Bunch-by-bunch Beam Length Measurement Using Two-frequency System at SSRF

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SSRF BI Group

Outline

- Motivation
- Principles
- System Setup
- Beam Based Calibration
- Applications
- Next Works
- Summary

Motivation

For Users

- FB and Top-up make users happy usually
- Unstable beam conditions will damage data quality
  - Beam instabilities
  - The injection transient every 5mins (top-up)

Need better knowledge of instability phenomenon for optimization

For BI Engineers

- Only static information can be monitored during daily operation
- Injection transient is a very good window to learn more about machine

Get more information during routine injections

For Physicists

- A bunch is a basic unit for physics study
- Parameters of individual bunch is better than average values for physicists

Need parameters of every bunches

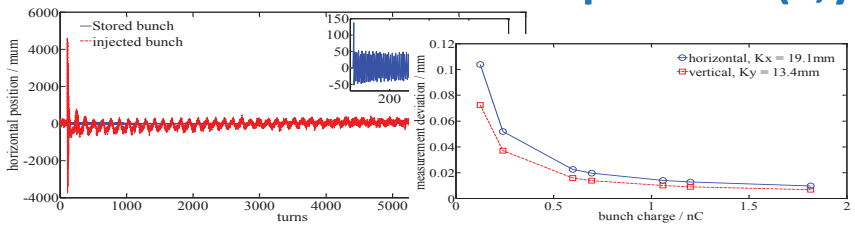
All requires

An eye on every bunches to ***study*** their behaviors

We are building a ***6-dimensional bunch-by-bunch*** diagnostic system

Motivation

Beam position (x,y)

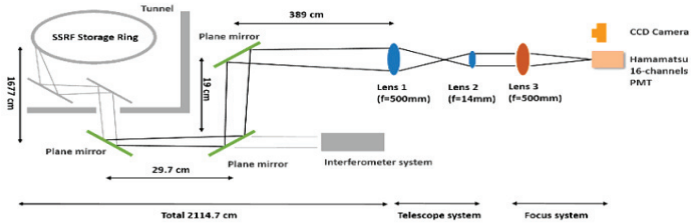


Button pickups + BBB DAQ + Δ&Σ algorithm

Resolution ≤ 10μm

(Y. Yang, IPAC13; Y.B. Leng, IBIC13; Y.B. Leng, IPAC15;)

Beam transverse size(horizontal , vertical)



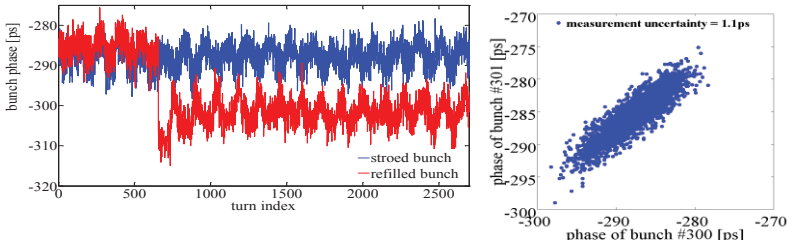
SR light + PMT array + BBB DAQ

+ Gaussian fitting algorithm

(H. J. Chen, IPAC17; Under development)

6-dimensional bunch-by-bunch diagnostic system

Beam longitudinal phase (z)



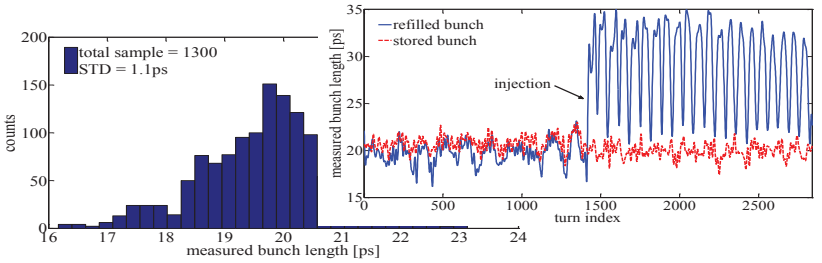
Button pickups + BBB DAQ

+ Rising edge detection

Resolution ≤ 2ps

(Y.M. Zhou, IPAC17; Poster TUPWC02 in IBIC17)

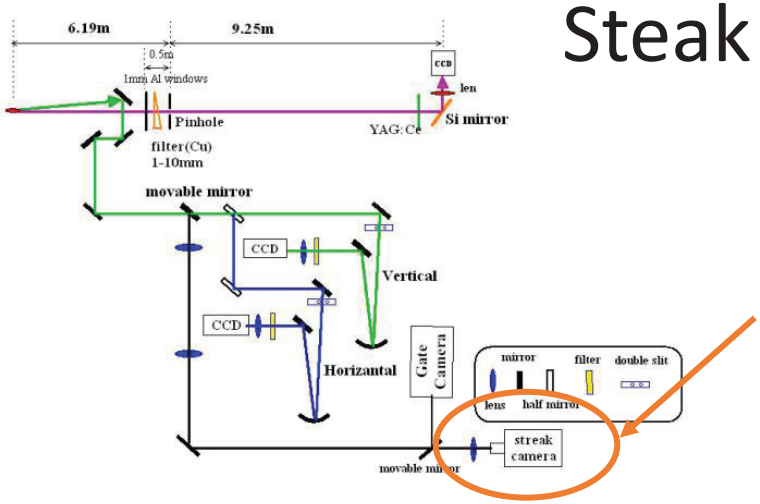
Beam longitudinal length



Button pickups + ***Two-frequency system***

✦ discussed in this talk

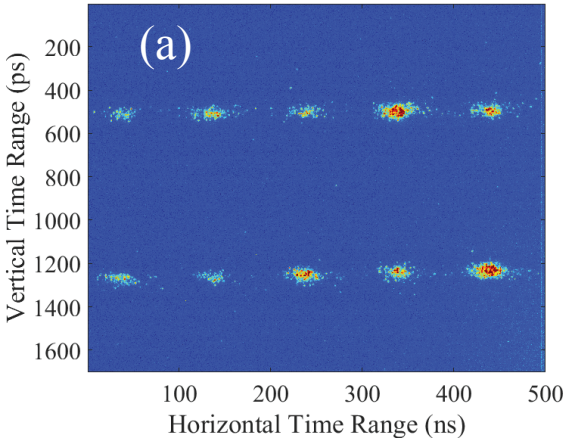
Steak Camera system at SSRF

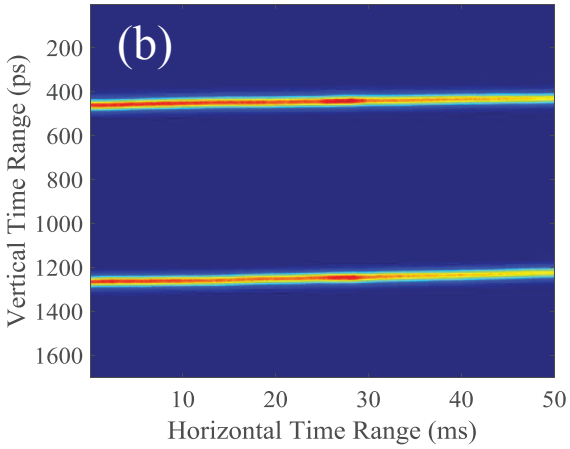


Steak Camera Location:

