Precise Bunch charge measurement using BPM pickup

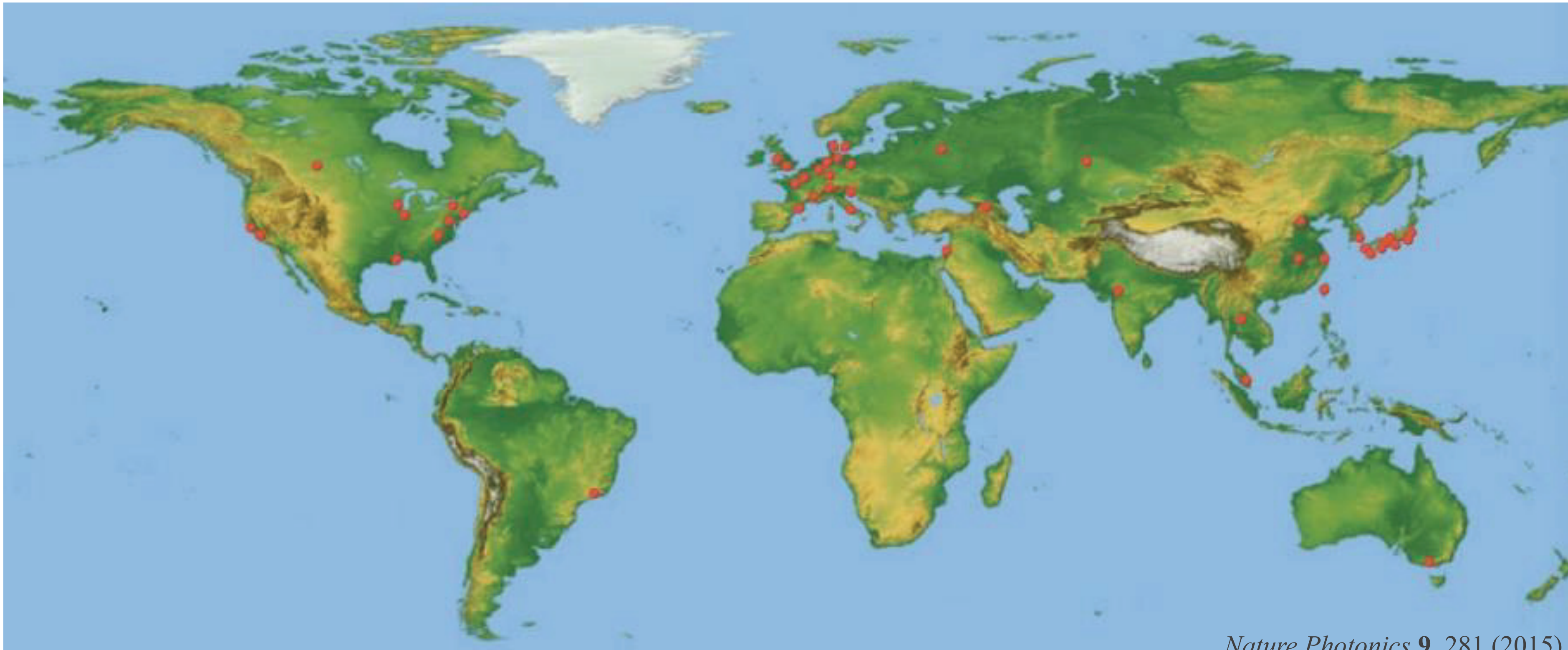
Jian Chen, Yongbin Leng, Lai L.W, Gao B, Cao S.S,
Chen F.Z, Zhou Y.M, Xu X.Y, Wu. T, Yuan R.X, Yu L.Y
SSRF BI Group

IBIC 2020
International Beam Instrumentation Conference
Brazil, 14-18 SEP, 2020

Outline

- Introduction & Background
- Theory & Simulation
- Signal conditioning & Data processing
- Beam experiment
- Discussion & Summary
- Acknowledge

Introduction



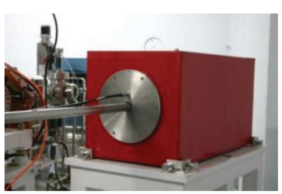
Nature Photonics **9,** 281 (2015)

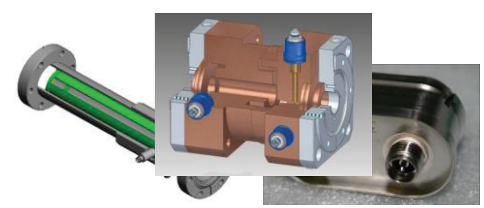
- With the development of accelerator technology, more than 60 accelerator facilities are in operation or under construction worldwide
- For accelerator facilities, especially for user facilities, precise measurement and feedback of bunch charge is very important for its stable operation

Introduction

Methods of measuring bunch charge

Methods	Faraday cup	DCCT	ICT	BPM	…
Characteristics	Intercepting low current Absolute measure	Non-intercepting DC current Absolute measure	Non-intercepting Ultrafast short pulse Absolute measure	Non-intercepting High resolution Relative measure	
Measured parameters	Pulse current Long / short pulse waveform	Beam lifetime DC current	Impulse charge	Pulse current / Bunch by bunch current / DC current	
Time response	ns ~ us	DC ~ ms	ps ~ ns		
Performance		~ μA	~ 1% (~ pC)	~ 0.1%	
Applications	LINAC / transfer line	Storage ring / Booster	LINAC / transfer line	Storage ring / LINAC/transfer line	



Typical application

Lab or Machine	method	Parameters	Application	Performance	Reference
ALS	Sum of BPM	ADC、FPGA、phase shift	Beam charge (storage ring) Beam loss	0.2 pC	[1]
BEPC-II	Sum of BPM	Board band RF front-end、peak-value sampling	Bunch-by-bunch charge (storing ring)	10 uA / bucket	[2]
Euro-XFEL	Toroid	Commercial AMC(SIS8300-L2D) MTCA.4	Machine protection Interlocks Dark current monitor (FLASH)	< 0.2pC rms	[3]、[4]
SWISS - FEL	Turbo-ICT	BCM-RF、NI-USB-9162	Low bunch charge (FEL)	55 fC @ 5pC (~1.1 %)	[5]
SWISS - FEL	Resonant SBPM	Freq.: 500 MHz / Qload: 6.2@monopole 5 GSPS direct Sampling	Low bunch charge	< 30 fC @ 2 pC (~1.5 %)	[6]
Euro-XFEL	CBPM	3.3GHz / Q = 70 16-bit、161 MSPS （IQ）	Bunch charge Machine protection	85 fC rms @ 210 pC （~ 0.04 %）	[7]、[4]
SWISS - FEL	CBPM	4.9266 GHz / Q =1000 16-bit、161 MSPS （~134M IF） 3.2844 GHz / Q =40 16-bit、161 MSPS （IQ）	Low bunch charge (FEL)	2 fC @ 5 pC （~ 0.04 %） 5 fC @ 7 pC （~ 0.07 %）	[8]
CLC	CBPM	15 GHz / Q = 120 10-bit、2 GSPS（~200M IF）	Bunch charge	0 .011 nC @ 3.4 nC （~ 0.32 %）	[9]
FLASH	CBPM	3.3GHz / Q = 70 MBU by PSI （IQ）	Bunch charge	< 0.2 pC @ 100 pC （~ 0.2 %）	[3]

[1] Santis SD, Li D, Norum W, Portmann G. Proceedings of the 7th International Beam Instrumentation Conference, September 12-16, 2016[C]. Shanghai, China.

[2] Deng Q.Y, Cao J.S, Ye Q, *et al.,* Bunch current measurement system for BEPCII storage ring[J]. *High Power Laser and Particle Beams*, 2014, 26: 075101.

[3] N. Baboi，D. Nölle, *et al.* Commissioning of the FLASH2 Electron Beam Diagnostics in respect to its Use at the European XFEL, IBIC14

[4] The Diagnostic System at the European XFEL; Commissioning and First User Operation，IBIC18

[5] S.Artinian, J.Bergoz, *et al*. DEVELOPMENT AND FIRST TESTS OF A HIGH SENSITIVITY CHARGE MONITOR FOR SwissFEL , IBIC'12

[6] Keil B, Citterio A, Dehler M, et al. Commissioning of the low-charge resonant stripline BPM system for the SwissFEL test injector[C]//Proc. FEL. 2010: 429.

[7] M. Stadler, et al. Beam test results of undulator cavity BPM electronics for the European XFEL[C], IBIC2012, Tsukuba, Japan.

[8] V. Schlott, V. Arsov, et al. Commissioning Results and First Operational Experience with SwissFEL Diagnostics, IBIC'17.

[9] F. J. Cullinan, *et al.* Long bunch trains measured using a prototype cavity beam position monitor for the Compact Linear Collider[J]. Physical review special topics. 2015, 18(112802).

