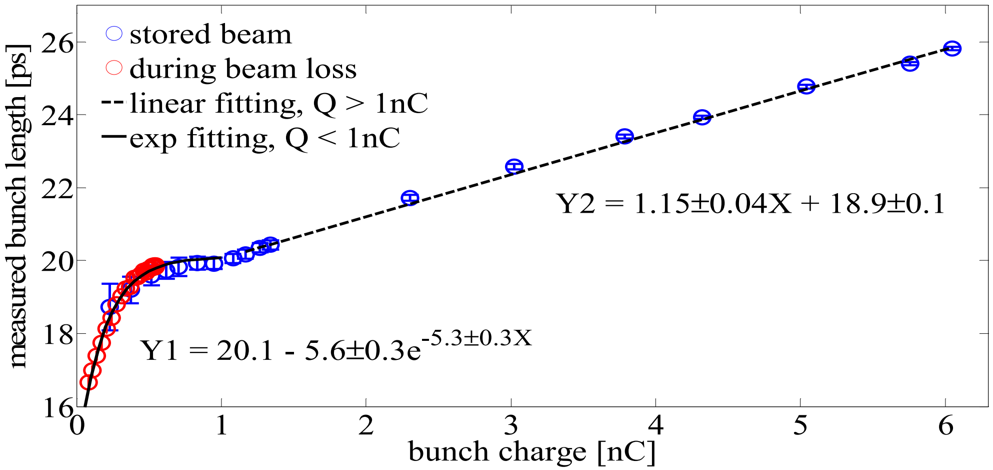
$\boldsymbol{m_2, m_1, \omega_0}$ are theoretically knowable

V1/V2 is measured from two-frequency system

Limitations:

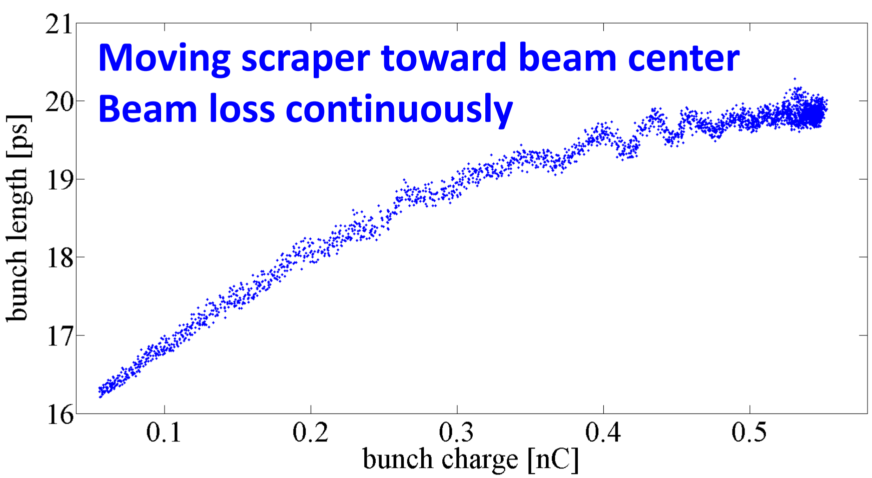
- Only two frequency points are also not suitable for non-Gaussian distribution

Performance evaluation (σz)

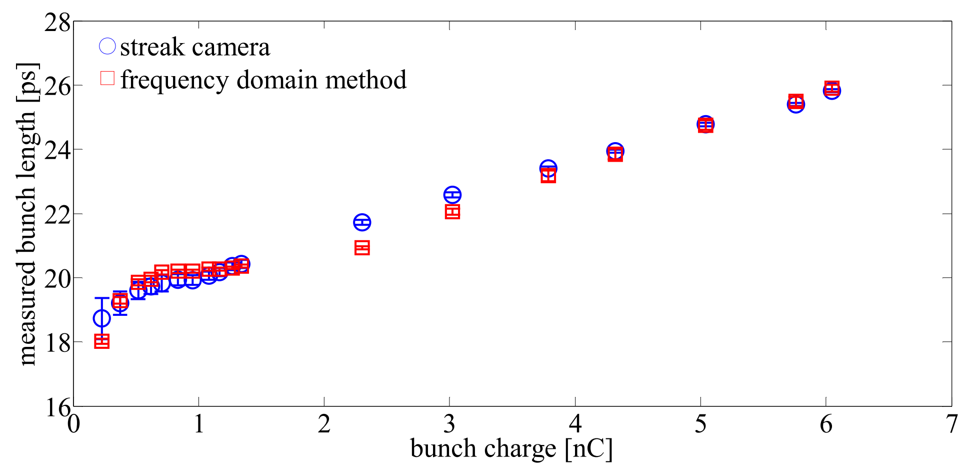


Bunch length has been measured in very large dynamic range (30pC to 6nC)

Results of small charge accidentally obtained by moving the scraper toward beam center



Bunch length shortening during beam loss



Bunch length measurement with stored single bunch beam

New method agreed with Streak Camera very well

Charge (Q)

Charge information acquisition:

- Charge (Q) is in Gaussian distribution

$$I(t) = \frac{Q_0}{\sqrt{2\pi}\sigma} \exp(-\frac{t^2}{2\sigma^2})$$

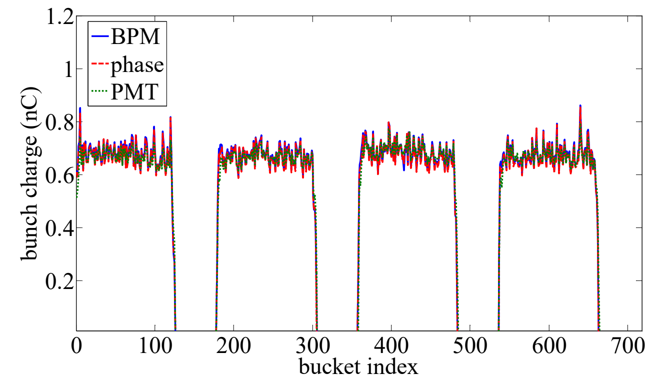
- Get the peak value of the BPM signal or SR signal

$$V_{peak} = K_Q \cdot Q_0$$

$$K_Q = k_0 Z \sqrt{\frac{e}{2\pi}} \frac{1}{\sigma^2}$$

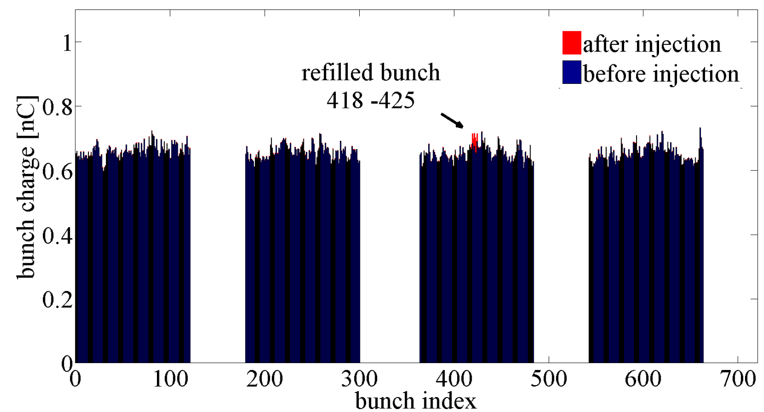
K_Q is calibrated with DCCT readings in single bunch operation

- **All subsystems can get bunch charge**
- **The results are consistent with each other**



Refilled charge acquisition:

Refilled charge	=	Charge after injection	-	Charge before injection



Bunch charge before and after injection

Injection transient study: Data analysis method

Why injection transient study

- **Change machine parameters**

  compare the measured value
  with the expected value

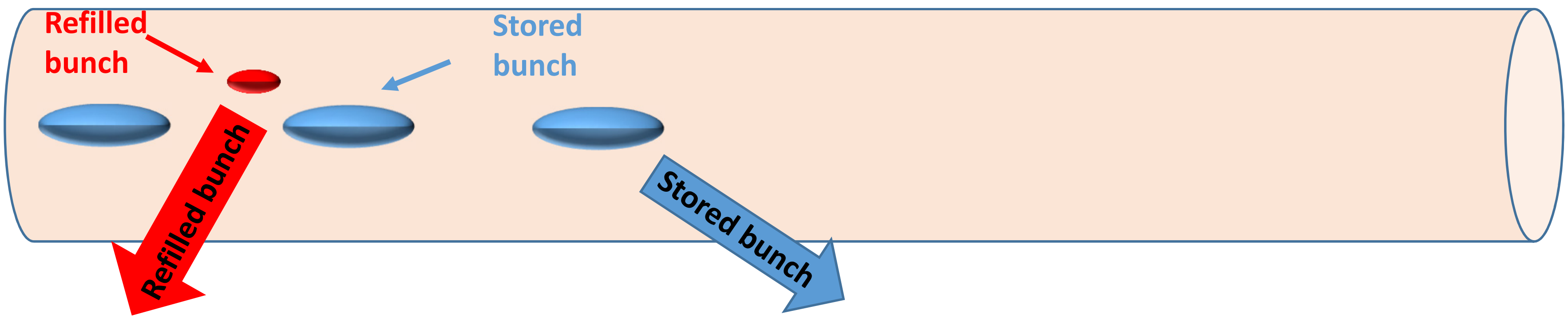
  (Ideal experiment for beam instability study, Require dedicated machine study time)

