The removal of interference noise of ICT using PCA method

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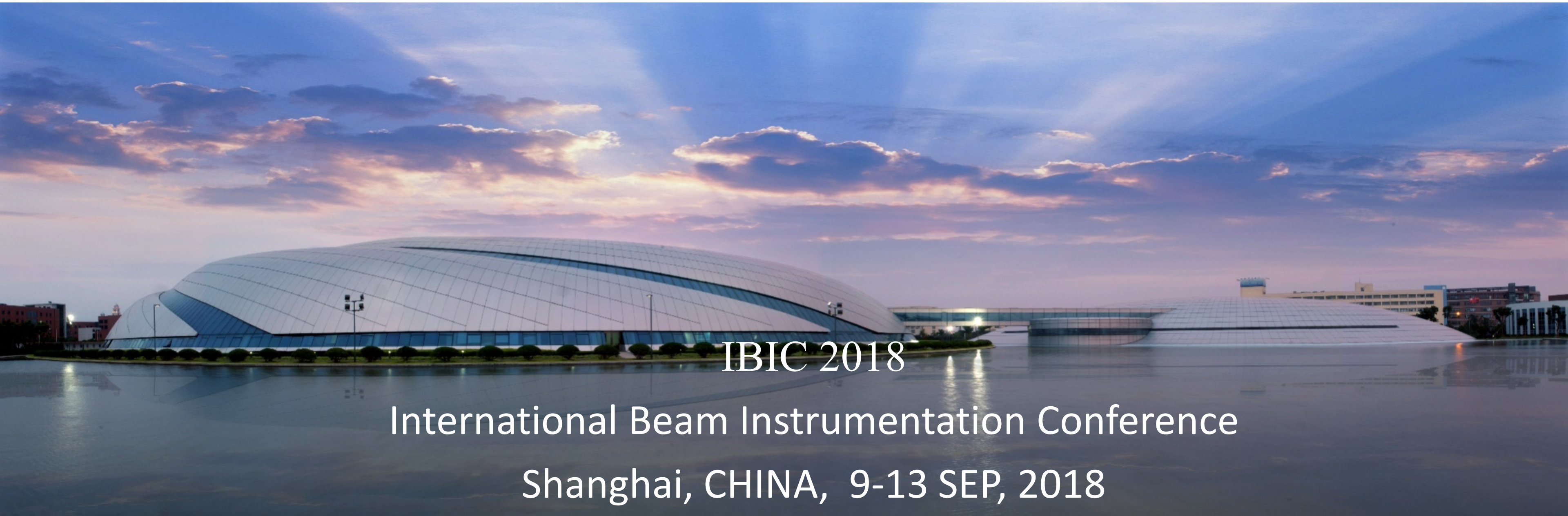
SSRF BI Group



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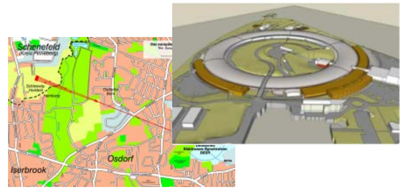
Outline

- Introduction
- Data processing methods
- Discussion & Summary
- Next work
- Acknowledge

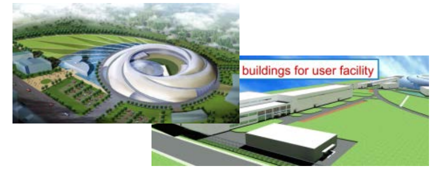
Introduction

ESRF & E-XFEL



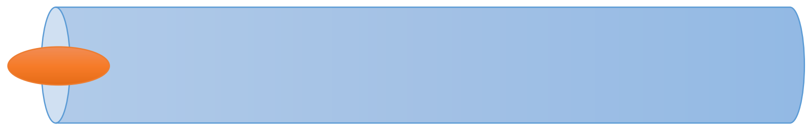
Swiss–FEL & SLS

SSRF & SXFEL



Spring-8 & SACLA

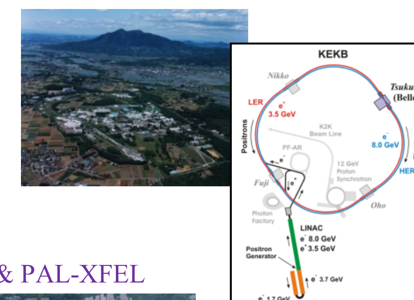
LCLS & NSLS & FERMI-LAB



■ Synchrotron radiation facilities are based on relativistic electron beam

■ For high quality electron beams, accurate measurement of beam charge and its stability is one of the most important parameters for stable operation of accelerator