Research Motivation & Object

SSRF

- Precise measurement of Bunch-by-bunch charge
- Online bunch-by-bunch beam life time measurement
- High-efficiency bunch injection for top-up operation, which is the basis for providing high-quality SR light

SXFEL & SHINE

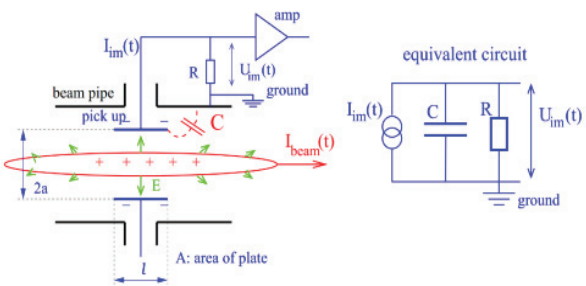
- Precise measurement of bunch charge and feedback
- High-precision beam loss monitor (~0.01%) for machine safety interlock

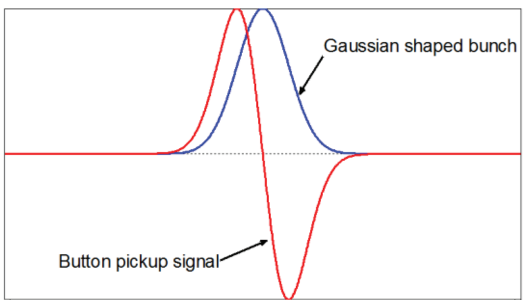
Theory & Simulation

Principle of measurement

- Button BPM
- Stripline BPM
- Cavity BPM

Button BPM



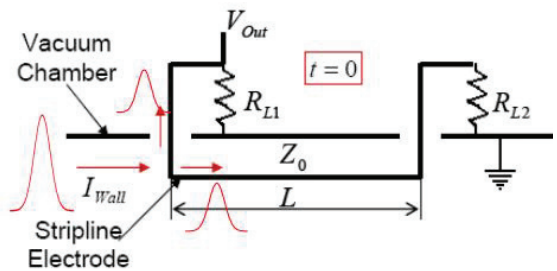


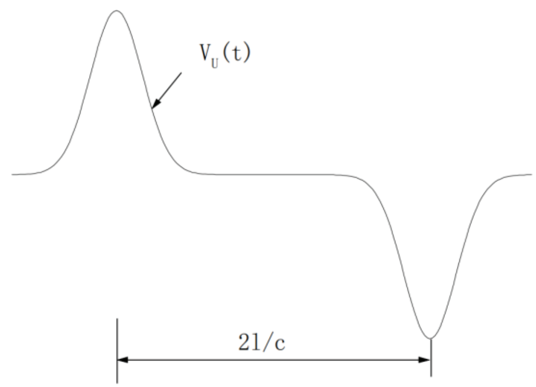
Charge

$$V_B(t) = \frac{Q}{2\pi^{3/2}} \cdot \frac{\varphi l R}{\beta_b c} \cdot \frac{t}{\sigma_t^3} \cdot e^{-\frac{t^2}{2\sigma_t^2}}$$

Bunch length

Stripline BPM



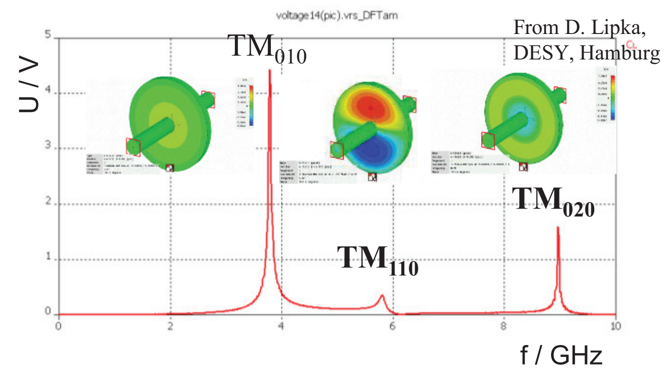


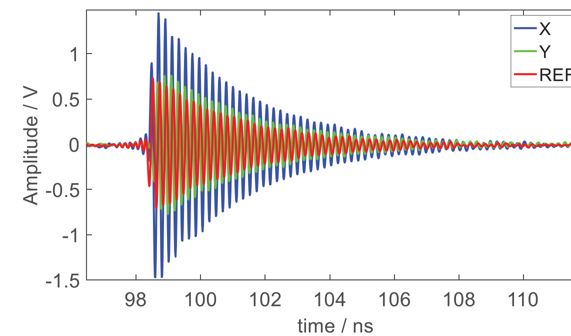
Charge

$$V(t) = \frac{\phi Z}{4\pi} [e^{-\frac{t^2}{2\sigma^2}} - e^{-\frac{\left(t-\frac{2l}{c}\right)^2}{2\sigma^2}}] \cdot \frac{Q}{\sqrt{2\pi}\sigma}$$

Bunch length

Cavity BPM





Charge

Cavity length

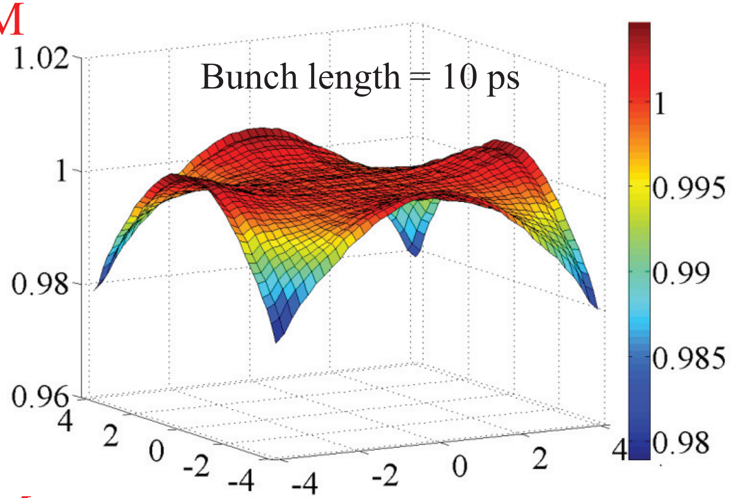
$$V_p^{010} = \frac{q\omega_{010}}{2} \cdot \sqrt{\frac{Z}{Q_{ext}^{010}} \cdot \frac{2LT^2}{\varepsilon\omega_{010}\pi a^2 J_1^2(\chi_{01})}} \cdot J_0\left(\frac{\chi_{01}}{a}\rho\right) \cdot e^{-\frac{t}{\tau_{010}}} \cdot e^{-\frac{\omega_{010}^2\sigma_z^2}{2c^2}} \cdot \sin(\omega_{010}t + \varphi)$$

Bunch length

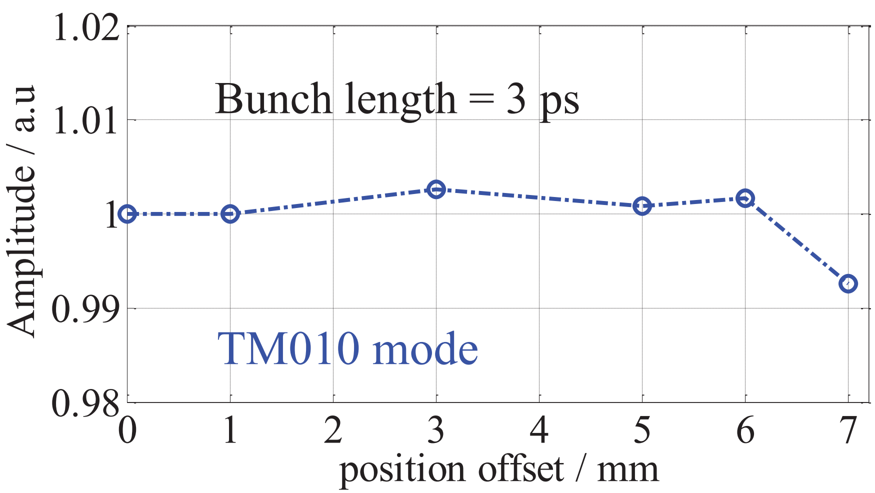
Simulation of Dependency

Transverse Position Dependency

SBPM



CBPM



- Sum signal has a hyperbolic parabolic relationship with bunch position
- Based on the simulation results, the bunch position offsets needs < (1mm,1mm) if want to achieve 0.01% bunch charge measurement resolution

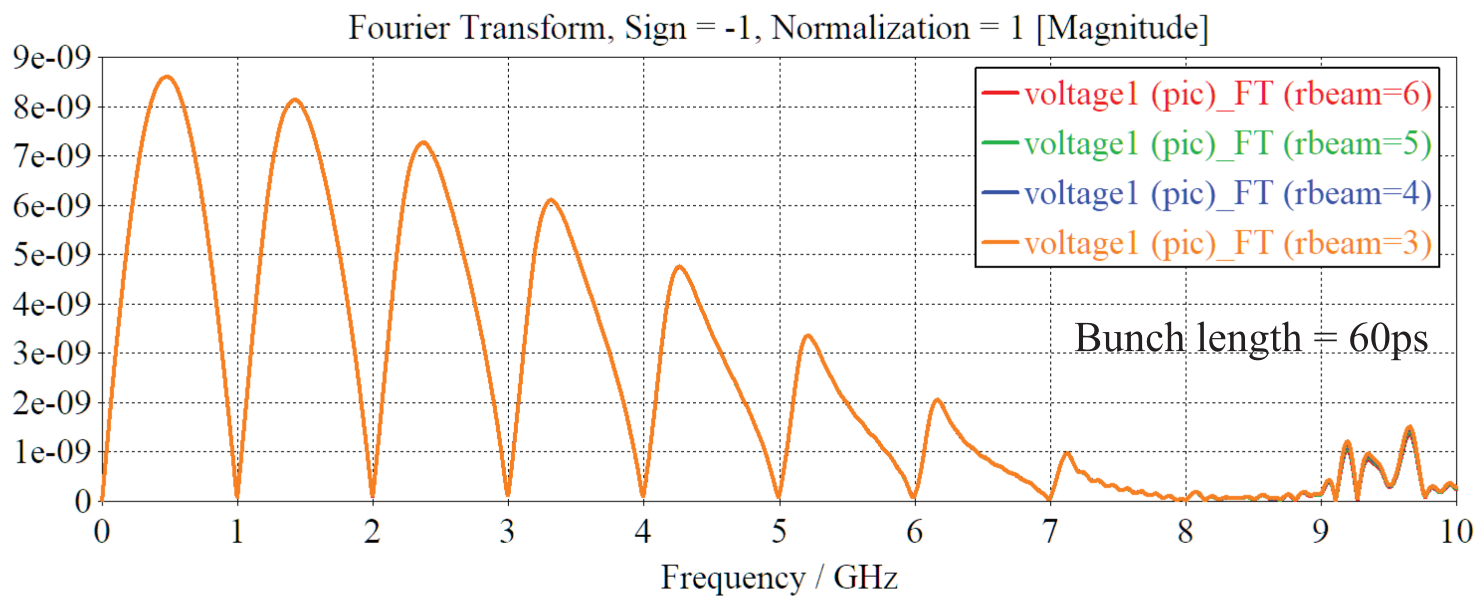
- In the case of position offset within 6mm, TM010 mode signal has no obvious position dependence