- **Injection transient process**

  separate stored bunch and
  refilled bunch

  (frequently observe in the user operation mode at SSRF)

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



- ***Refilled charge / Q_r***
- ***Betatron amplitude / A_r***
- ***Synchrotron amplitude / z_m***
- ***Synchrotron damping time / τ***
- ***Initial position in phase space / φ_0***

- ***Stored charge / Q_s***
- ***Transverse tune / ν_x, ν_y***
- ***Betatron amplitude / A_s***
- ***Betatron damping time / L_x***

Challenges

Biggest → **Separation of stored charge and refilled charge**

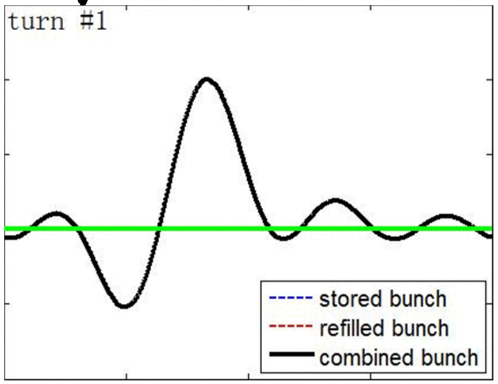
(Refilled bunch parameter acquisition)

Transverse position	Adjacent bunch position + **charge-weighted averaging**
Longitudinal phase	Adjacent bunch phase + **charge-weighted averaging**
Transverse size	• **Four sampling points** are not enough to obtain the refilled bunch size.
Longitudinal length	• **Two frequency points** are not enough to obtain the refilled bunch length.

- **Bunch length of the stored charge is unchanged during the injection process.**

Focus on → **(x, y, z, σx)**

Refilled bunch longitudinal phase extraction



Signal fusion model with different phase of the refilled bunch

Charge-weighted averaging + Zero-crossing detection

$$V_m = V_s + V_r \qquad Q_m = Q_s + Q_r \qquad t = \frac{V_1}{V_1 - V_2} \cdot T$$

Refilled bunch phase Extraction Formula:

$$t_r = \frac{Q_s}{Q_r}\left[t_m\left(1 + \frac{Q_r}{Q_s}\right) - t_s\right]$$

Q_s: Obtained from the **averaged charge of stored bunches**

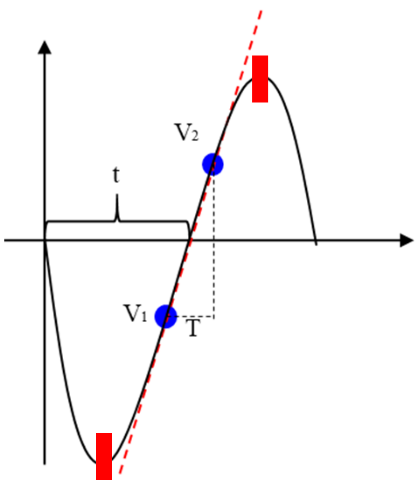
Refilled charge acquisition:

Q_r = **Charge after injection** - **Charge before injection**

t_m: **Measured phase** by **zero-crossing detection method**

Stored phase acquisition:

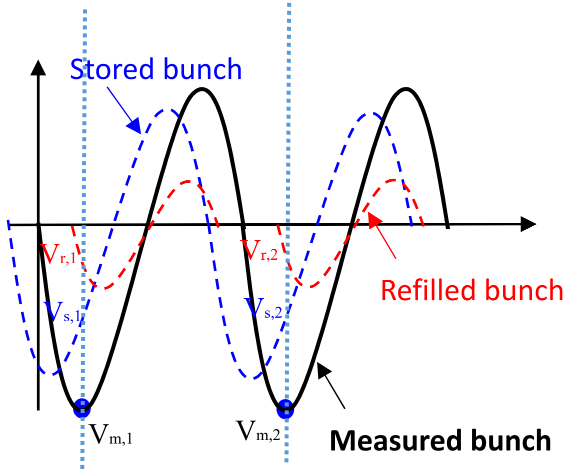
t_s = **Mean(Phase after injection , Phase before injection)**



Refilled bunch transverse position extraction

Charge-weighted averaging +Δ/Σ algorithm

$$V_m = V_s + V_r \qquad Q_m = Q_s + Q_r \qquad X = \frac{V_1 - V_2}{V_1 + V_2}$$



Refilled bunch position
Extraction Formula:

$$X_r = \frac{Q_s}{Q_r}\left[X_m\left(1 + \frac{Q_r}{Q_s}\right) - X_s\right]$$

Q_s: Obtained from the **averaged charge of stored bunches**

Refilled charge acquisition:

Q_r = **Charge after injection** - **Charge before injection**

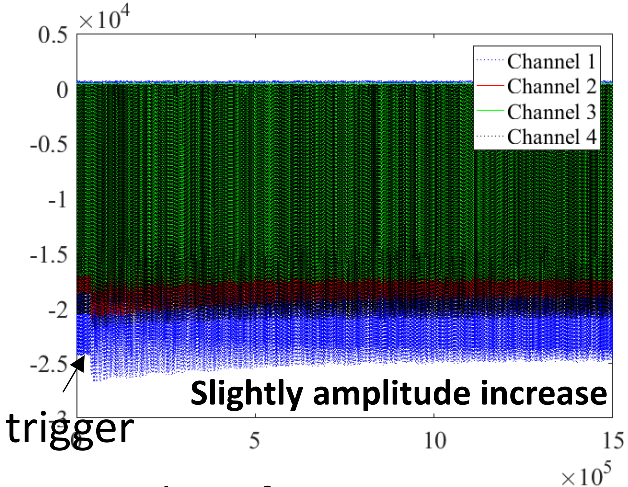
X_m: **Measured position** by **Δ/Σ algorithm**

X_s: **Stored bunch position** obtained by **interpolation of neighbor bunches**

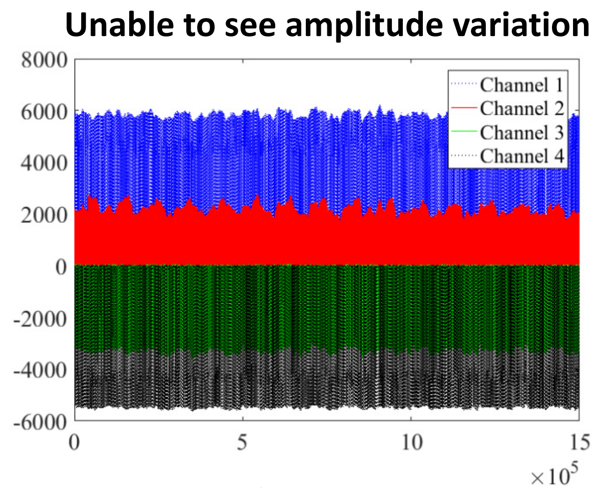
Injection transient study:

A typical injection event

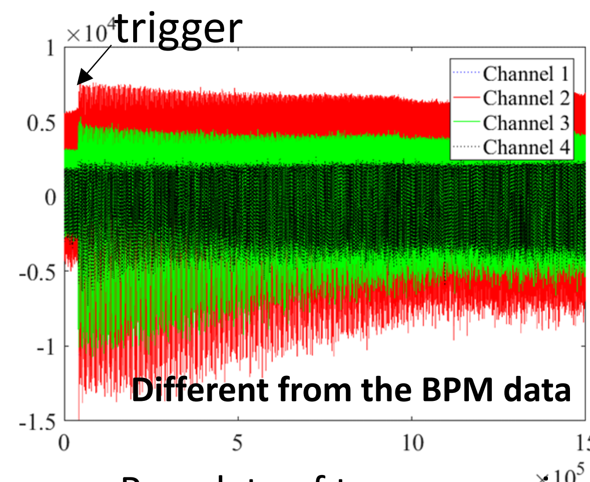
Raw data of injection capturing



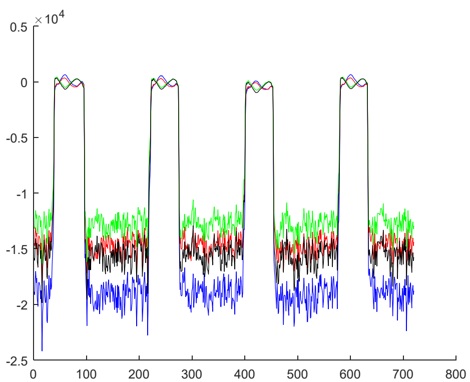
Raw data of transverse position from **Button BPM**