- Hamamatsu C5680 Streak Camera
- Resolution: 2ps @high-speed sweep
  50ps @low-Speed sweep
- Synchroscan rate: 125MHz (1/4 RF)
- Trigger rate: 2Hz (figure reputation rate)

Figure 1: Layout of the Optical Diagnostic Beamline (J. Chen, IPAC13)





individual bunch measurement long term measurement

Due to the limited pixels number

- **Individual bunch measurement with very small time scale (sub us)**
- **Long term (ms) measurement with bunches averaging**

Can't cover both

Streak Camera not Sufficient for 6D system

Our directions

- Bunch-by-bunch longitudinal oscillation studies
- One part of 6-dimensiontal bunch-by-bunch diagnostic system
- Intelligent trigger for beam abnormal status
- Bunch length control system for higher beam current in SSRF phase II, online monitor required

Our requirements

- ***Real-time*** bunch-by-bunch beam length measurement synchronized with other monitors (position, phase, etc)
- ***High resolution*** for individual bunch measurement (ps)
- Enough ***measurement range*** up to several thousands turns (ms)
- Easy to operate and connect to EPICS

Our limitations

- Off-line data analyze
- Low photons for bunch-by-bunch measurement
- Contradiction between enough data length and resolution of single bunch
- Complicated and stand-alone system,

Streak camera is good for dedicated machine study, not good for online monitoring. Frequency domain method (two-frequency) was adopted for 6D system. SC can be used to do calibration.

Principles of two-frequency method

- A typical bunch longitudinal charge distribution is ***Gaussian***. Fourier component of ***mi-th harmonic*** is:

RF frequency 499.654 MHz of SSRF

$$V(m_i\omega_0) = 2V_0\exp\left(-\frac{{m_i}^2{\omega_0}^2{\sigma_0}^2}{2}\right) \quad (1)$$

the bunch length
obtained with voltage radio of two-frequency

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

- V1 and V2 : the value at two mi-th harmonic frequencies
- $m_2 > m_1$

Basic Concept

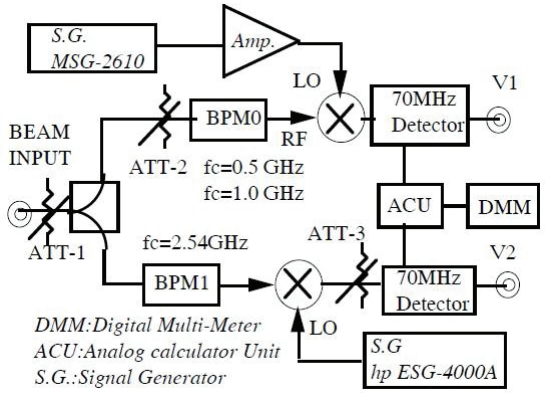
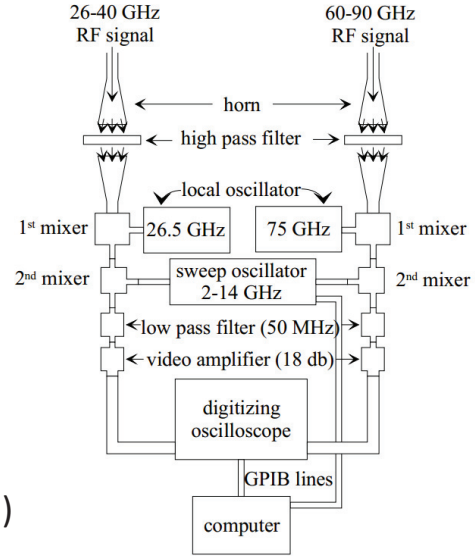


Figure 3: Two-frequency method at KEK (Takao Ieiri, EPAC2000)
Two-frequency points: 1GHz($2f_{RF}$), 2.54GHz ($5f_{RF}$)
Successfully ***average*** bunch length measurement



'Old method'
Narrow band system, slow DAQ

Figure 4: Two-frequency method at CLIC (H. H. Braun, EPAC1998)
Two-frequency points:
26-40GHz; 60-90GHz
Resolution around ***0.7ps***
Single shot measurement

Bunch-by-bunch data acquisition techniques @SSRF

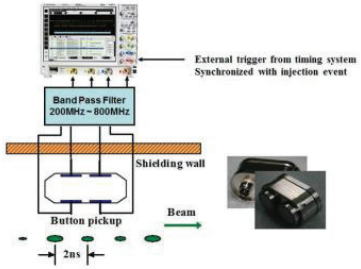


Figure 5: Hardware setup of the concept prototype of bunch-by-bunch processor (Yongbin Leng, IPAC2015)

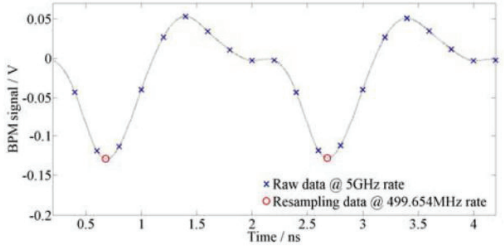


Figure 6: Raw data and resampling points from oscilloscope (Yongbin Leng, IBIC2013)

Contribute to a
Bunch-by-bunch two-frequency
bunch length monitor

Working Frequency Choice

The resolution: $$\frac{\Delta\sigma}{\sigma} \simeq \frac{\sqrt{2}}{|{m_1}^2-{m_2}^2|{\omega_0}^2{\sigma_0}^2}\left[\left(\frac{\Delta V_1}{V_1}\right)^2+\left(\frac{\Delta V_2}{V_2}\right)^2\right] \quad (3)$$