(The error is limited by the accuracy of the meshing of the simulation tool)

- All parameters used for simulation comes from SSRF and SXFEL

Simulation of Dependency

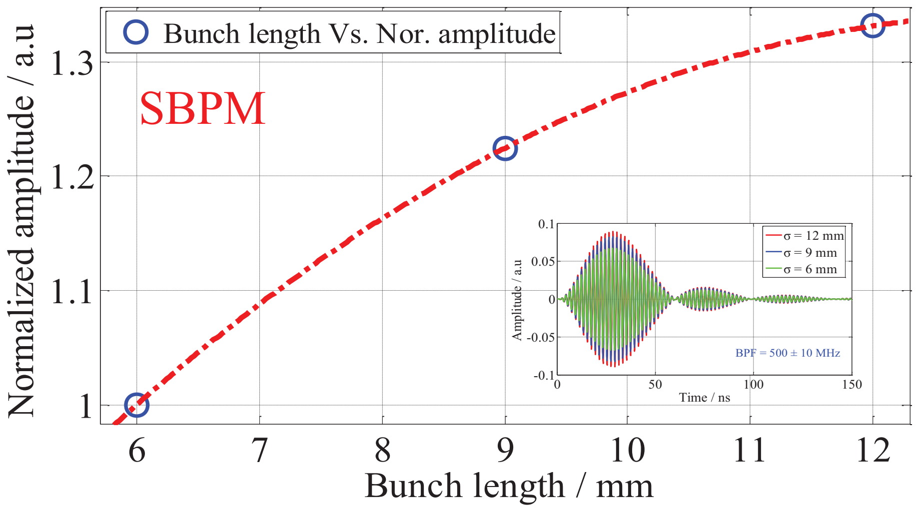
Transverse Distribution Dependency



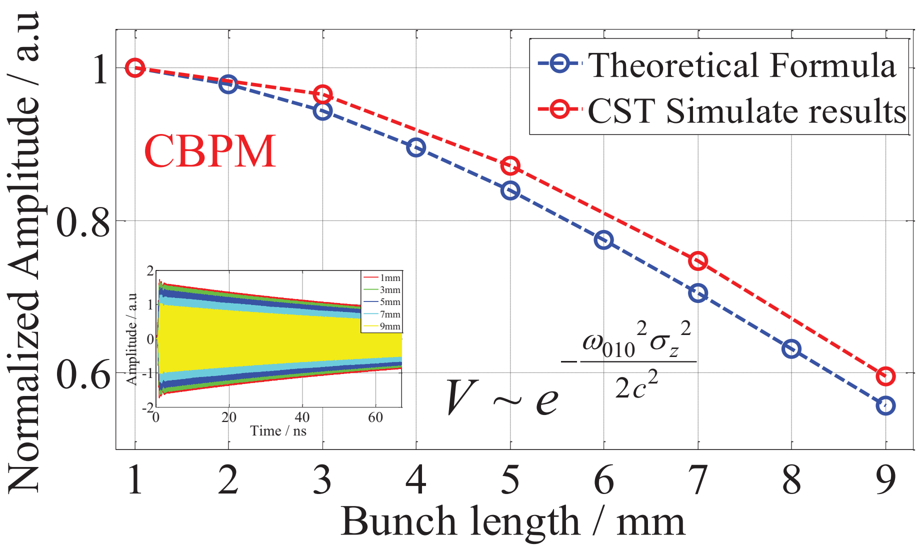
- For SBPM, when the operating frequency < 10 GHz, the transverse distribution dependence is less than 0.01%, so the influence on the measurement of the bunch charge can be ignored
- For Cavity BPM, no big difference in position dependence within 6mm; Theoretically, there will be no obvious dependence on transverse distribution

Simulation of Dependency

☐ Bunche length Dependency



- Base on the results, the output signal changes about 4% when the bunch length changes 0.5ps around 2ps was estimated



- The simulation results are in good agreement with the theoretical formula
- Considering the working bunch length is 2ps, the bunch length jitter need < 7% if want to achieve 0.01% measurement resolution

Theoretical Limit

- Ideal DAQ and processing system, the probe information can be obtained completely --- limited by thermal noise of the system
- Thermal noise： $V_n = \sqrt{4kTRB}$ → 0.92uV/sqrt(MHz)@50Ω·300K

For Cavity BPM - TM010 mode:

$$V_p^{010} = \frac{q\omega_{010}}{2}\sqrt{\frac{Z}{Q_{ext}^{010}}\cdot\left(\frac{R}{Q}\right)}$$

Parameters of SXFEL：

$$f_{010} = 4.693GHz$$
$$BW_{3dB} = 2\,MHz$$
$$Q_{ext} = 1.54\cdot E4$$

→ Sensitive: 5.4V/nC

↓

- 100MHz bandwidth system， theoretical limit： ~ 1.7 fC

For Stripline BPM :

$$V(t) = \frac{\phi Z}{4\pi}\left[e^{-\frac{t^2}{2\sigma^2}} - e^{-\frac{\left(t-\frac{2l}{c}\right)^2}{2\sigma^2}}\right]\cdot\frac{Q}{\sqrt{2\pi}\sigma}$$

Parameters of SXFEL：

σ=2ps

$l = 150mm$

$\varphi = 30^o$

→ Sensitive: ~12V / 0.1nC

↓

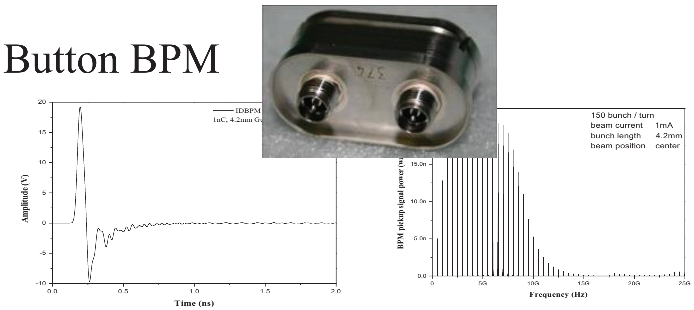
- Ideal ADC， 100GHz BW， enough input range， theoretical limit： ~ 2.4 fC
- For 500 ± 10MHz BW, theoretical limit : ~ 4 fC