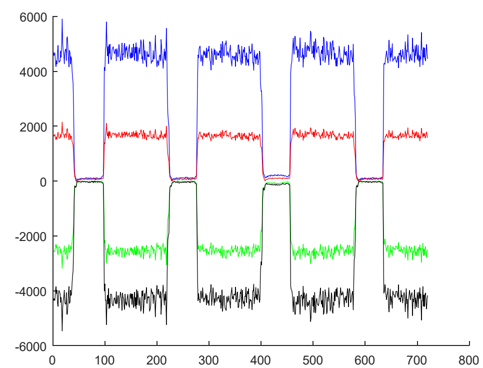
Raw data of longitudinal phase from **Button BPM**



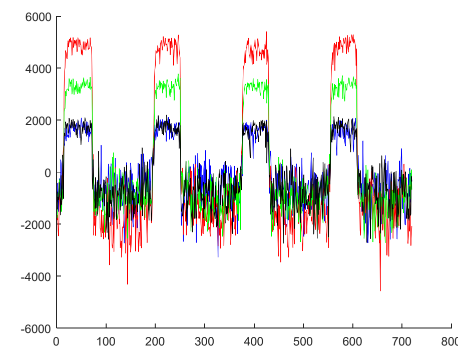
Raw data of transverse size from **SR light**



Negative peak of each channel

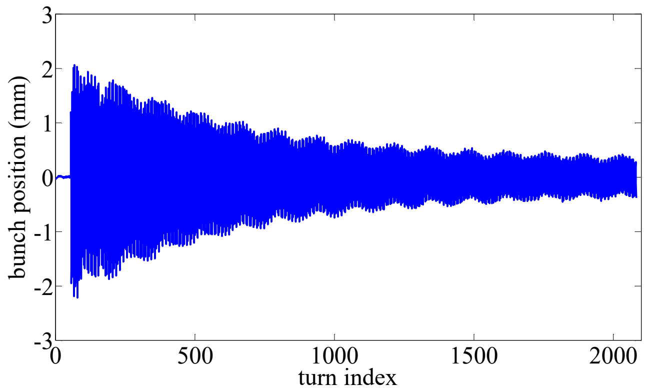


Around the zero-crossing point

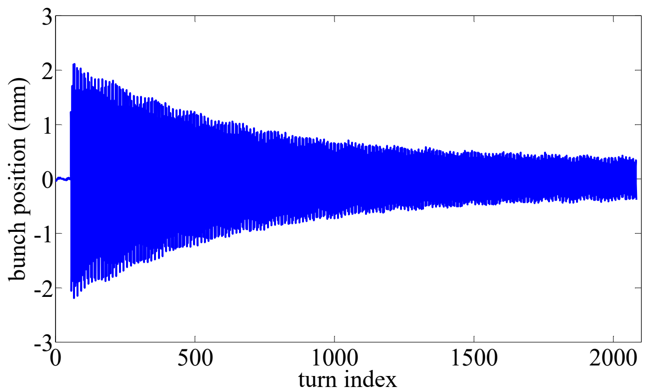


Negative peak of each channel

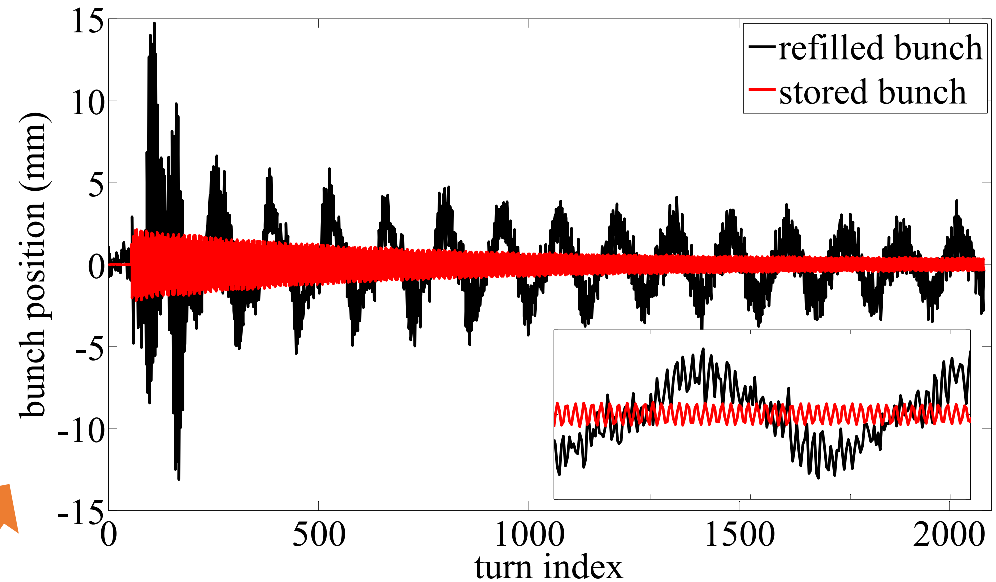
Refilled bunch: transverse position



Measured combined bunch position (Xm)



Stored bunch position (Xs)



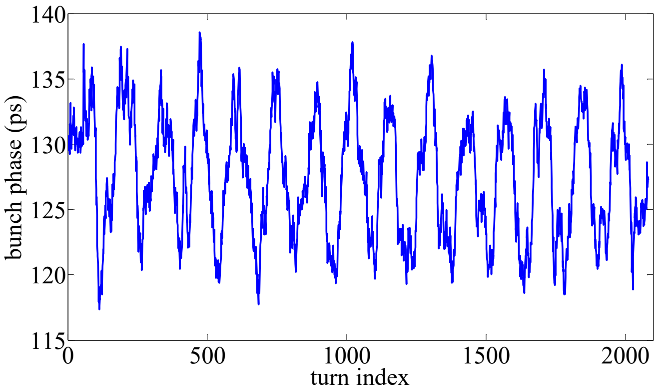
Refilled bunch position (Xr)

$$X_r = \frac{Qs}{Qr}\left(X_m\left(1+\frac{Qr}{Qs}\right) - X_s\right)$$

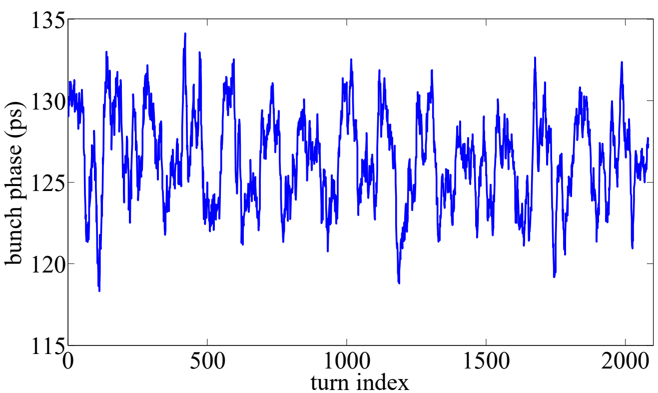
Injector performance evaluation:

Peak to peak value of refilled bunch position indicates the transverse mismatch between injector and storage ring

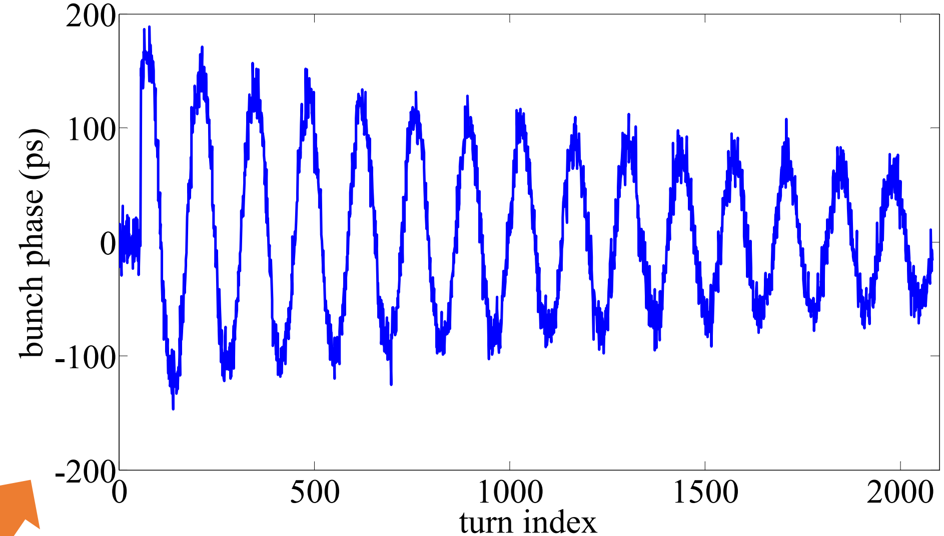
Refilled bunch: longitudinal position



Measured combined bunch phase (tm)