$\Rightarrow$ ${m_1}^2-{m_2}^2$ ↑, resolution ↓

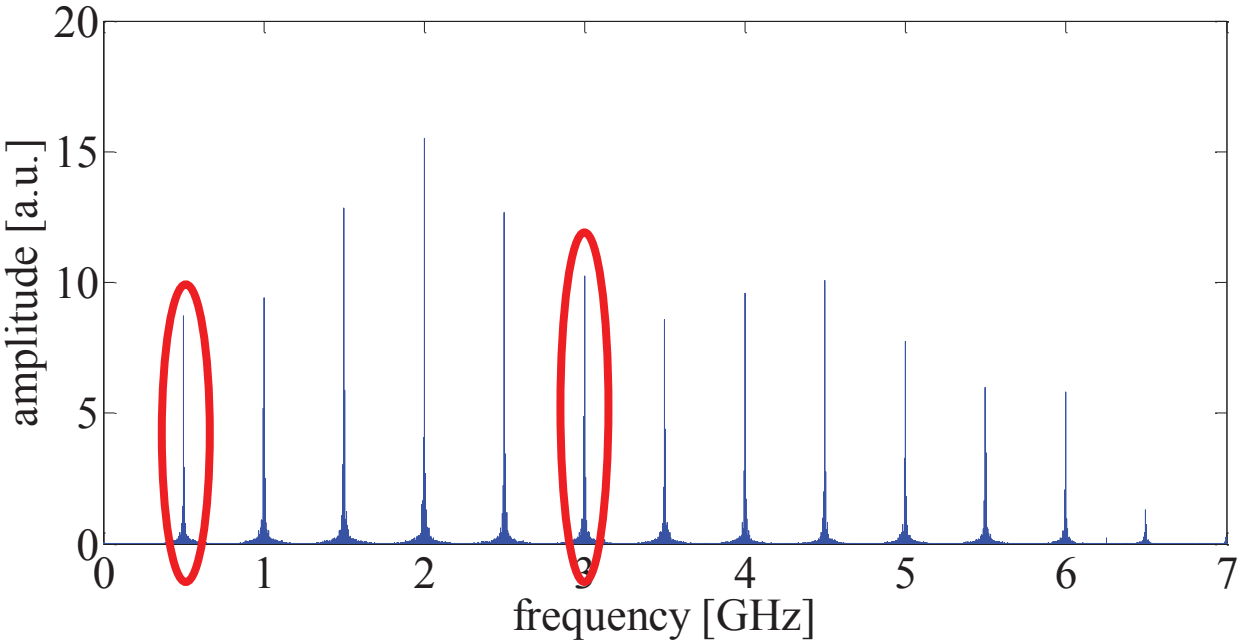


Figure 7: Beam Spectrum at storage ring of SSRF

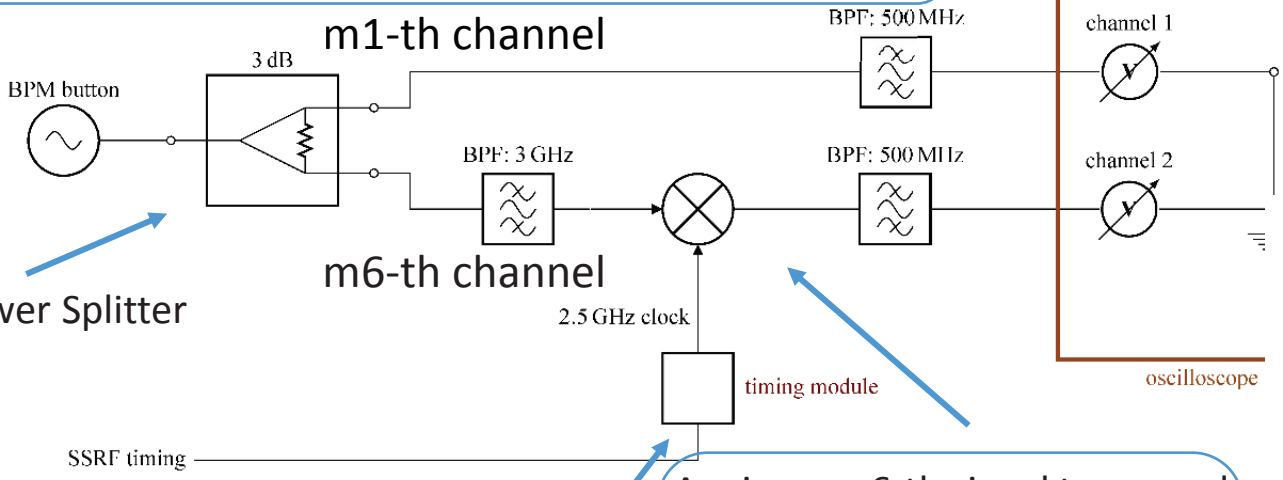
- Enough signal amplitude
- RF component limitation

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

Hardware Setup

Agilent DSO9064A Oscilloscope
Sampling rate: 5GS/s
Analog bandwidth: 600MHz

HPF+LPF from WI company
Center Frequency: 500MHz
Bandwidth: ~ 500MHz



Two-way Power Splitter

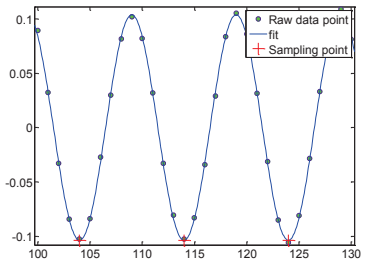
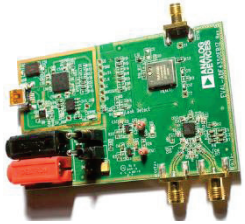
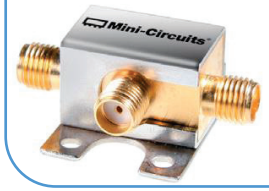


Figure 9: Data resampling with RF clock (499.654MHz)



LO signal as 5 times of RF signal
Generated from a programmable timing module EVAL-ADF4351

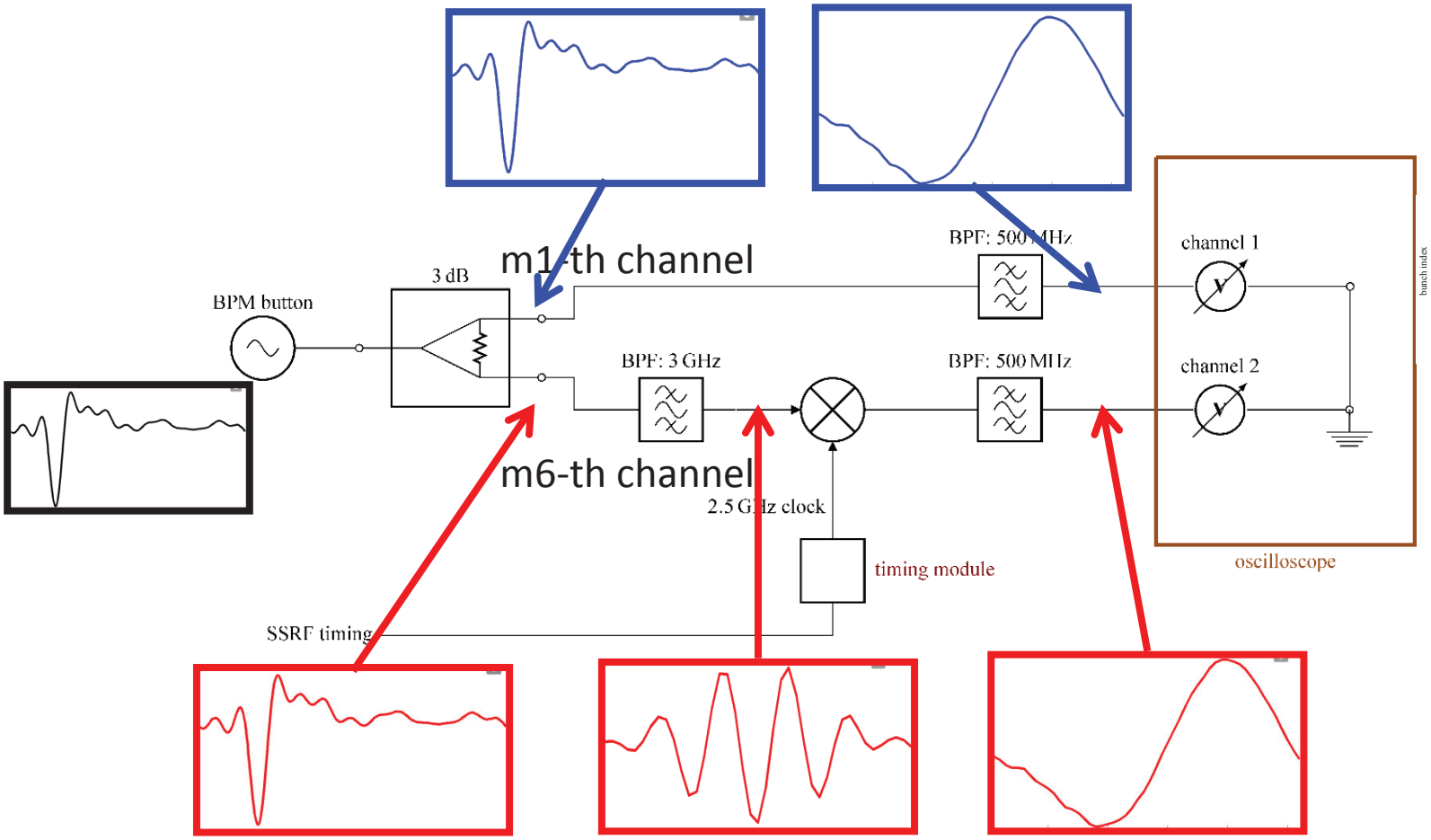
A mixer: m6-th signal to around 500 MHz with LO signal