Signal conditioning & Data processing

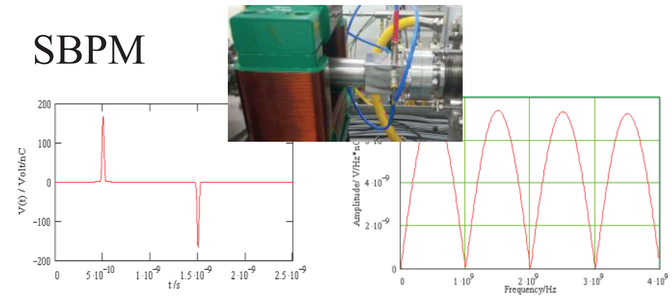
Signal conditioning & Data processing

- Signal conditioning methods @ SBPM & Button BPM

Button BPM



SBPM



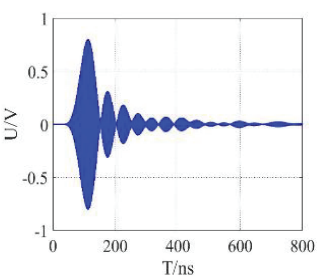
Signal conditioning / Sampling method

Narrow - band

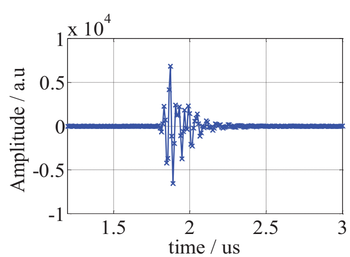
Broad - band

Signal filter broadening

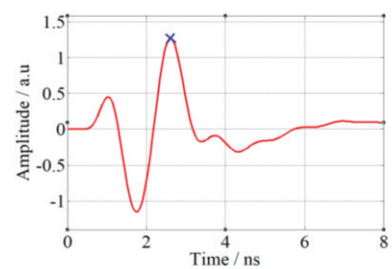
Peak Sampling

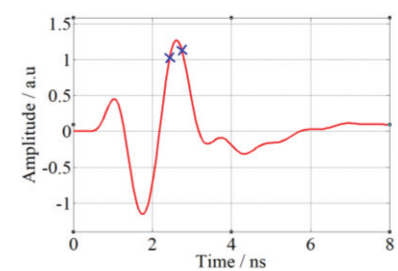


+ ADC



Int / Ext Clock / Trigger

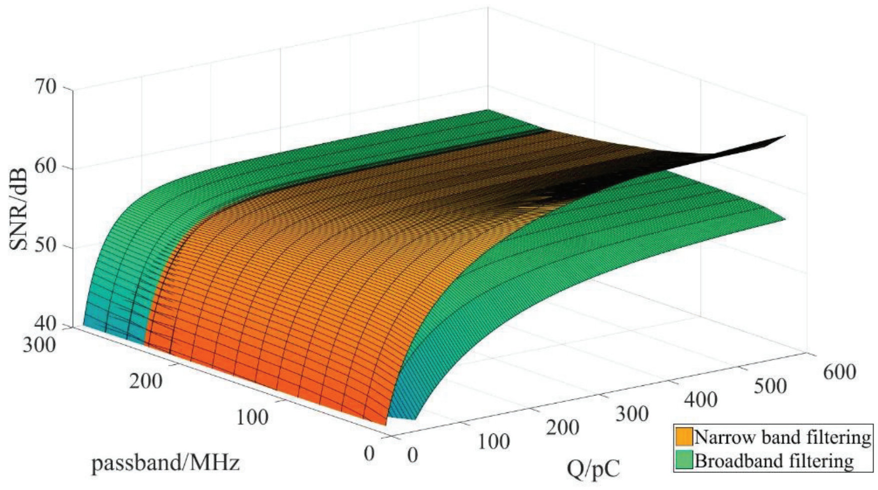


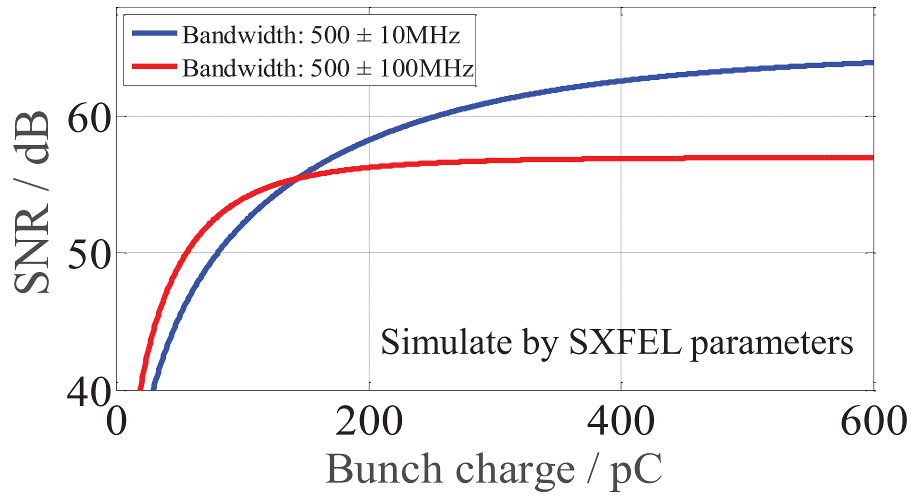


Ext Clock / Trigger

Signal conditioning & Data processing

- Choice of Narrow-band filtering & Wide-band sampling





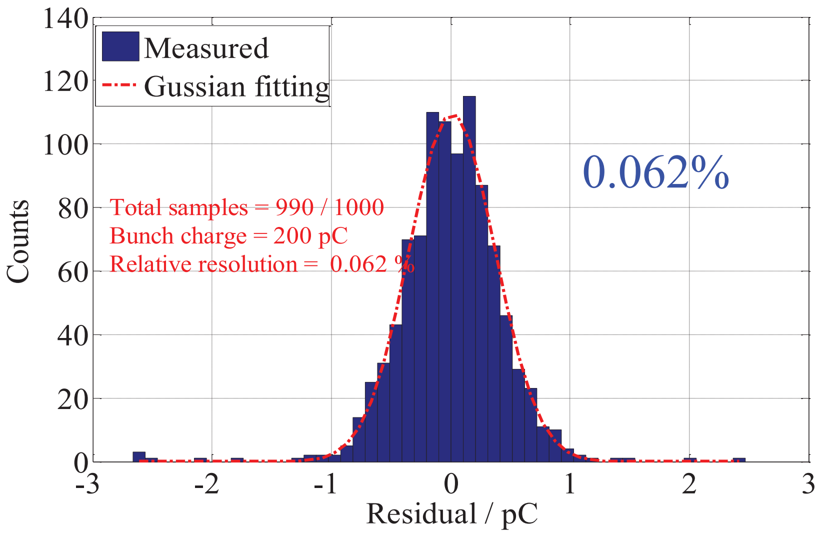
- With a bigger bunch charge, the narrow-band filtering method can obtain larger processing gain and better SNR
- With a smaller bunch charge, the wide-band sampling method can output more energy and can improve the single-point SNR

Signal conditioning & Data processing

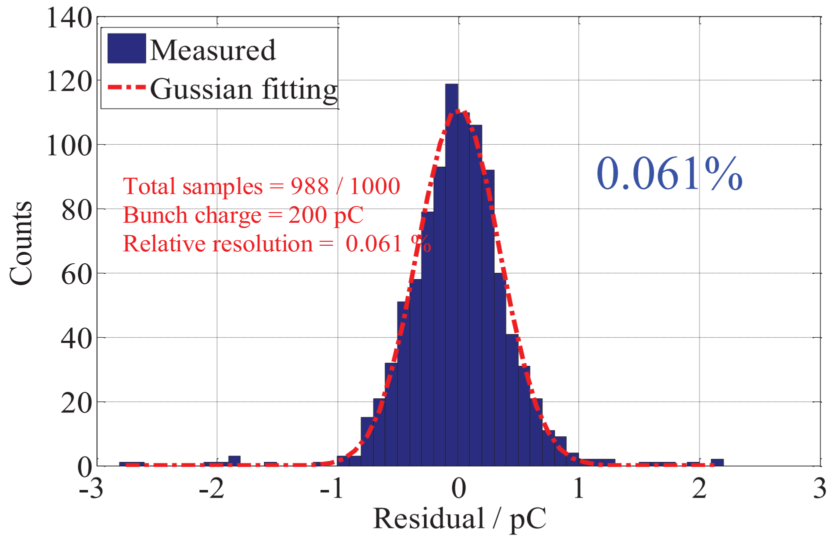
- Internal / External Clock & Trigger @ SXFEL

Narrowband Filtering

Internal Clock & Trig

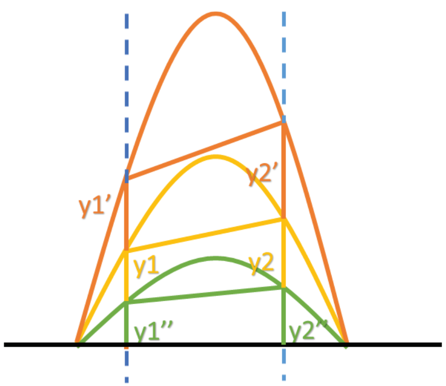


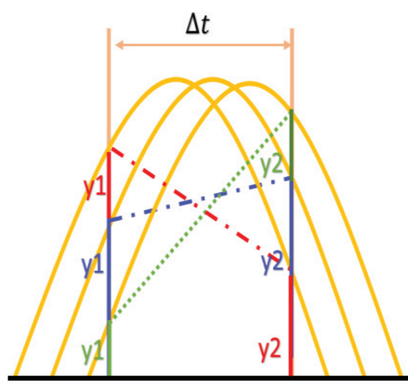
External Clock & Trig



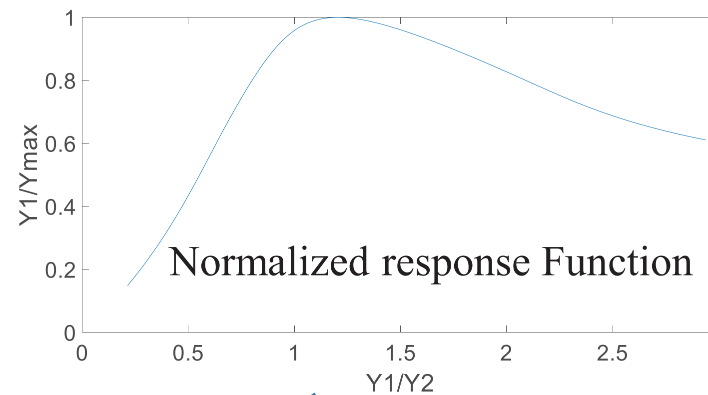
- when the ADC sampling rate is much larger than the system bandwidth (at least 4 times), there has no big difference in the improvement of resolution by external clock and trigger

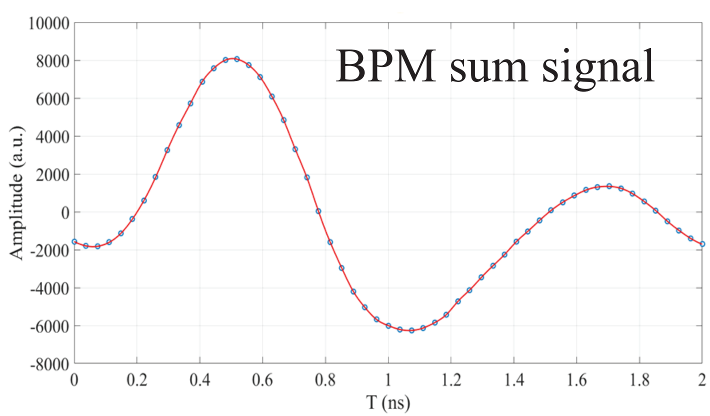
- SBPM / Button BPM --- “ Two-phase sampling based peak seeking method ”





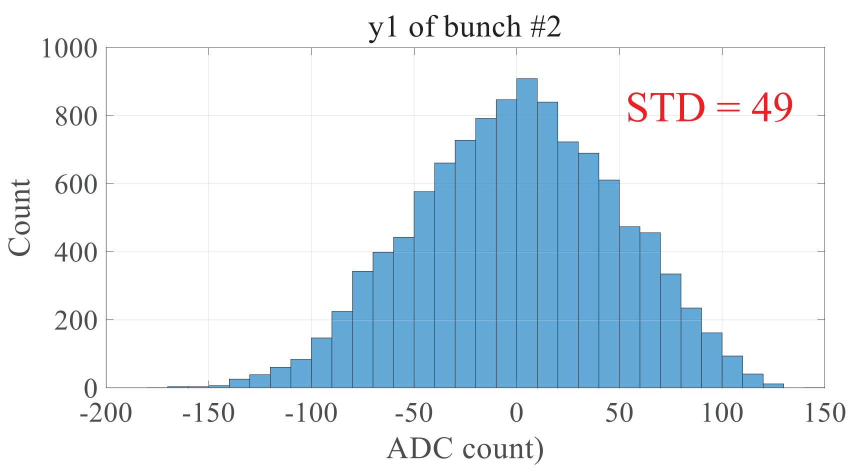
- Target： Minimize the impact of sampling phase jitter