Stored bunch phase (ts)



Refilled bunch phase (tr)

$$t_r = \frac{Qs}{Qr}\left(t_m\left(1+\frac{Qr}{Qs}\right)-t_s\right)$$

Injector performance evaluation:

Oscillation amplitude of refilled bunch phase indicates the longitudinal mismatch between injector and storage ring

Refilled bunch: Synchrotron damping

***Longitudinal phase fitting method* is used to study the *synchrotron damping oscillation*.**

$$z_d = z_m \sin(\omega t + \varphi_0) \cdot e^{-\frac{t}{\tau}}$$

Maximum oscillation amplitude

Initial phase

Damping time

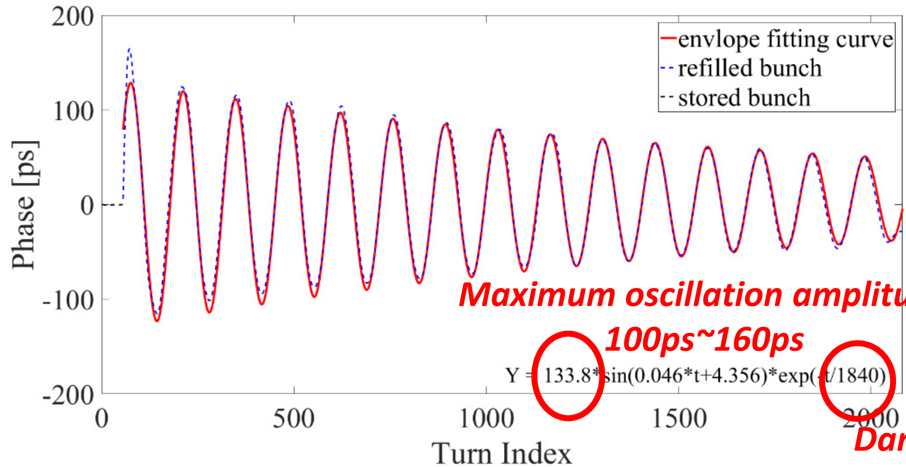
$$\alpha_s = \frac{1}{\tau}$$

$$\omega = \sqrt{\Omega^2 - \alpha_s^2}$$

Synchrotron frequency (~0.0072)

Storage Ring performance evaluation:

- Synchrotron damping time can be retrieved from the refilled bunch phase oscillation.
- A flag to monitor longitudinal dynamic behavior of storage ring.

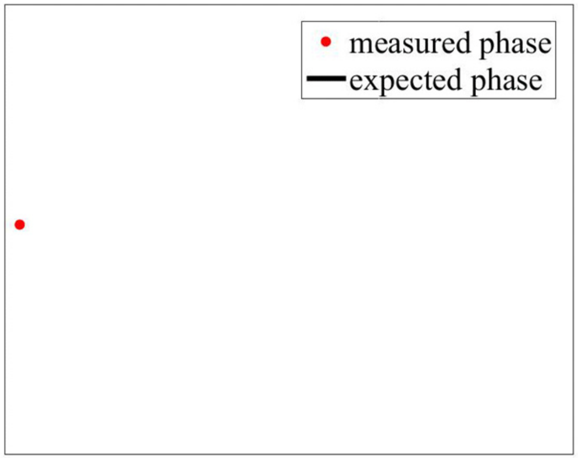


Fitting results of the refilled bunch

Maximum oscillation amplitude 100ps~160ps

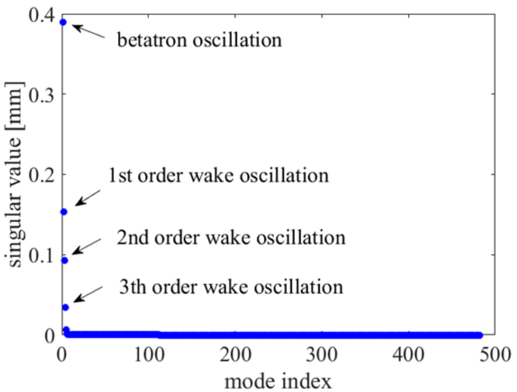
Damping time 2.5ms~3ms

The fitting results agreed with the measured results very well.

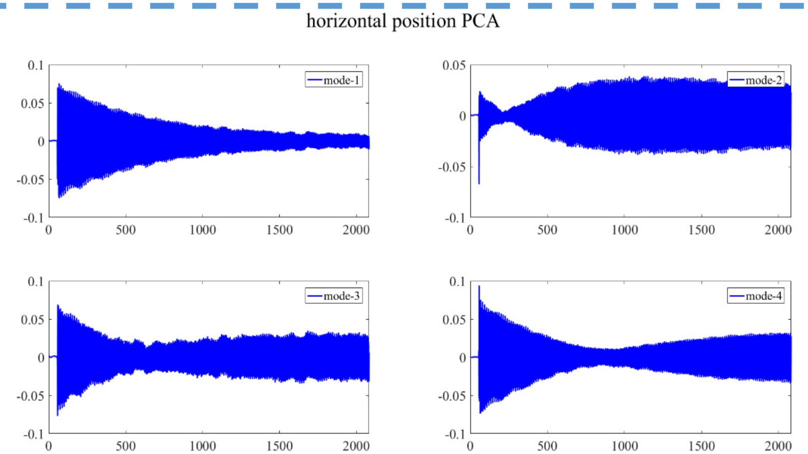


Stored bunches : transverse position

PCA modes separation



Singular values of different modes

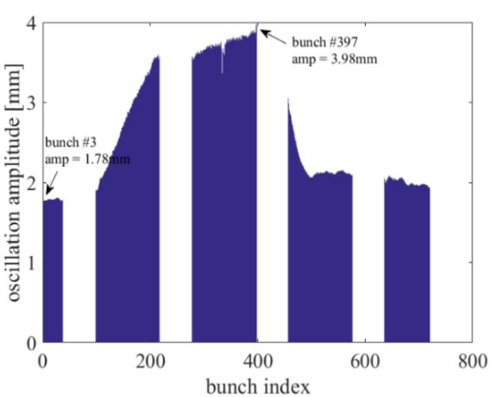


The first four principal components of the oscillation after injection

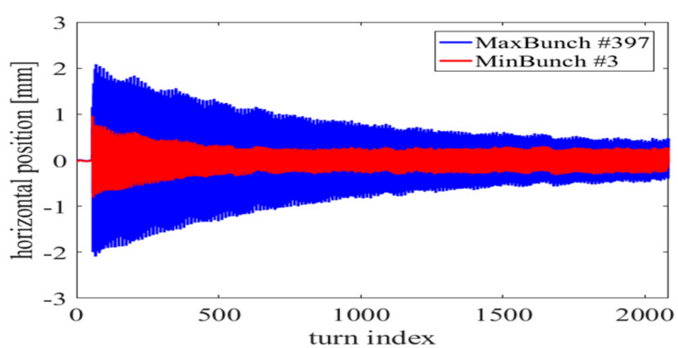
Betatron oscillation

introduced by :

- mismatch of **kicker field** (typical damping oscillation)
- **Wake-field effects** (oscillation expansion after transmission)



Betatron amplitude
of each bunch



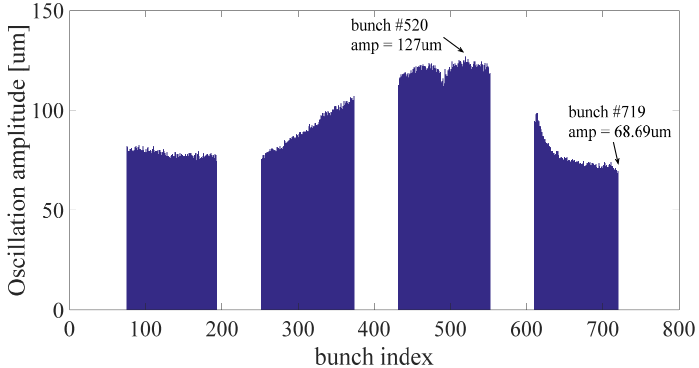
BPM position oscillation
of different bunches

Different bunch showed different oscillation amplitude.