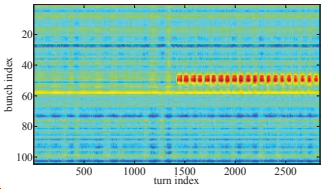


Mini-Circuit
ZX05-42MH+

Figure 8: Block diagram of two-frequency bunch length measurement system
(L. W. Duan, *Nucl. Sci. Tech, 2017*)

Beam signal





Data resampling
Bunch length calculation

Modification of Bunch Length Equation

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

Formula modification due to two channels
transfer functions difference and ***limited bandwidth***

$$\sigma = \sqrt{\frac{2}{m_2{}^2\omega_0{}^2 - m_1{}^2\omega_0{}^2} \ln\left(K_1\frac{V_1}{V_2} + K_2\right)} \quad (4)$$

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

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

V1/V2 is measured from two-frequency system

$$R_{12}{=}K_1\frac{V_1}{V_2}{+}K_2{=}\exp\left[\frac{\sigma^2\cdot(m_2{}^2\omega_0{}^2 - m_1{}^2\omega_0{}^2)}{2}\right]$$

Calculated from Steak Camera measurement

Beam Based Calibration-Coefficient Calibration

Beam conditions

Single bunch filling pattern

Bunch charge from 0.23nC to 6.05nC

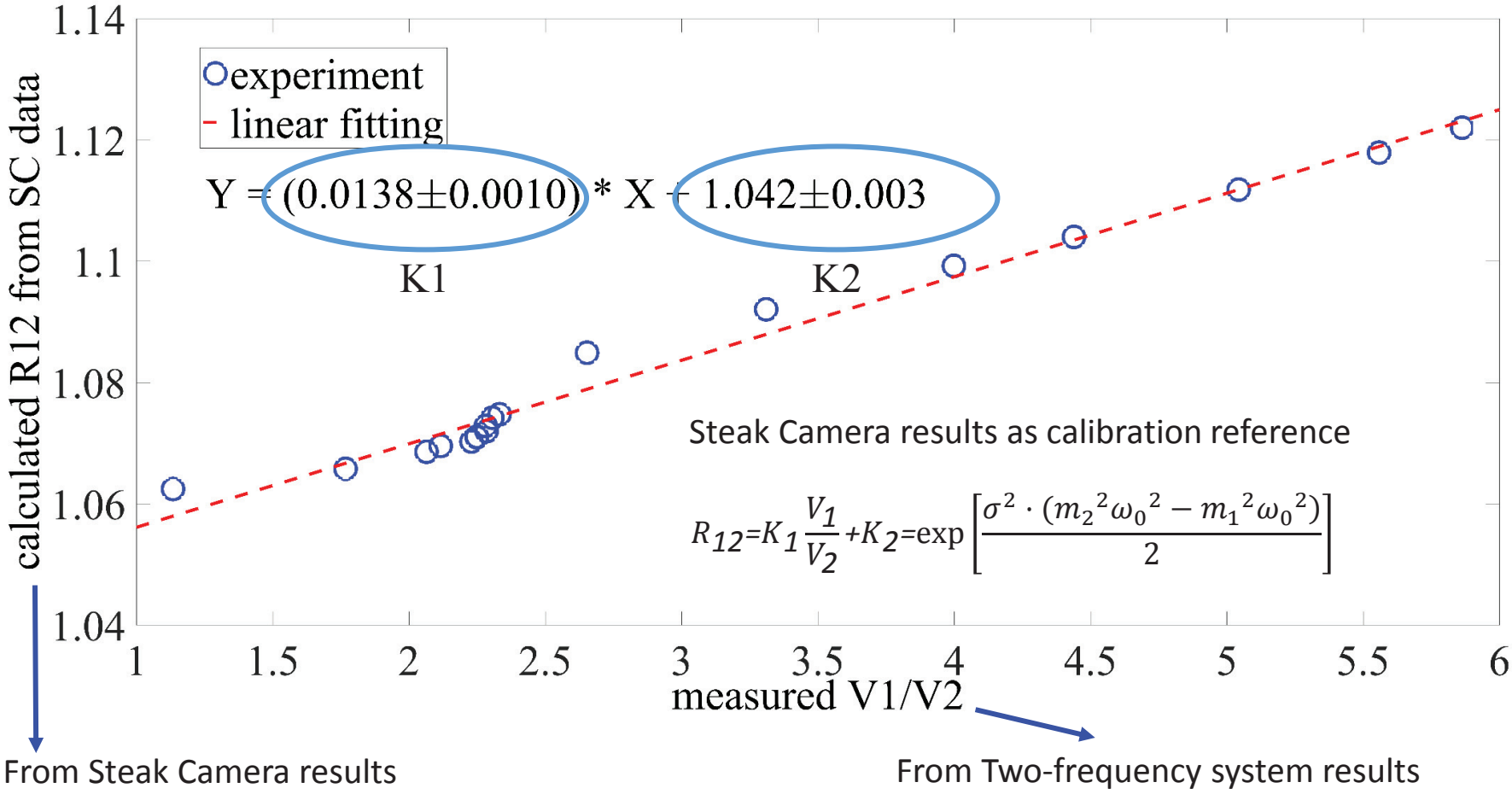
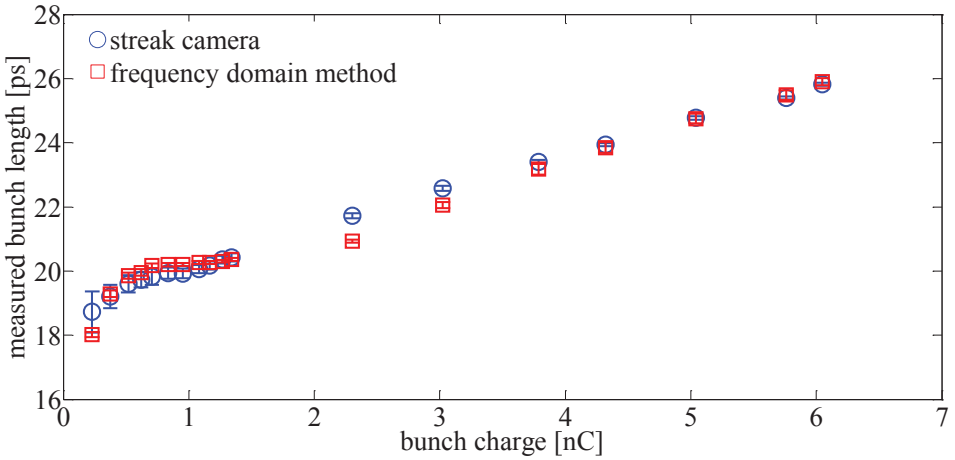
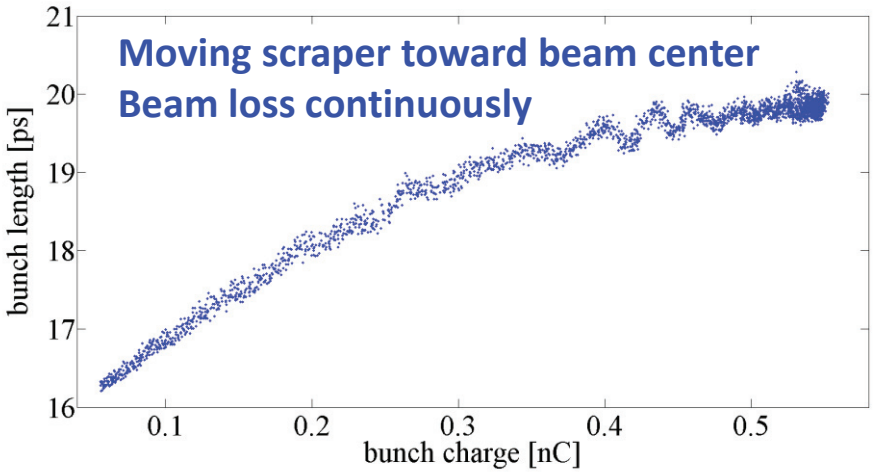