KEKB & ATF



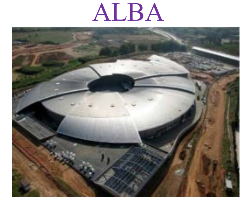
APS

SOLEIL

DESY

DIAMOND

ALBA

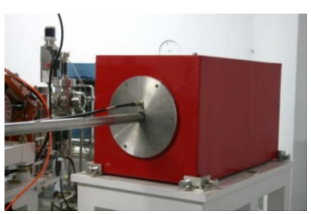


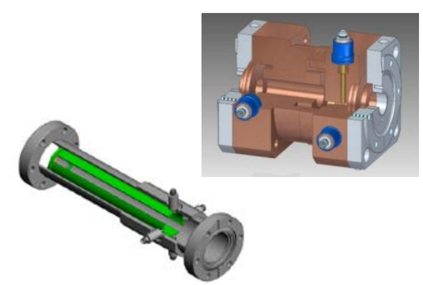
PLS & PAL-XFEL

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		
Applications	storage ring LINAC/transfer line	storage ring Booster	LINAC transfer line	storage ring LINAC/transfer line	





Introduction

Typical usage

BCM-IHR-E

- The secondary coil of the transformer coupling electron pulse signal
- And be widened through the shaping network (ps - ns)
- The integral area of the output pulse is proportional to the bunch charge