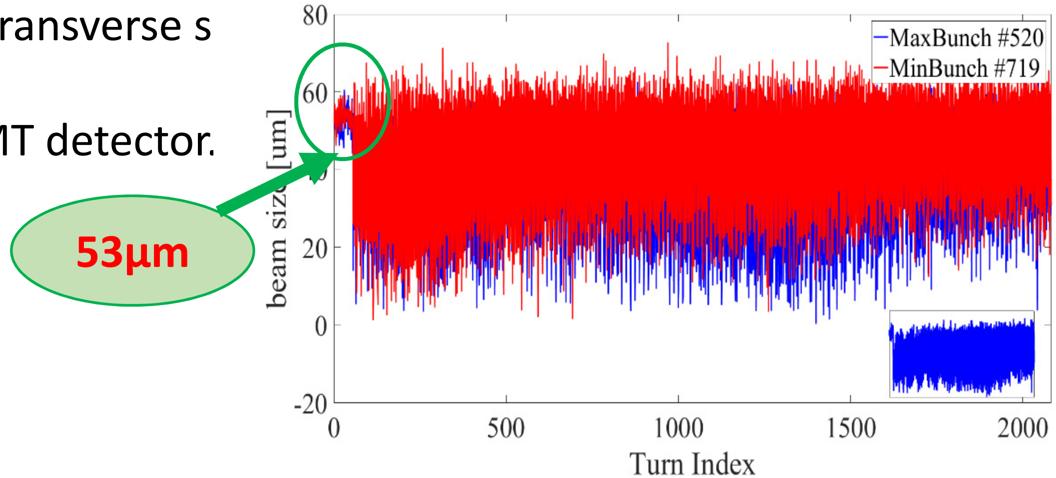
- Largest amplitude bunch #397: mostly contributed by **kicker mismatch**
- Smallest amplitude bunch #3: contributed by **kicker mismatch and wake-field effects**

Stored bunch: transverse size (σx)

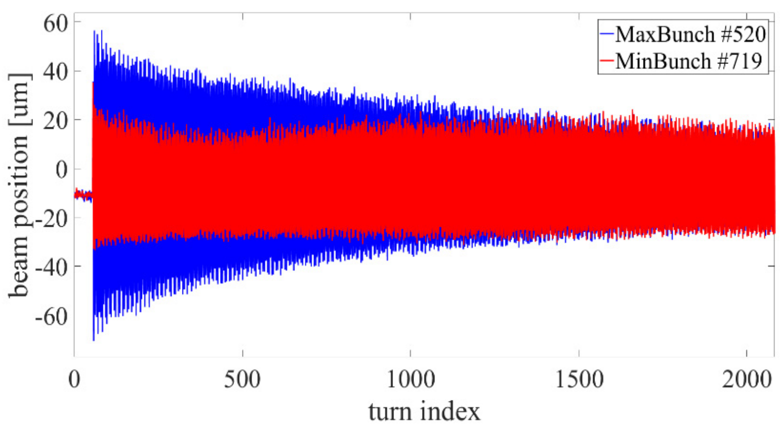
- Same analysis method is used for transverse s measurement
- Data from **SR light**, captured by PMT detector.



Betatron amplitude of each bunch



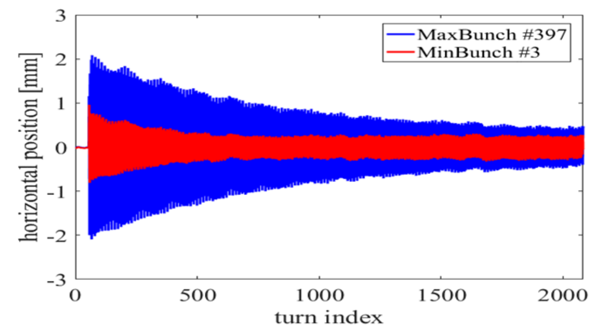
Horizontal size oscillation of different bunches



Transverse **position oscillation from the SR light**

Qualitative analysis

In good agreement with the **position results from the button BPM**.



Bunch #520 and Bunch 719: combined effects of **kicker field mismatch** and **wake-field**

Injection transient study : long term data

Long term data

Stored bunch train

Refilled bunch

Reflect the match between the injector and the storage ring

Synchrotron amplitude

Betatron amplitude

Betatron amplitude

Betatron damping time

Reflect the dynamic behavior of the storage ring

Synchrotron damping time

Betatron amplitude distribution

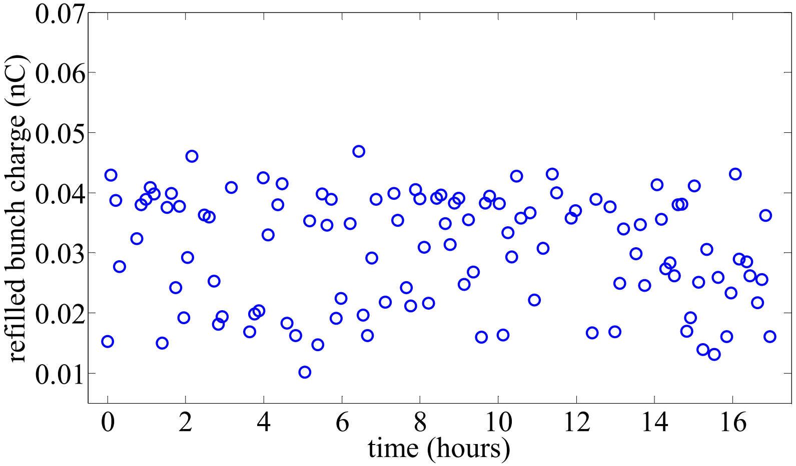
Tune distribution

Wake field and impedance study
Stability and repeatability of the storage ring

Refilled bunch parameters

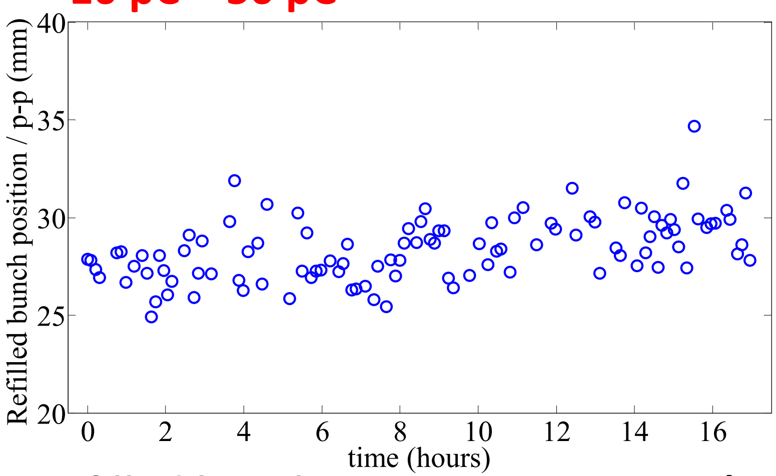
Mismatch between the injector and the storage ring

- **Large variation**
- **Can be improved by optimizing injector**



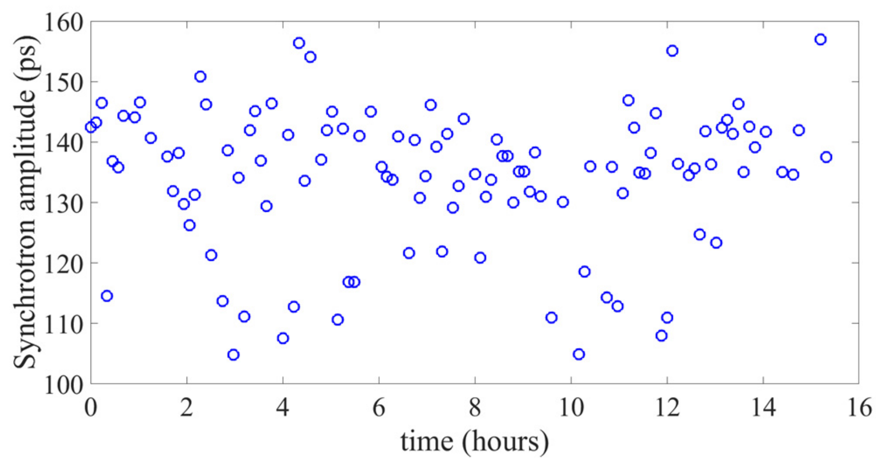
Refilled bunch charge

10 pC ~ 50 pC



Refilled bunch transverse position (p-p)