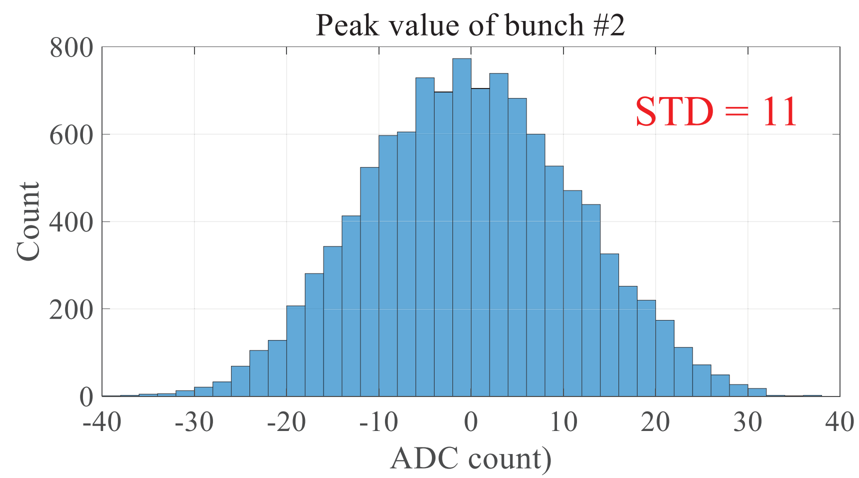


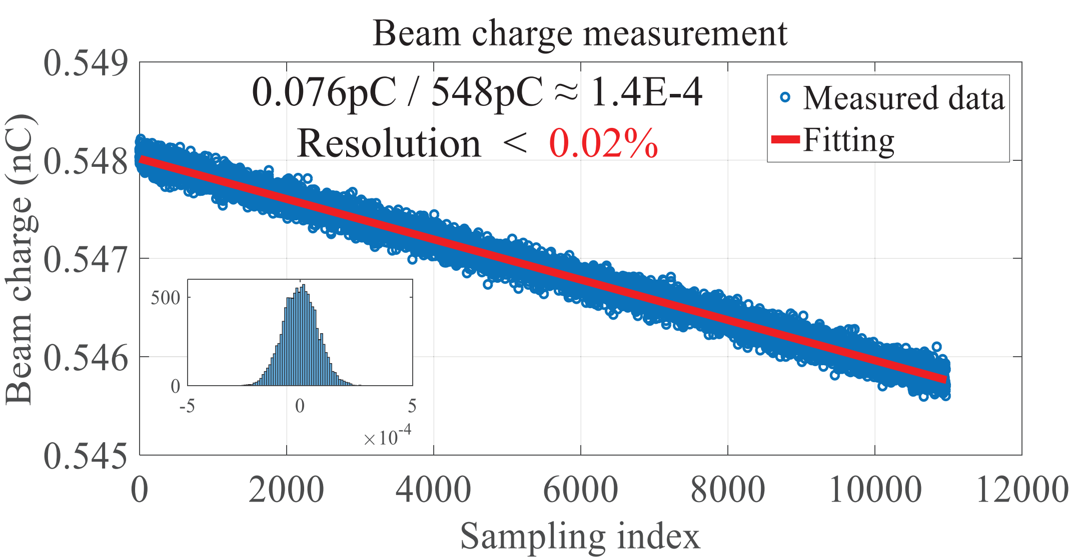


$$\frac{y_1}{y_{peak}} = f\left(\frac{y_1}{y_2}\right)$$

Signal conditioning & Data processing





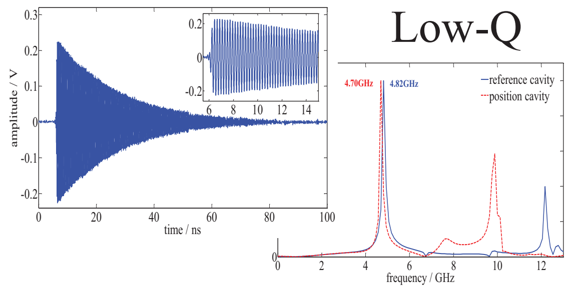


- " Two-phase sampling based peak seeking method " basically minimized the influence of sampling phase jitter
- Resolution of beam charge measurement better than 0.02%

（1W+ sets of data average）

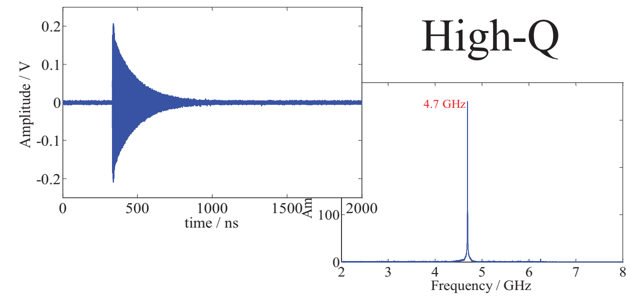
Signal conditioning & Data processing

Signal conditioning methods @ Cavity BPM



Low-Q

High-Q



Signal conditioning / sampling method

Down Conversion

RF Sampling

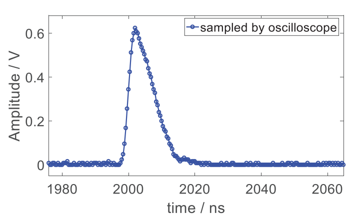
Low-Q

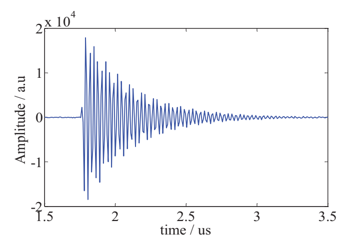
High-Q

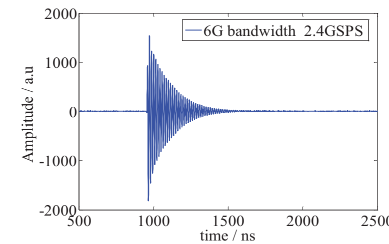
Analog IQ demodulation

Down Conversion to low IF

ADC with High bandwidth、sampling rate







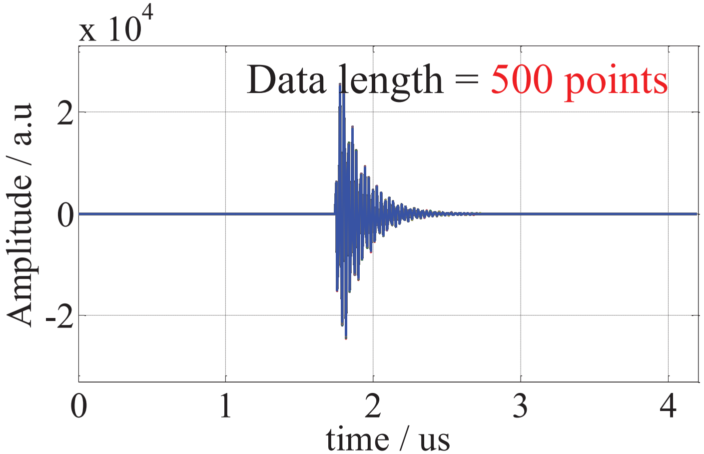
- High Q Cavity can get more processing gain (longer decay time), the algorithm is also more diversified
- Optimize the data processing window can improve the system resolution effectively