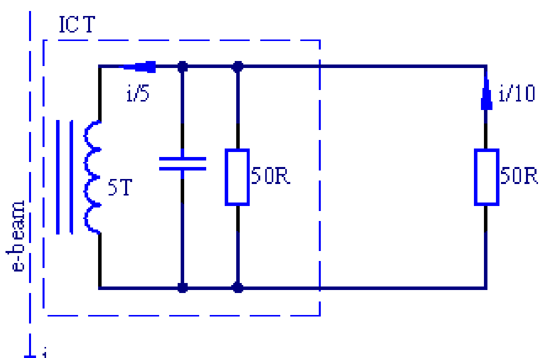


Diagram of ICT

$$V_{out}=\frac{i_{beam}}{5}*\frac{1}{2}*50\Omega$$

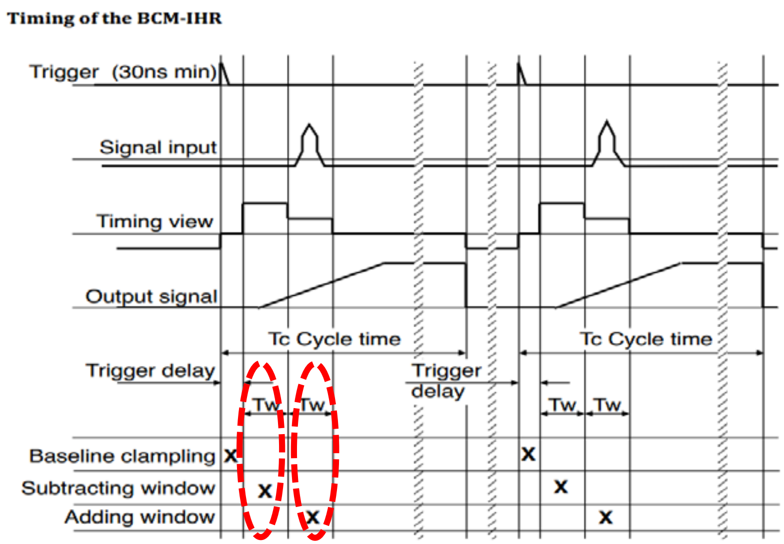
$$Q_{beam}=\int i_{beam}\,dt$$

$$=\int\frac{5*2*V_{out}}{50\Omega}dt$$

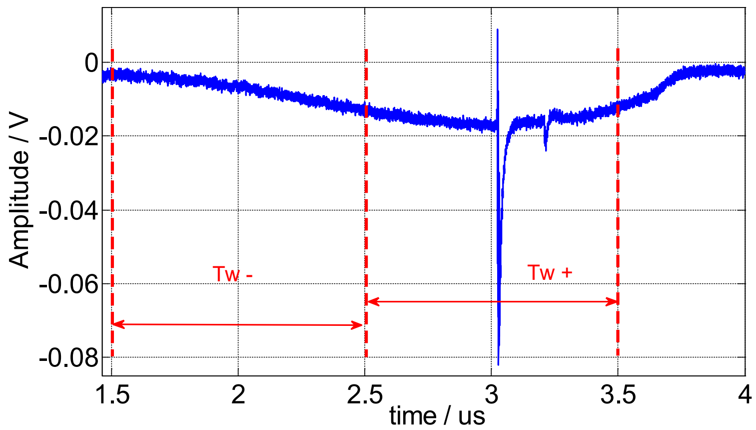
- An analog integrator integrates the output pulse signal of ICT
- Output a level signal proportional to the integral value
- A slow ADC is used to sample and quantify the level signal and calculate the beam charge

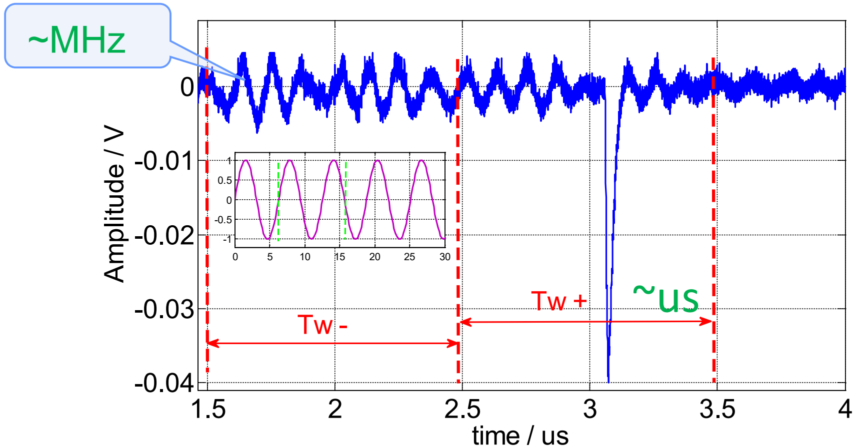
Introduction

BCM-IHR-E signal processing



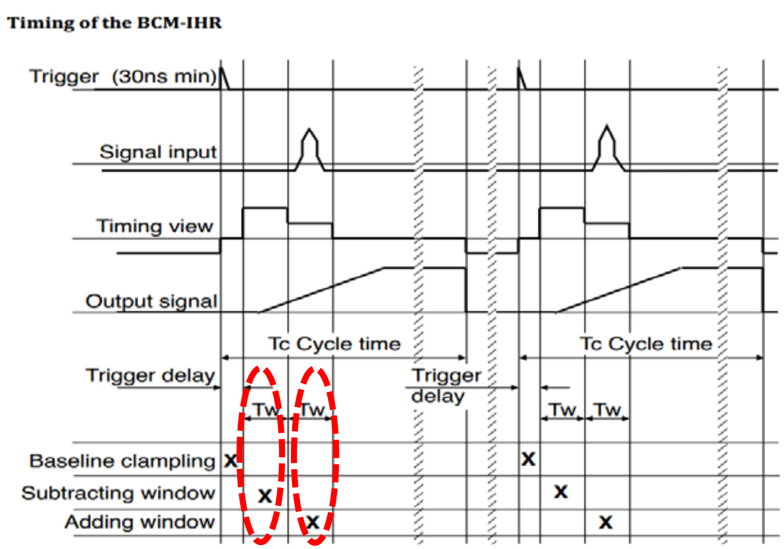
- **Working principle:**
  - The baseline is clamped to set the zero reference
  - One integrates the input noise and baseline offset
  - The other integrates the pulse signal
  - The pulse charge is obtained by summing the two integrators
- **Advantages and disadvantages:**
  - Low requirements for DAQ：～kHz
  - Easy to be interfered by external noise
  - Noise signal will be also integrated in the output results