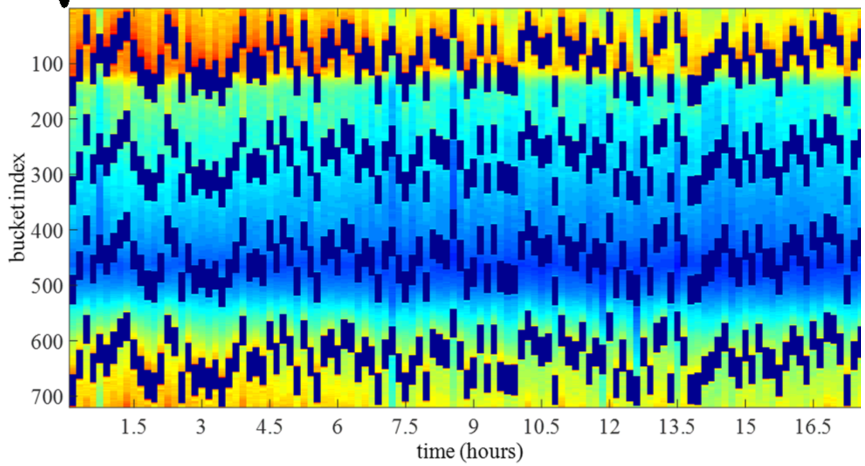
25 mm ~ 35 mm



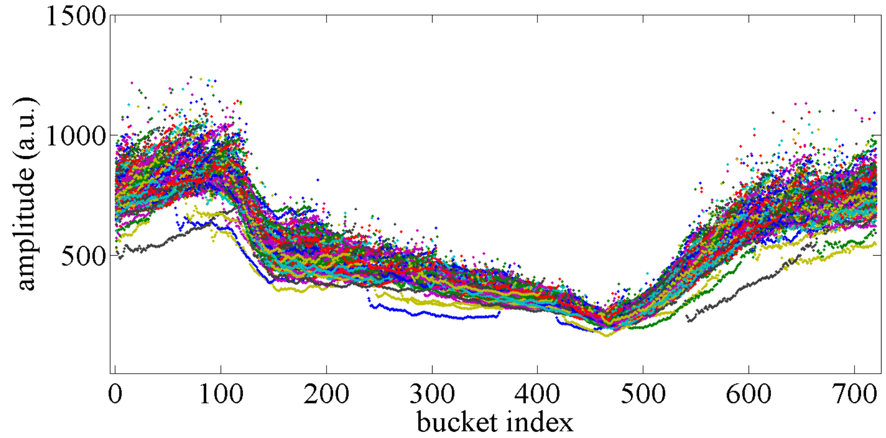
Refilled bunch longitudinal osc. amplitude

105 ps ~ 158 ps

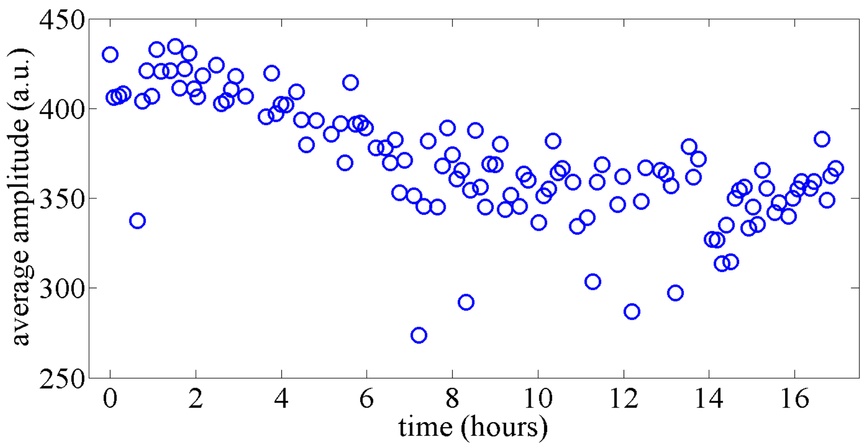
Stored bunches Betatron oscillation



The evolution of horizontal betatron oscillation



Projection distribution in the horizontal direction



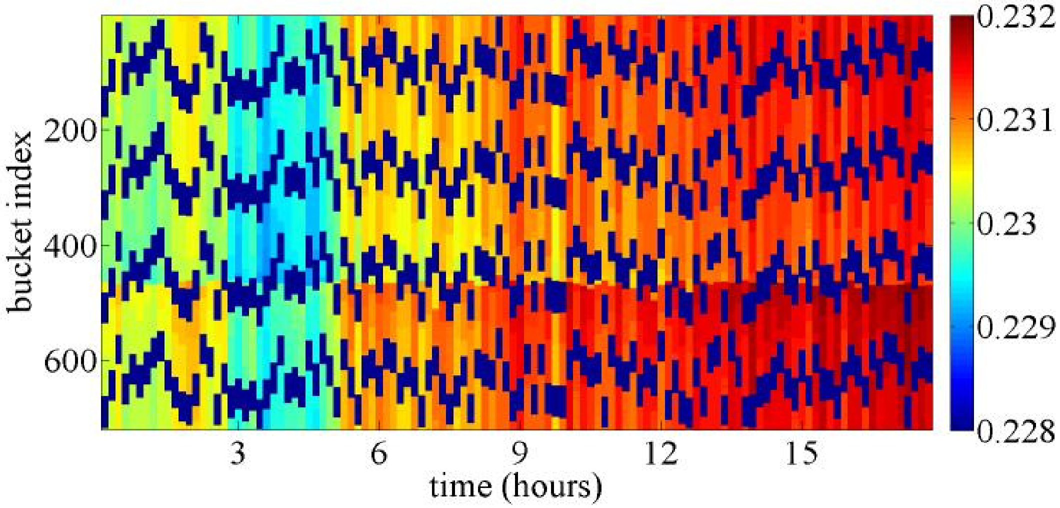
Average betatron amplitude distribution over time.

Hor.

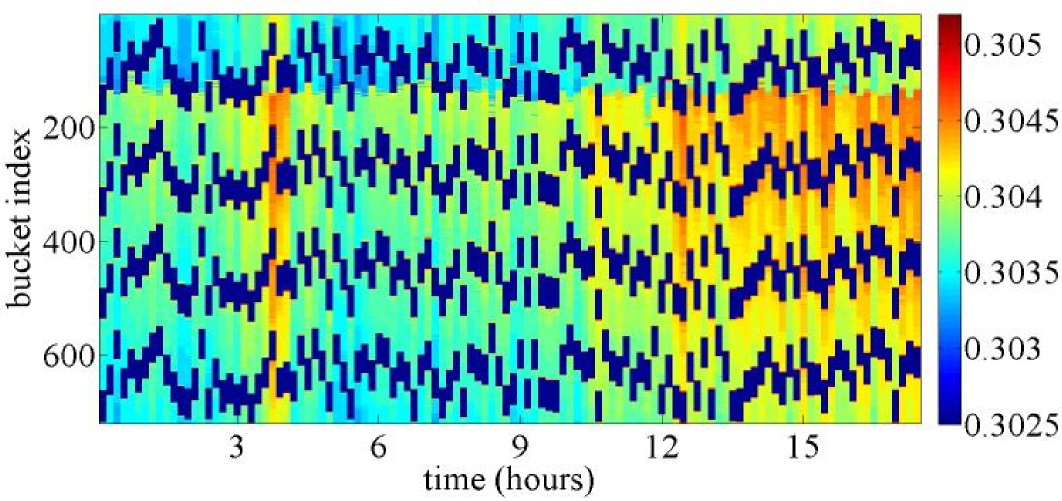
300~450

- **Stable distribution : basically not change over time**
- **Changed amplitude value: gradually decrease**

Tune distribution (ν_x, ν_y)



The evolution of **horizontal** tune distribution.

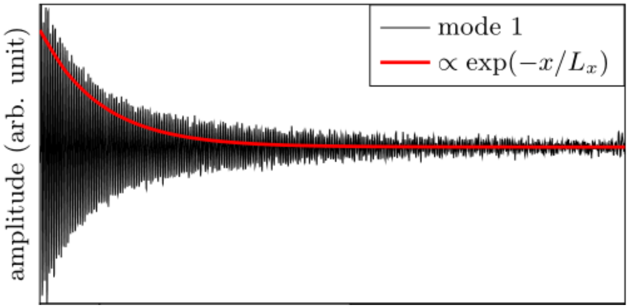


The evolution of **vertical** tune distribution.