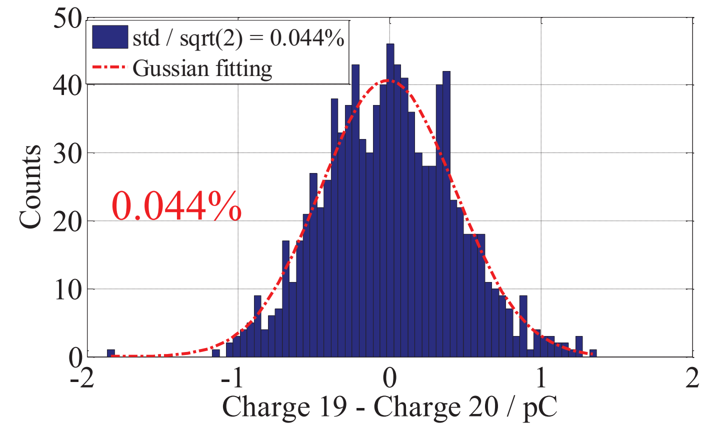
Signal conditioning & Data processing

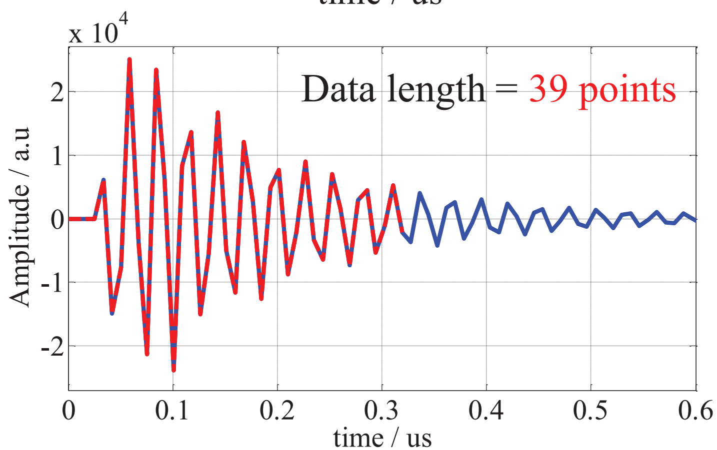
Frequency: 4.7GHz

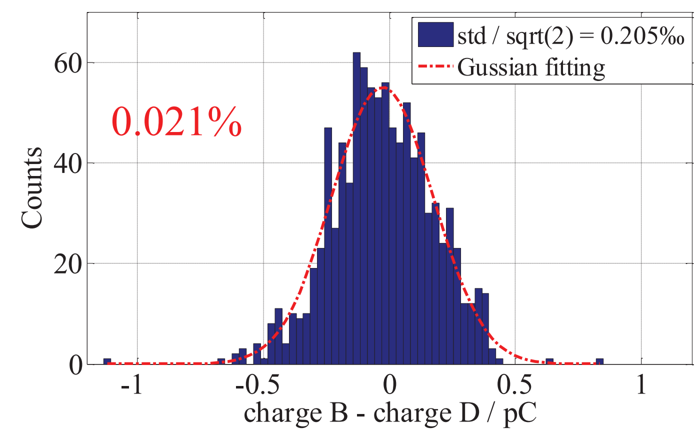
Loaded Q: 2350

- Performance after select data processing window @ SXFEL





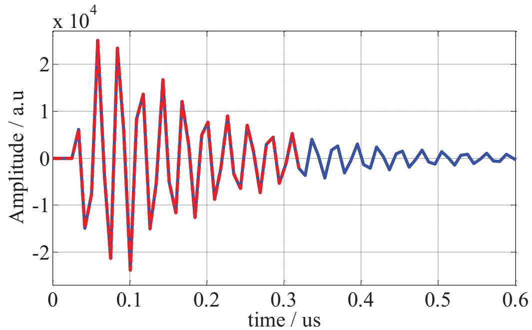


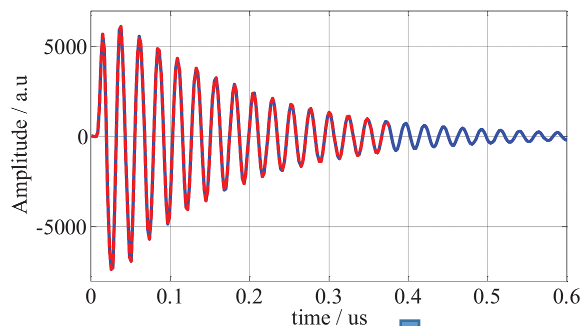


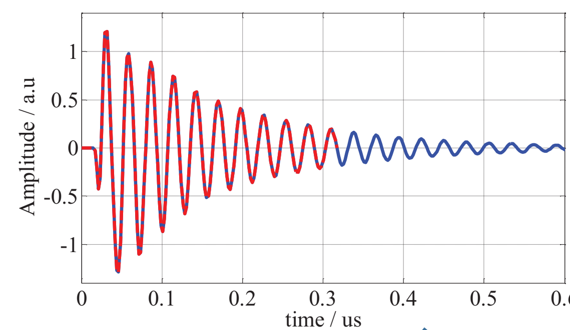
- By selecting an appropriate data processing window, the relative resolution can be improved from 0.044% to 0.021%

Signal conditioning & Data processing

Comparison of different DAQ system @ SXFEL







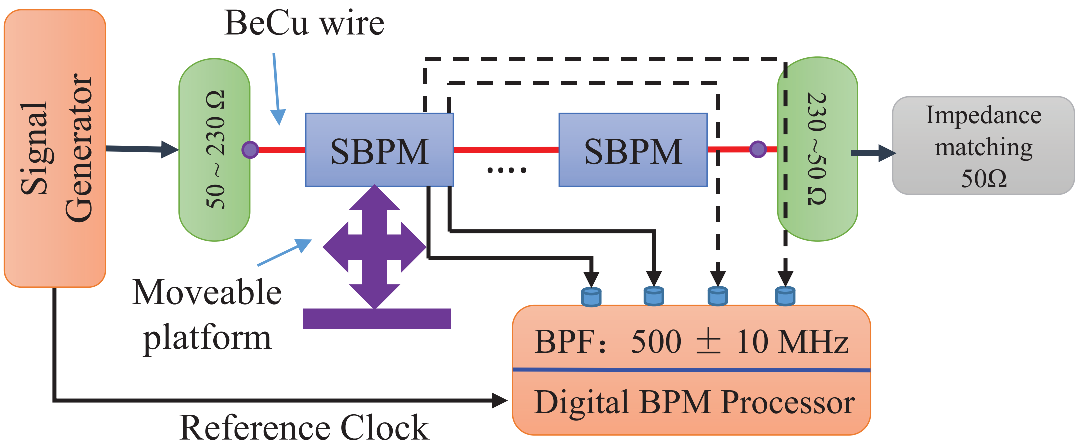
	Digital BPM (Homemade by SSRF)	**Libera Digit 500**	**NI - 5772**
Parameters	119 MSPS、16 bit	476 MSPS、14 bit	476 MSPS、12 bit
Data Length	327 ns	378 ns	319 ns
Relative Resolution	0.044% → 0.021 %	0.065% → 0.036 %	0.083% → 0.047 %

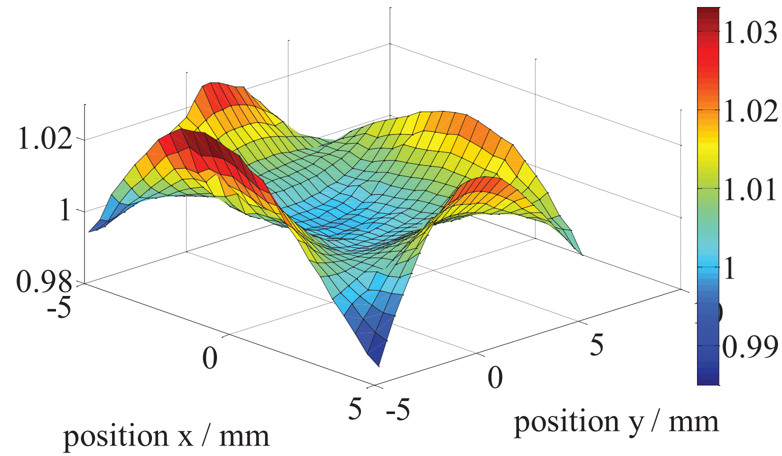
- Different parameters DAQ system, By selecting the appropriate data processing window, the performance is nearly doubled

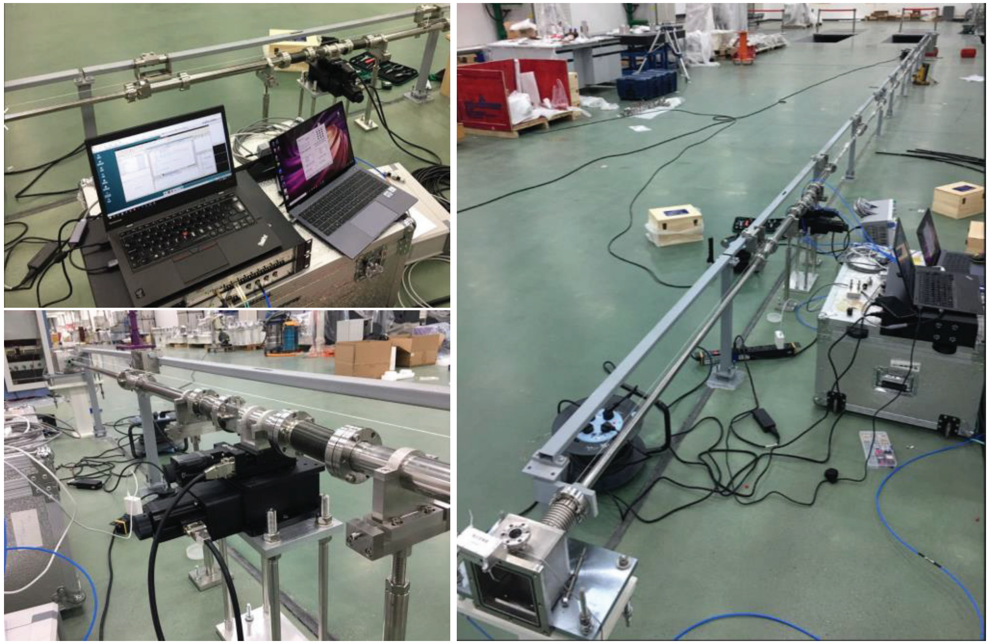
Beam Experiment

- SSRF
  - Position dependence evaluation
  - Performance evaluation (BYB charge monitor)
- SXFEL
  - Bunch length dependence evaluation @ SBPM
  - Position dependence evaluation @ CBPM