Figure 10: Two-frequency system coefficient calibration by Steak Camera

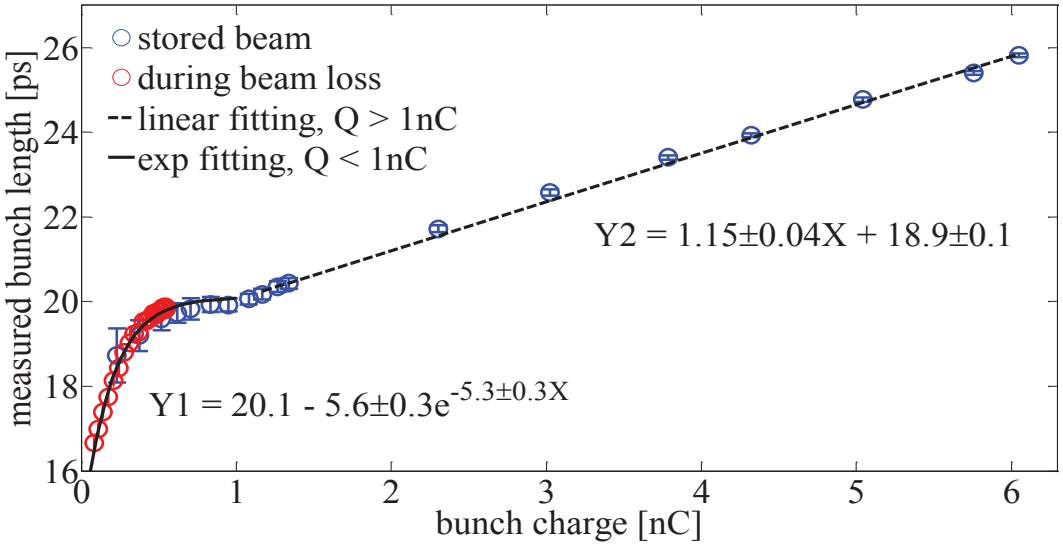
Application: Bunch length measurement



Bunch length measurement with stored single bunch beam



Bunch length shortening during beam loss

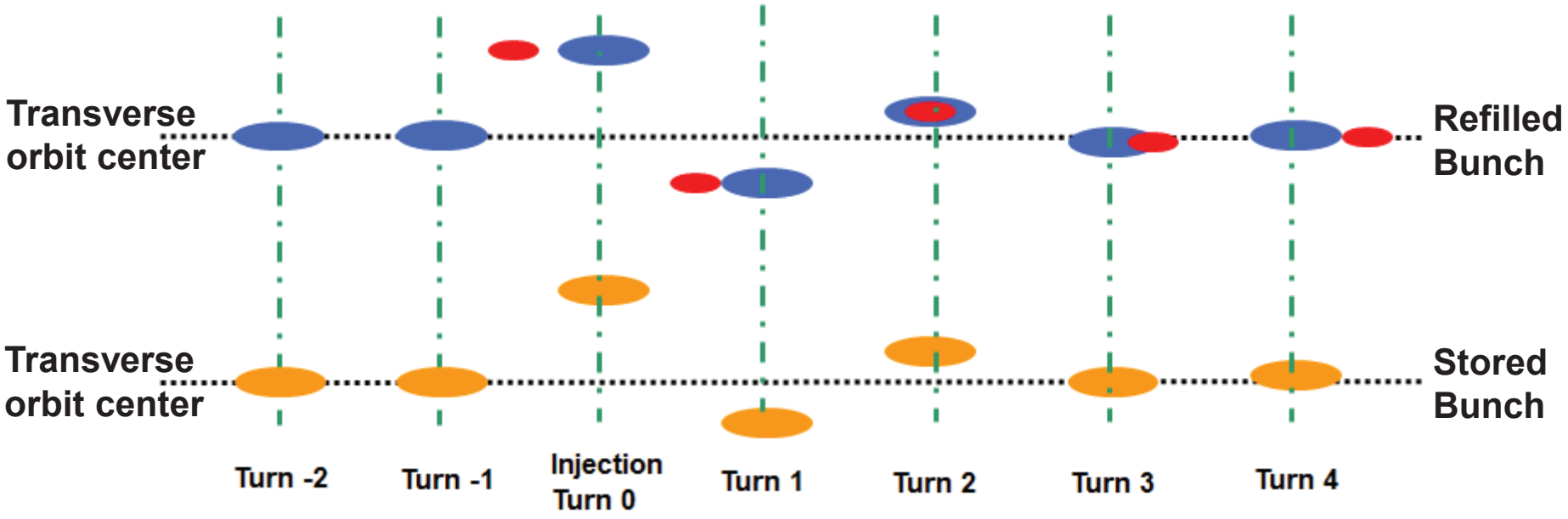


Bunch length has been measured in very large dynamic range (30pC to 6nC)

New method agreed with Streak Camera very well

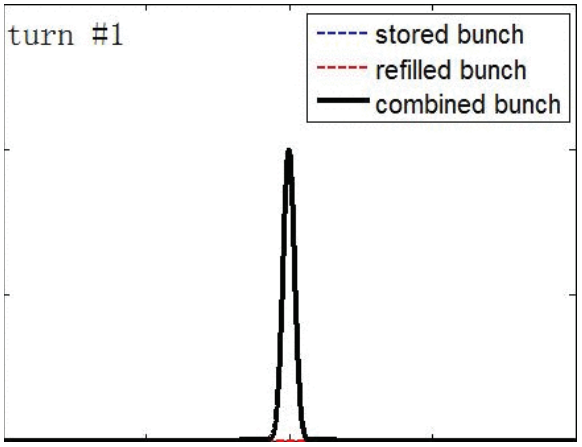
Application: Longitudinal oscillation observation after Injections