- **Data obtained from the stored bunch position.**
- **Tune distribution is stable**
- **Tune drift exists, the machine needs to be improved**

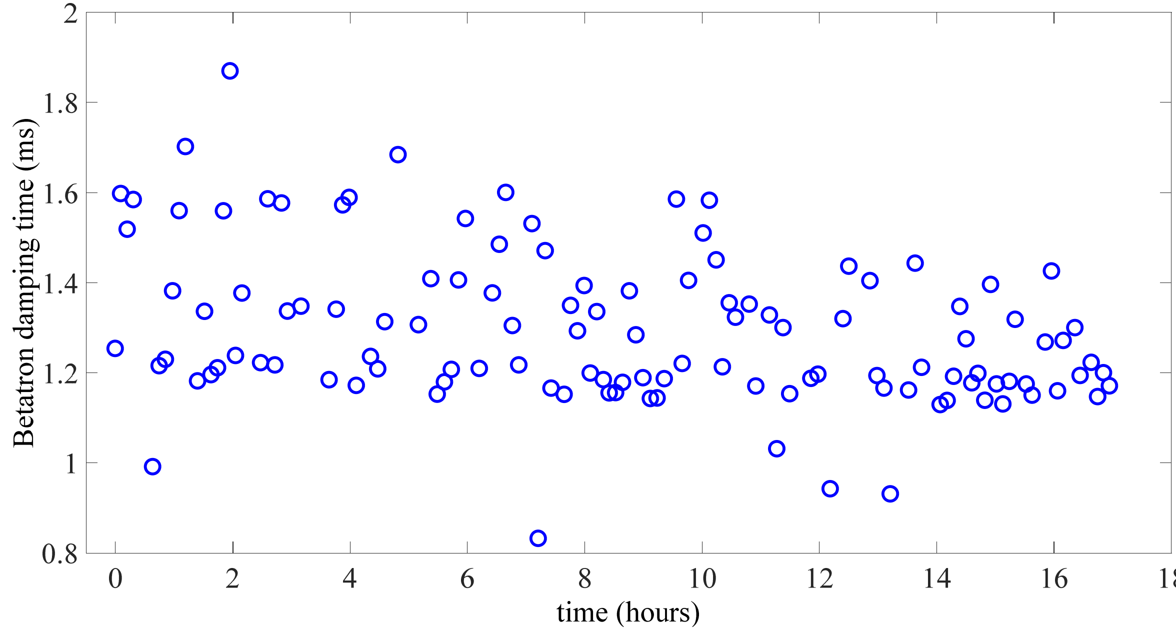
Transverse tune:
(0.23,0.30)

Betatron damping time (L_x)



$$y \propto \exp\left(-\frac{x}{L_x}\right)$$

Betatron damping time

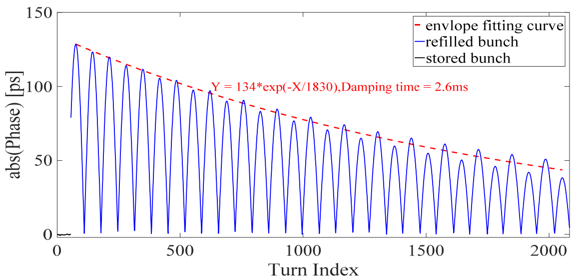


The evolution of Betatron damping time.

- **Obtained by the exponential fitting**
- **Useful for the betatron oscillation study**
- **Reflect the transverse dynamics of the storage ring**

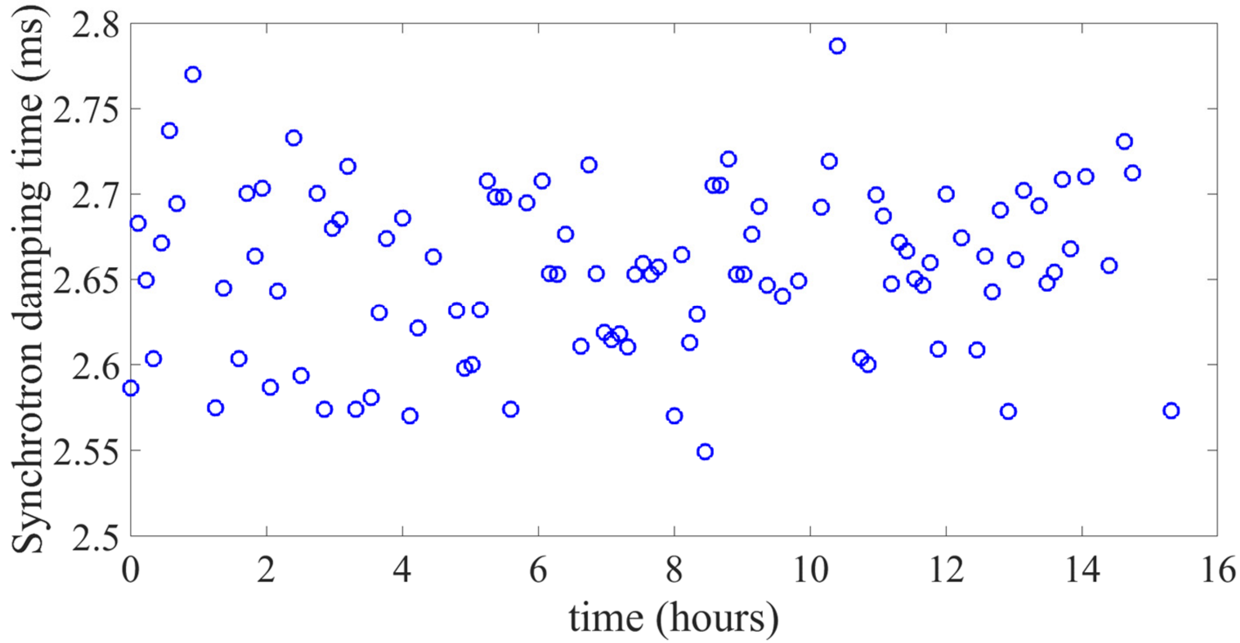
Betatron damping time: 1~2ms

Synchrotron damping time (τ)



$$y \propto \exp(-\frac{t}{\tau})$$

Synchrotron damping time



The evolution of synchrotron damping time.

- **Obtained by the exponential fitting**
- **Useful for the synchrotron oscillation study**
- **Reflect the longitudinal dynamics of the storage ring**