Position dependence -- SBPM

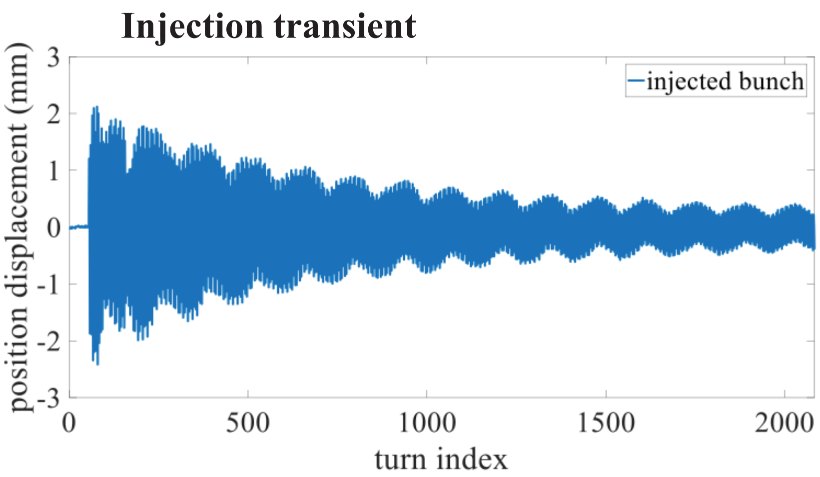


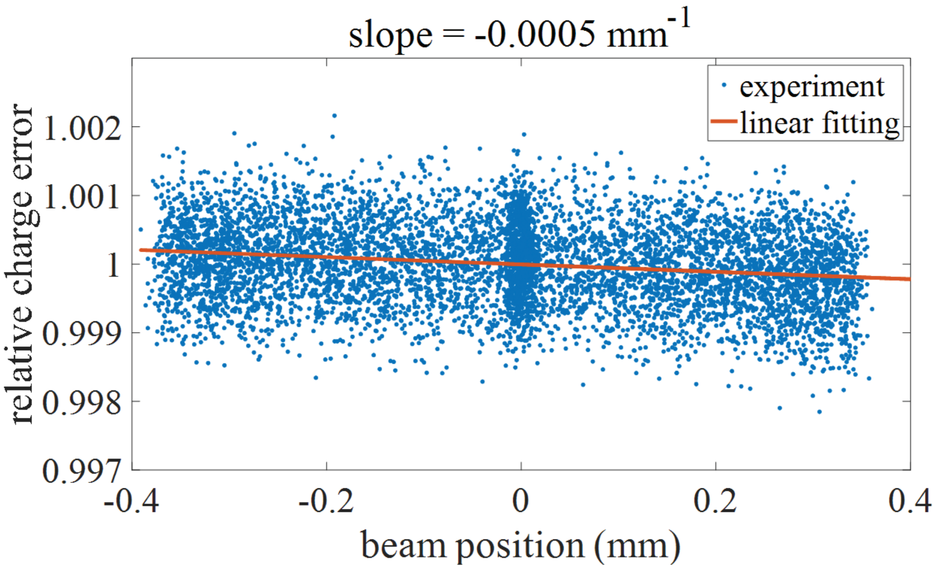




- A wire passes through BPM to simulate beam offset to verify the dependence of sum signal and position
- Qualitatively verified that the relationship is hyperboloid

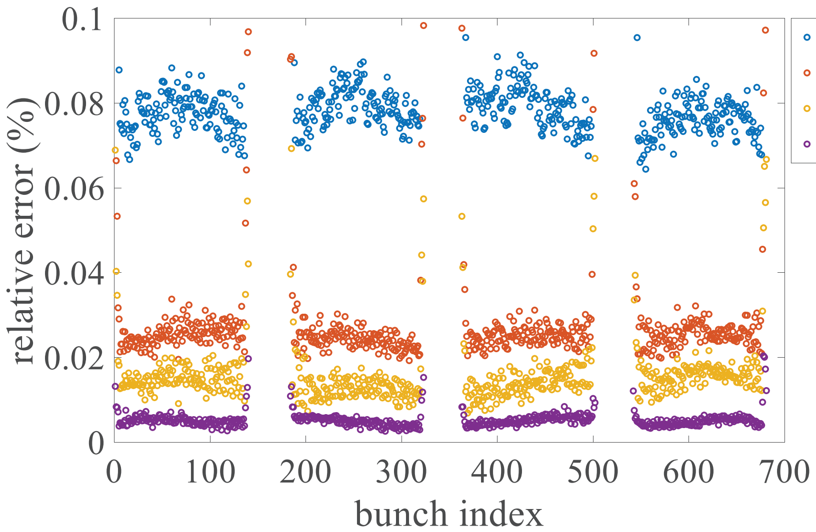
Position dependence -- Button BPM



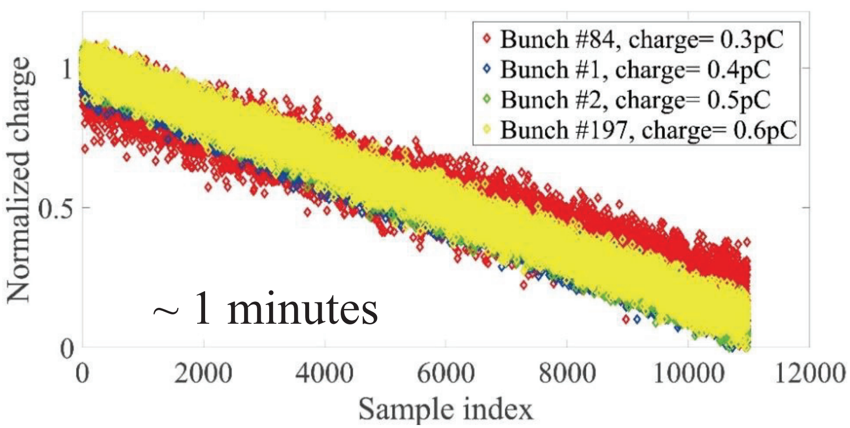


- The data of the beam position during the injection transient was used to evaluate the position dependence, the results shows that the slope is about 0.0005 / mm
- Closed-orbit measurement, position jitter controlled within micro-meter level, the contribution of position dependence is about 1E-6
- Turn-by-Turn measurement, the contribution of position dependence is about 1E-5 (10 σ ~20 um)

Performance (BYB charge monitor)



Data rate	Relative Error（σ）	10 σ	600pC
TBT	8E-4	8E-3	5pC
69kHz	3E-4	3E-3	2pC
7kHz	1.5E-4	1.5E-3	1pC
700Hz	5E-5	5E-4	0.3pC

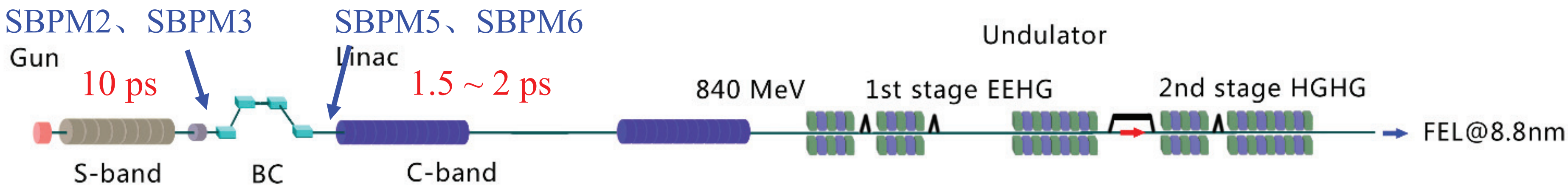


- Evaluate the BPM pickup to measure the charge of BYB, the resolution can reach 8E-4 (694KHz data rate)
- For the charge measurement of the storage ring, the position dependence is negligible
- Assume the beam with lifetime ~ 10h, bunch decay ~ 3E-5/s. The system can achieve BYB lifetime measurement within tens of seconds

Beam Experiment

- SSRF
  - Position dependence evaluation
  - Performance evaluation (BYB charge monitor)
- SXFEL
  - Bunch length dependence evaluation @ SBPM
  - Position dependence evaluation @ CBPM

Bunch length dependence -- SBPM

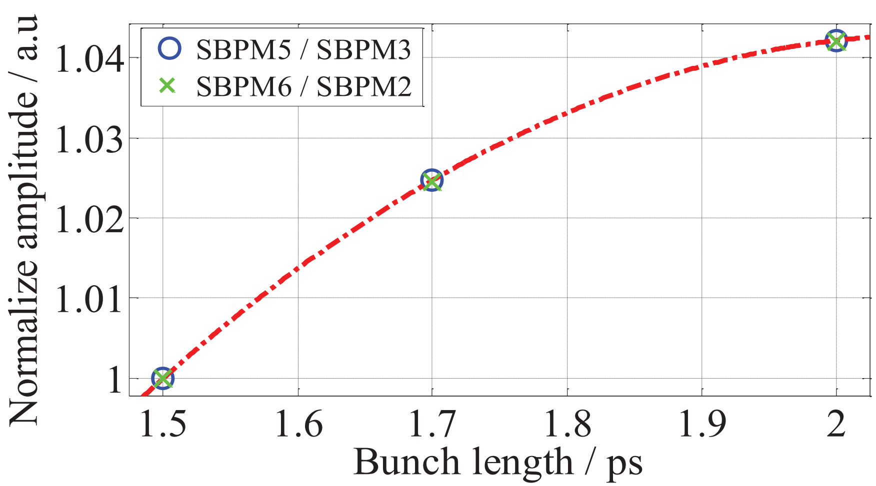


Injector beam parameters

Bunch charge (nC)	0.5
Beam energy (MeV)	129.4
Pulse length (ps, FWHM)	10
Norm. emittance (mm.mrad, rms)	0.95
Rep-rate (Hz)	1-10

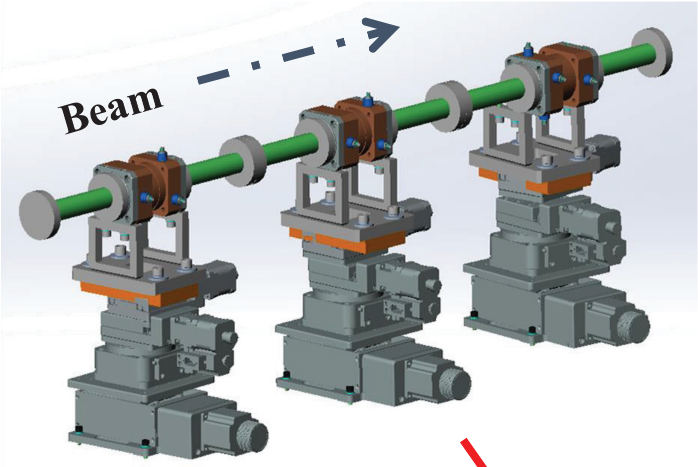
Main linac beam parameters

Bunch charge (nC)	0.5
Beam energy (GeV)	0.8
Bunch length (ps, FWHM)	1.5
Norm. emittance (mm.mrad)	< 2.0
Peak current (A)	≥ 500