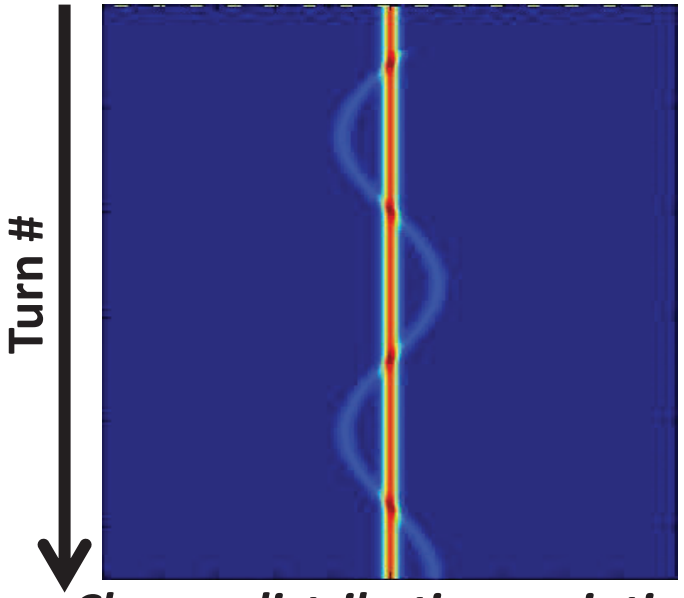
Equivalent bunch length oscillation will be observed after injection
Macro bunch (refilled charge + stored charge)



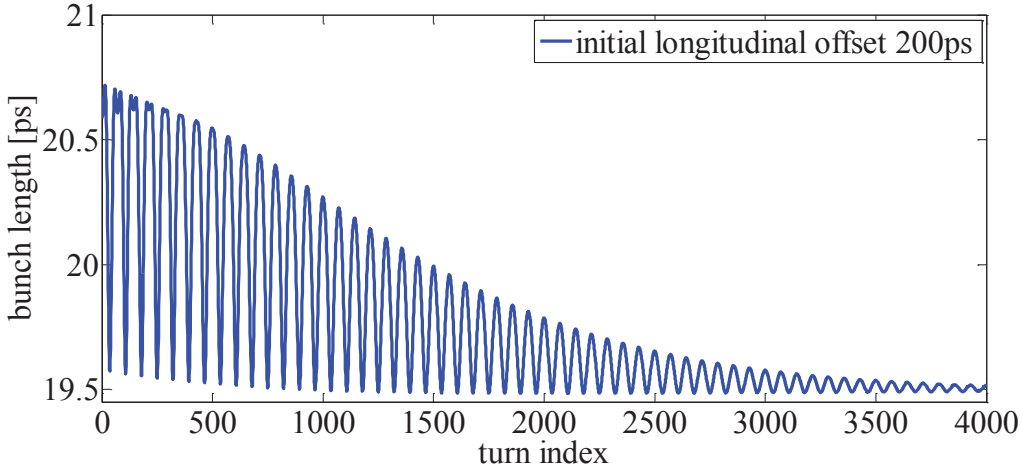
- ***Betatron oscillation*** : From timing or amplitude mismatch of kickers
- ***Synchrotron oscillation***: From phase or energy mismatch between injected charge and stored charge (double of the synchrotron frequency)

Application: Longitudinal oscillation observation after Injections





Charge distribution variation after injection

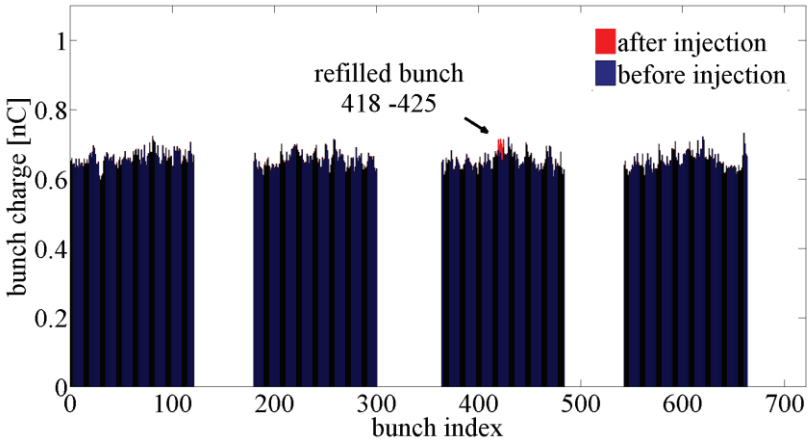


Equivalent bunch length oscillation after injection waveform can be calculated with the knowledge of

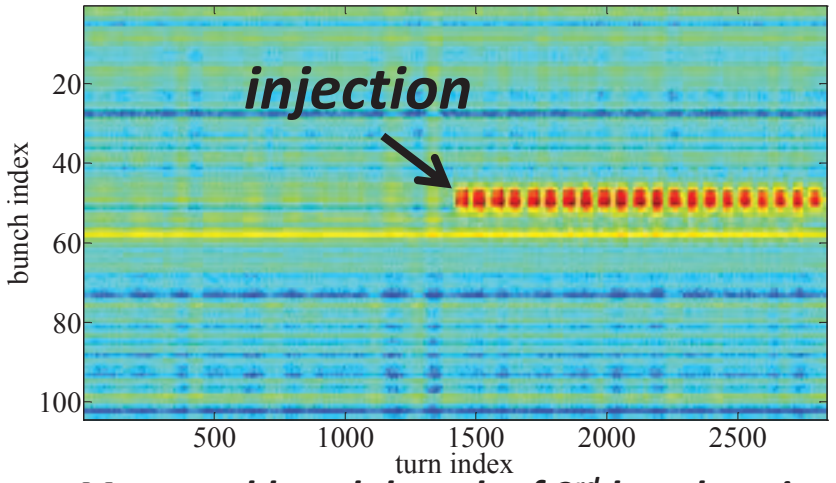
- ***Stored charge / Qs***
- ***Refilled charge / Qr***
- ***Synchrotron frequency / fs***
- ***Longitudinal damping time / τ***
- ***Initial position in phase space of refilled charge / φ, z***

Or all above parameters can be retrieved by fitting the measured waveform

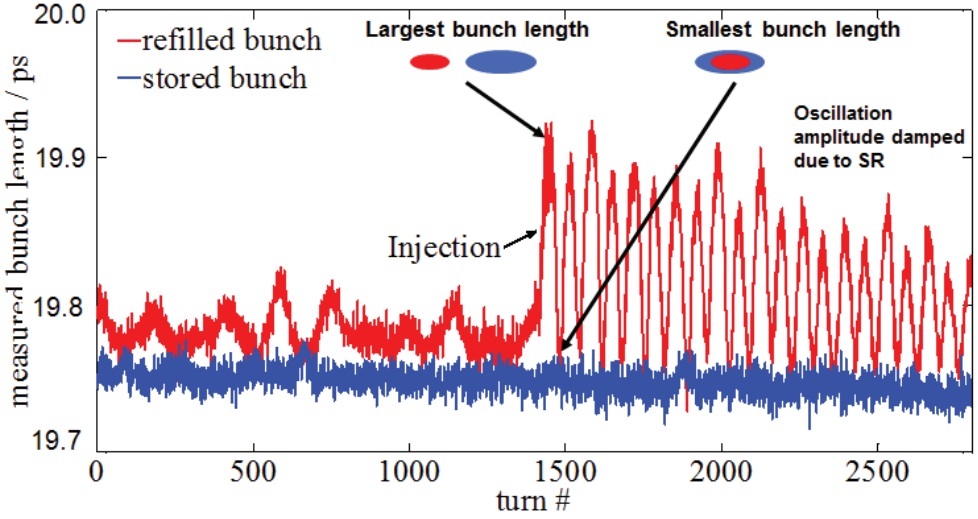
Application: Longitudinal oscillation observation after Injections