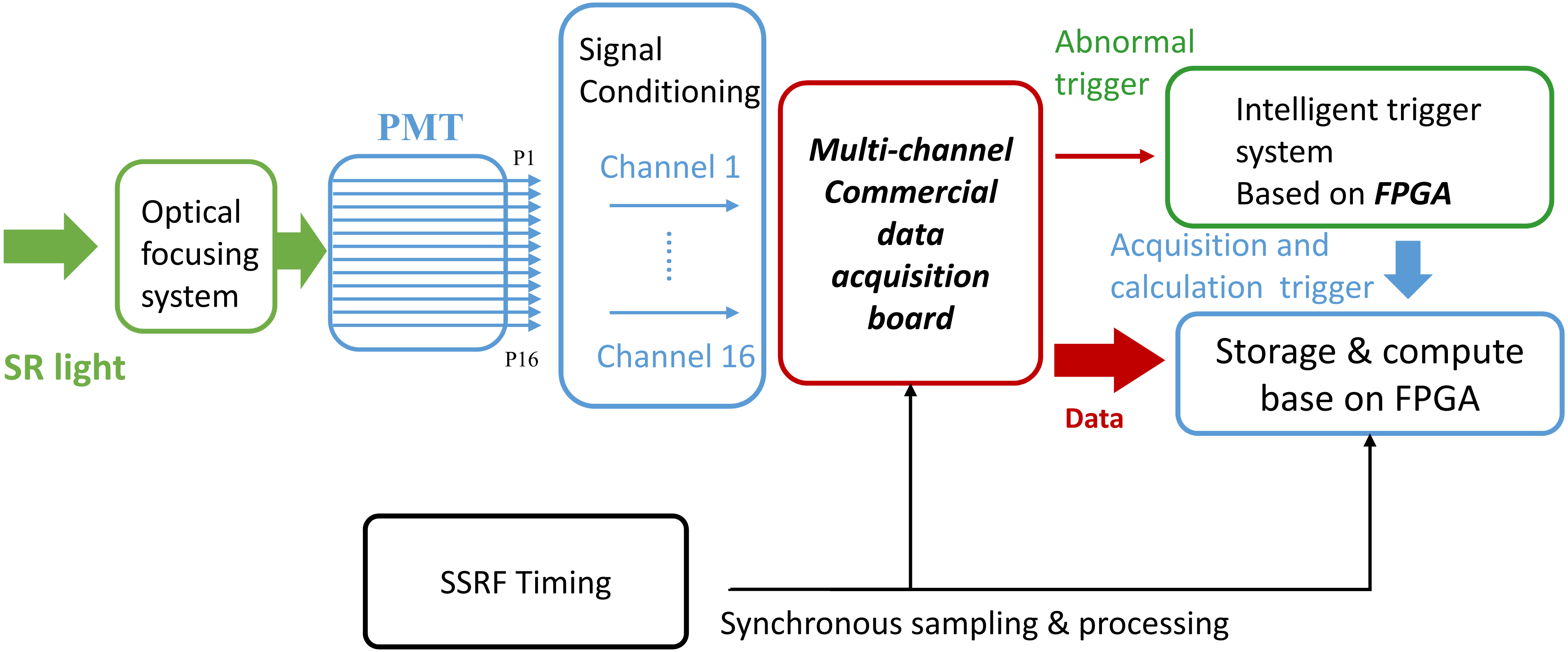
Synchrotron damping time

2.5ms~3ms

Next works

More channels for bunch size

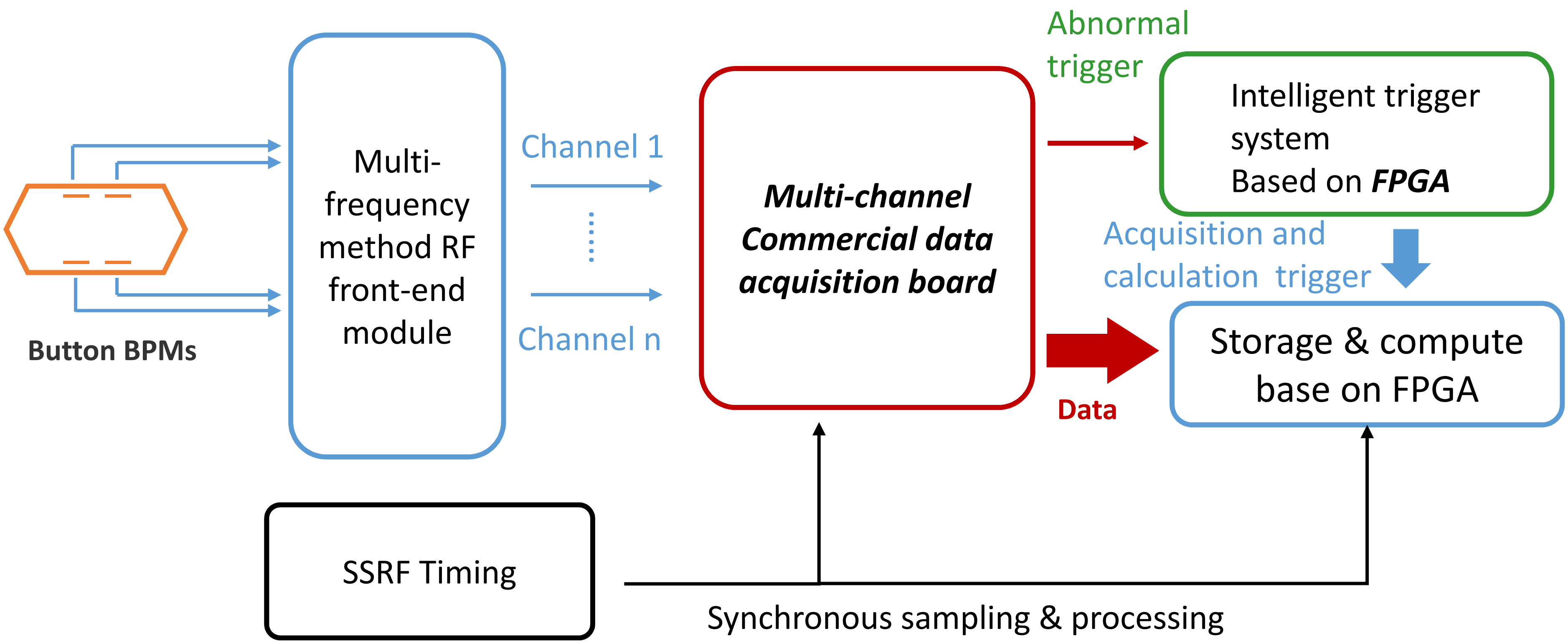
- **8-16 channels upgrade**
- **To achieve non-Gaussian distribution measurement**



Multi-channel bunch size online system based on commercial DAQ

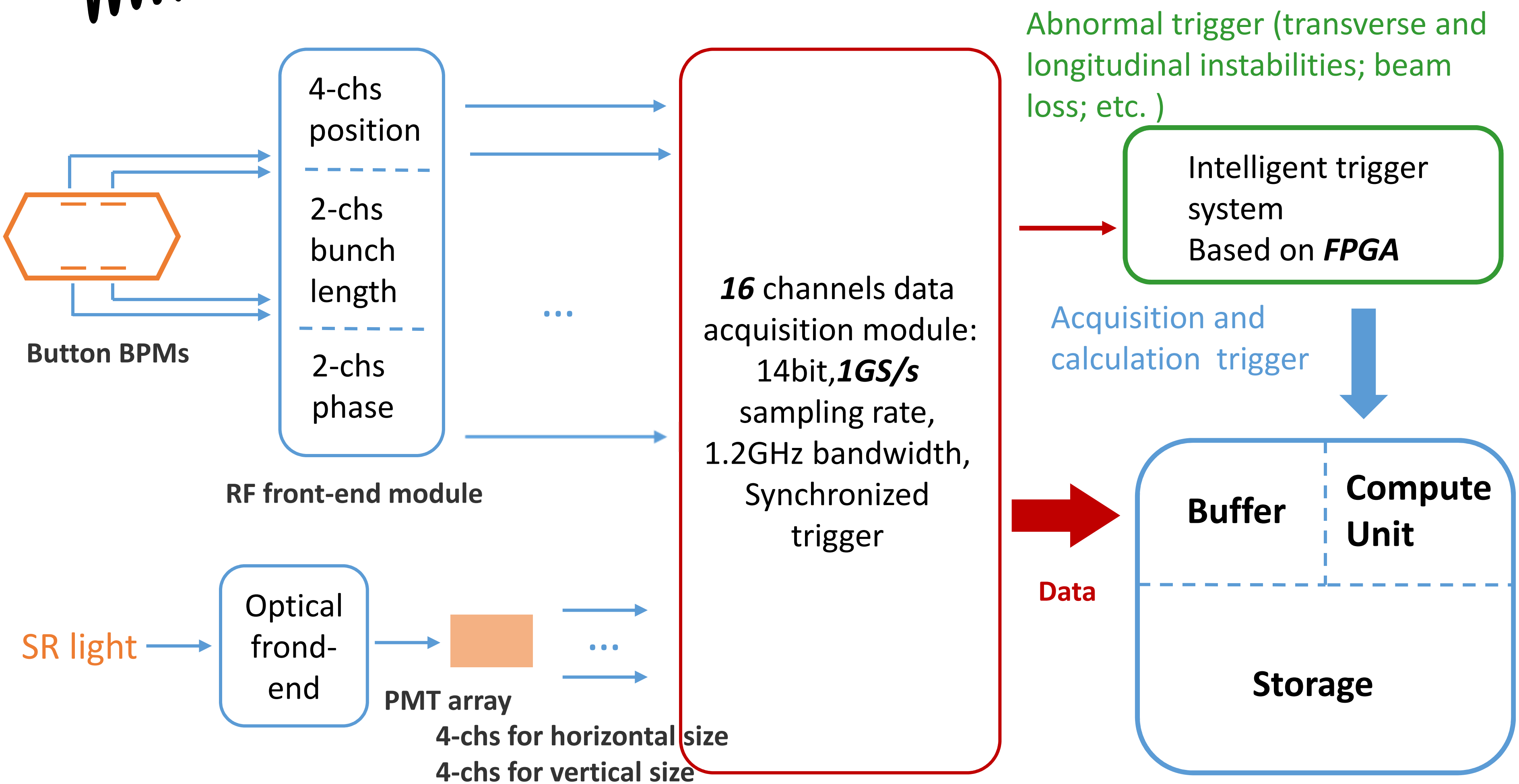
More channels for bunch length

- **To achieve multi-frequency measurement**
- **To achieve non-Gaussian distribution measurement**



Multi-frequency bunch length online system based on commercial DAQ

Intelligent trigger



6-dimentional bunch-by-bunch diagnostic system architecture

Intelligent trigger system to capture random beam instability events

Summary

- ***The 6-dimensional diagnostic system*** with bunch-by-bunch capability is successfully implemented at SSRF.

- The **beam position, size, phase and length** during the injection transient process are all measured by the system.

- With the **refilled bunch extraction algorithm,** the refilled bunch position and phase can be obtained. And the **dynamic parameters** of the storage ring also can be obtained from the injection transient study.

- **DAQ need to be upgraded** and **intelligent trigger mode** based on FPGA will be implemented. After upgrading, this system will be more useful for physicists to capture bunch-by-bunch data when unstable beam condition shows up.

Acknowledge

- Appreciated for the support from National Natural Science Foundation of China (No. 11375255 and No. 11375254)

- Appreciated for the help from beam physics group and beam operation group of SSRF in beam experiment

- Appreciated for the work from Zhichu Chen, Yong Yang, Liwu Duan, Hanjiao Chen

- Appreciated for the guidance of my supervisor Yongbin Leng

Thanks for your attention

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