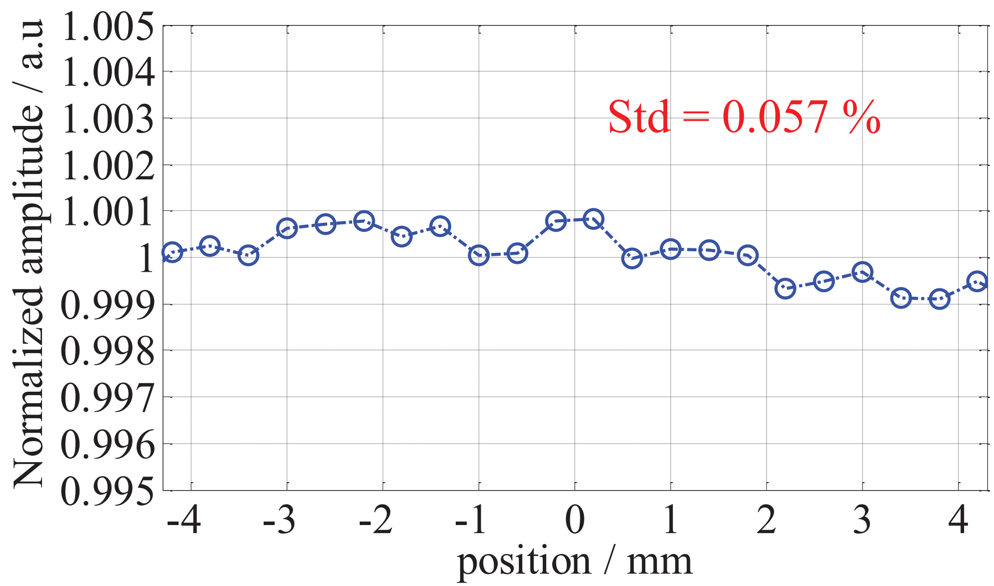
- Bunch length can be adjusted from 1.5ps to 2ps in BC section
- Bunch length changed from 1.5 to 2ps, the sum signal changed 4.2%, consistent with the simulation results
- Bunch length jitter need to be controlled with 0.1% if want to achieve 0.01% resolution

Position dependence -- CBPM



Hold position for reference

Move the cavity using the moveable platform



- The range of the movable platform is limited to ±4.2mm
- Within ±4.2mm, the position dependence of the TM010 cavity can be ignored, which is consistent with the simulation results

Discussion & Summary

Discussion 1 -- Update the current system

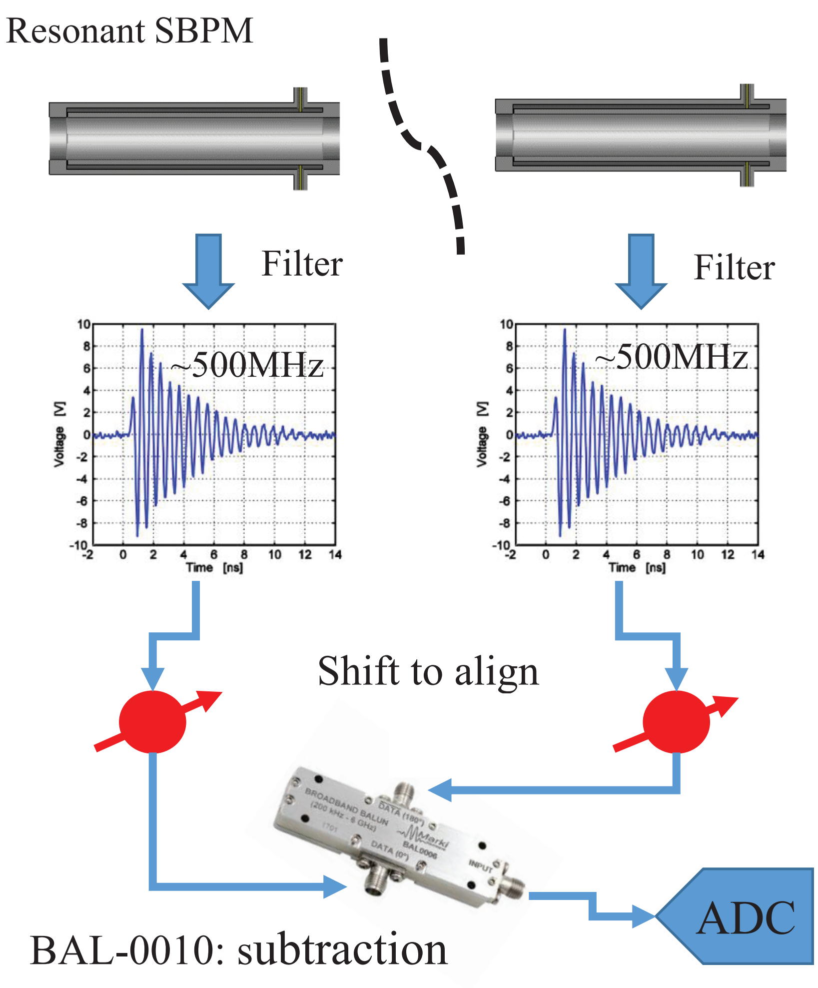
BPM for high precision beam loss monitor -- 0.01% resolution for key area (SHINE)

	Cavity BPM pickup	RF Front-end	DAQ system
Parameters	Frequency: 4.7 GHz Loaded Q: 2350	One channel to IF ~ 30MHz	4 channels, 119MSPS, 16 bit Bandwidth(ADC): 650 MHz
Performance	Thermal noise: -110dB (2MHz BW)	NF ~ 15	ADC noise level: 2.35 std (ENOB = 12.5)

- Current CBPM system in SXFEL can achieve the resolution of 2.1%
- Performance limited by the RF front-end, if NF < 9, the resolution of 0.01% can be achieved for current system
- New RF front-end for SHINE optimized to 8.5, can achieve < 0.01% in theory (waiting for beam experiment)

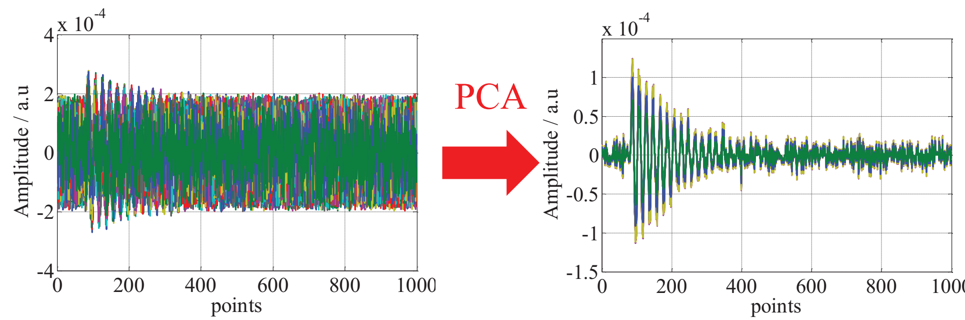
Discussion 2 – New Propose

BPM for high precision beam loss monitor -- 0.01% resolution for key area (SHINE)

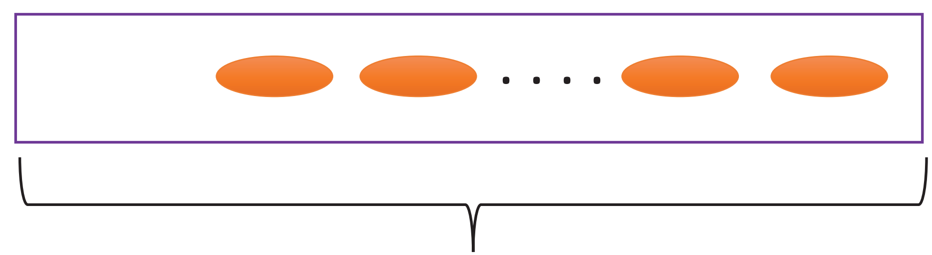


Weak signal amplified and quantified

Simulate 0.01% beam loss, PCA for noise reduction



Thinking: PCA implemented in FPGA?



Set a buff to keep ~100 bunches of BPM data for PCA processing

Summary 1

- BPM pickup can be used for precise bunch charge measurement
- The beam experiment results are basically in agreement with the theoretical simulation results; And Cavity pickup has less dependence on transverse position, transverse distribution and bunch length, more suitable for precise bunch charge measurement
- For Cavity pickup, the system resolution can be improved by optimizing the data processing window; In the SXFEL, the relative bunch charge resolution of the system can reach 0.021%
- The relative resolution of the SXFEL CBPM system is limited by the RF front-end, and when the NF < 9 is optimized, the measurement resolution requirement of 0.01% can be achieved
- Propose a new method based on differential resonant SBPM, which also is expected to meet the requirement of 0.01%

Summary 2

- In the storage ring of SSRF, the BPM pickup is used to measure the charge of BYB, the resolution can reach 8E-4 (694KHz data rate)
- Analyzed the position dependence of BPM in SSRF, combined with position stability of closed orbit and TBT, the error introduced by the position dependence can be ignored
- Therefore, it is very promising for BPM to achieve high-speed and precise BYB charge measurement in storage ring. It also can be used as a tool for beam loss and online bunch-by-bunch beam life time measurement

Thanks for your attention

Contact: chenjian@zjlab.org.ac.cn