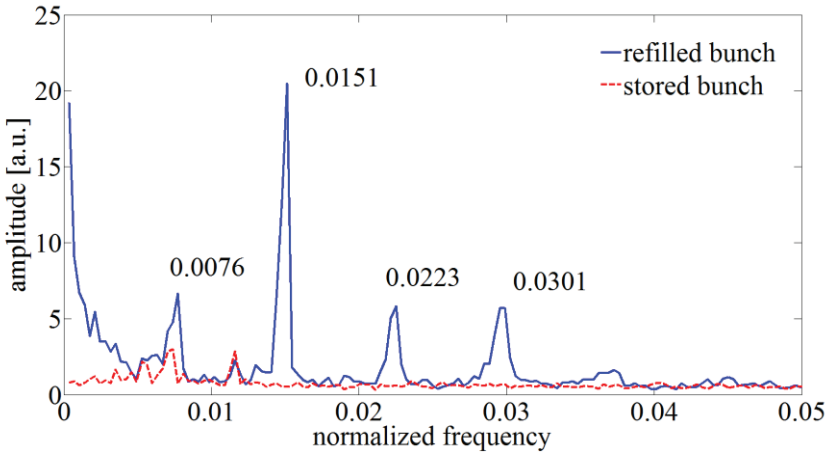
Filling pattern before and after injection



Measured bunch length of 3rd bunch trains



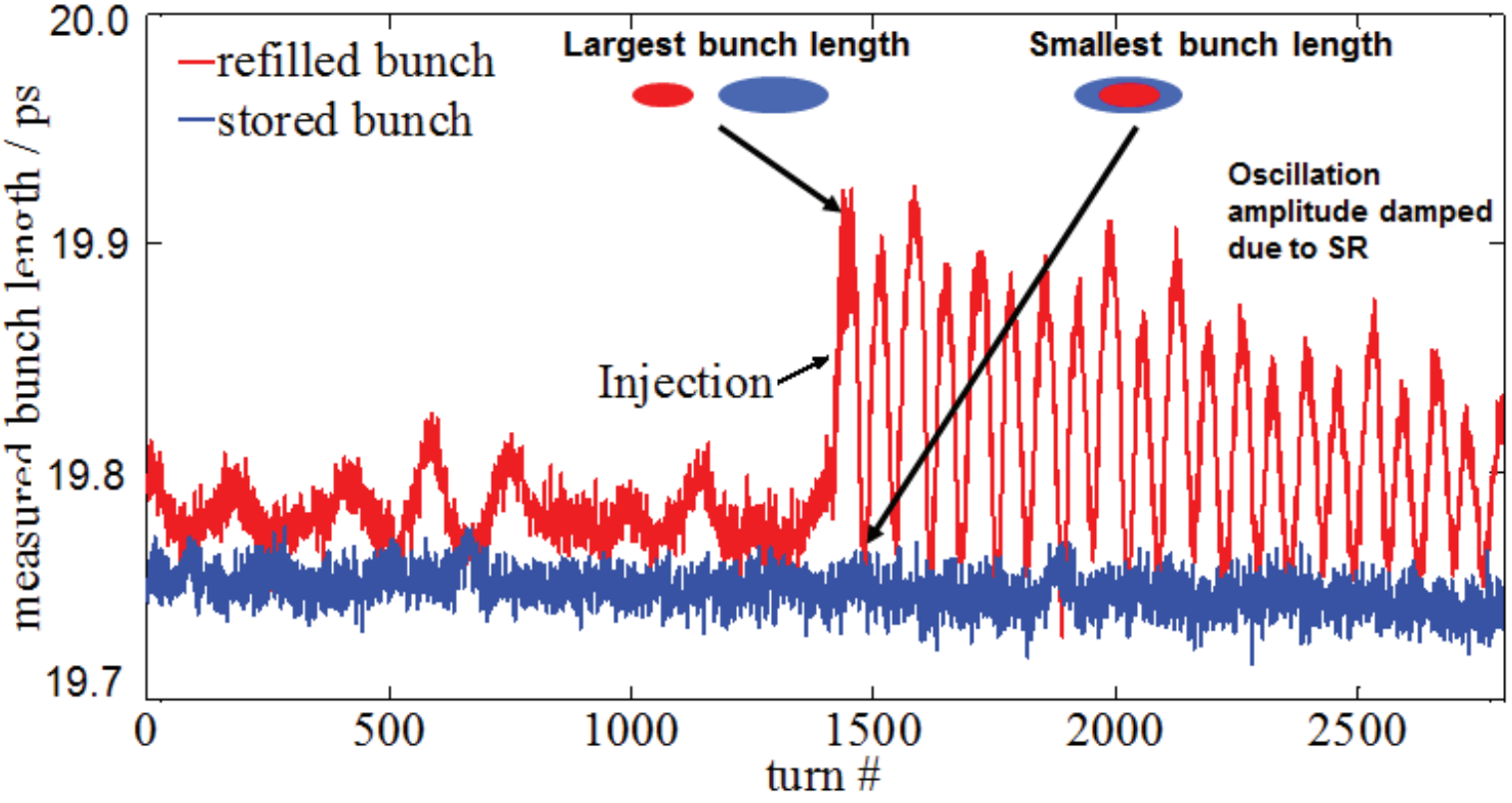
Bunch length variation of bunch #420 & # 430



FFT of the left waveforms

Next Work(1) – waveform fitting

- **Find a way to do multi-parameters curve fitting**
- **Full information of refilled charge in phase space can be retrieved to guide injection optimization**
- **Injection quality can be evaluated precisely**



Next Work(2) – DAQ upgrade

Random beam instability events can be captured with intelligent trigger

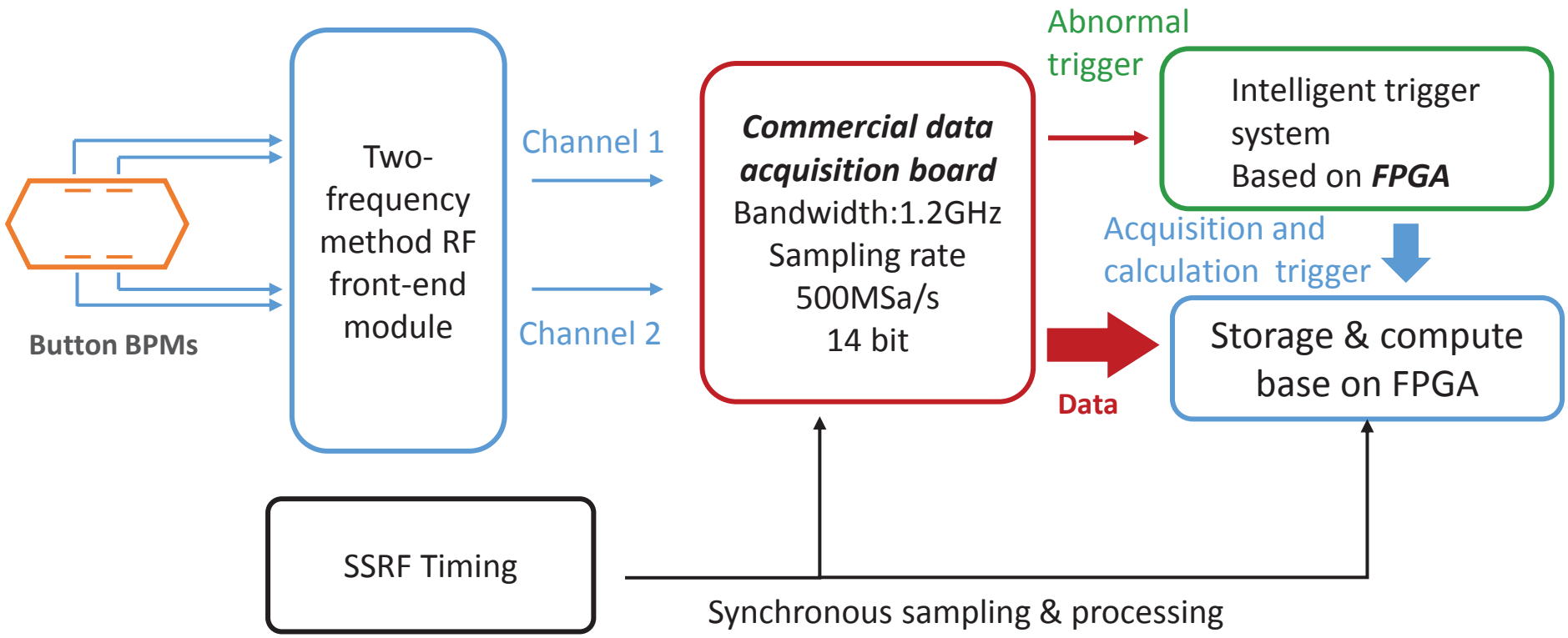


Figure 16: Two-frequency online system based on commercial DAQ

Next Work(3) – 6D BBB System integration

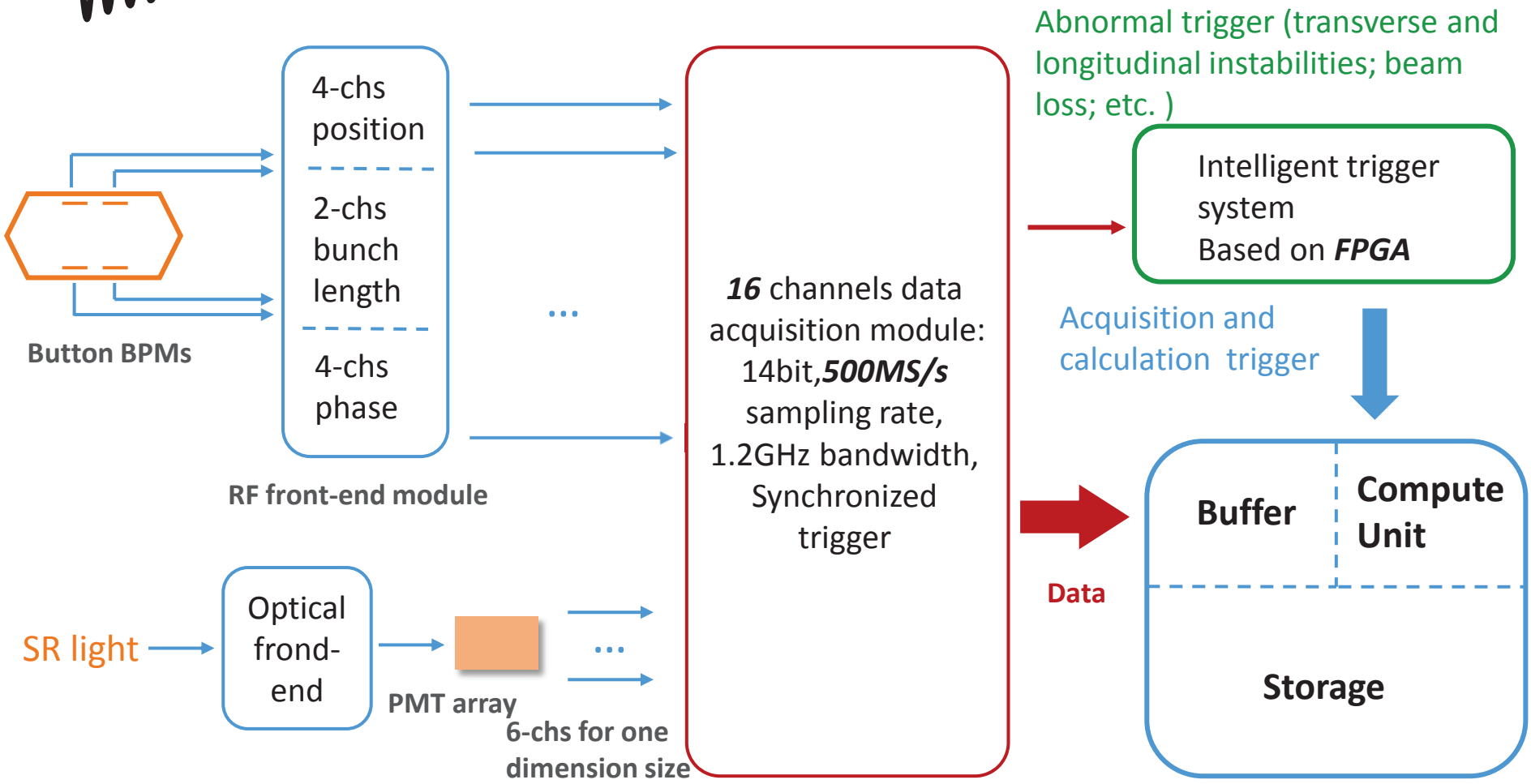


Figure 16: ***6-dimentional bunch-by-bunch*** diagnostic system architecture

Abnormal status ***capturing and analysis***
(Beam instabilities events, beam loss, etc.)

Next Work(4) – Multi-freq Schematic

Increase accuracy by adding more signal channels :
500MHz, 2GHz, 3GHz, 4.5GHz

Summary

- ***The two-frequency system*** with bunch-by-bunch capability is successfully implemented in SSRF.

- After the **beam based calibration using streak camera** as reference this system was used to measure bunch length in a very large charge dynamic range from 30pC to 6nC.

- This system also been used to monitor the **refilled bunch behavior during routine injection**. With further data analyzing the full information of refilled charge in phase space can be retrieved.

- **DAQ need to be upgraded** and **intelligent trigger mode** based on FPGA will be implemented. After upgrading this system will be more useful for physicist 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 of SSRF in design and analysis of beam experiment

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

Thanks for your attention

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Beam loss due to scrpation