Introduction

BCM-IHR-E signal processing



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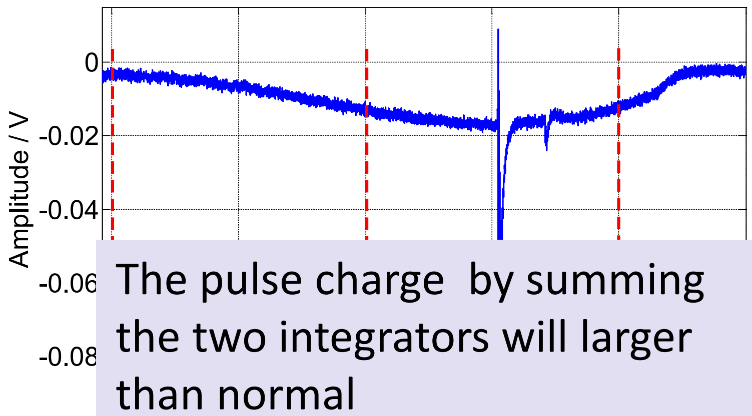
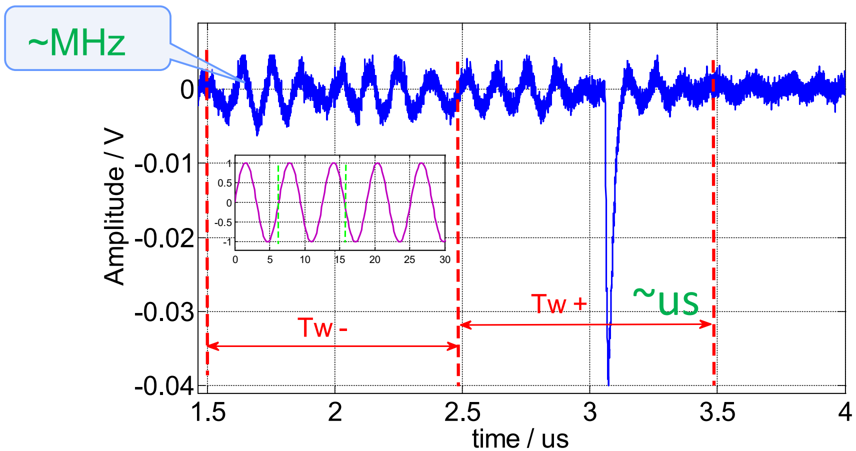
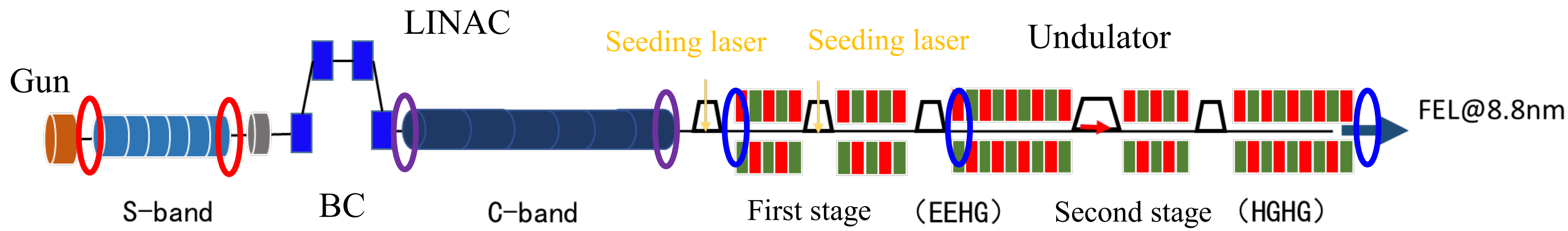
  - Low requirements for DAQ: ~ kHz
  - Easy to be interfered by external noise
  - Noise signal will be also integrated in the output results



The pulse charge by summing the two integrators will larger than normal



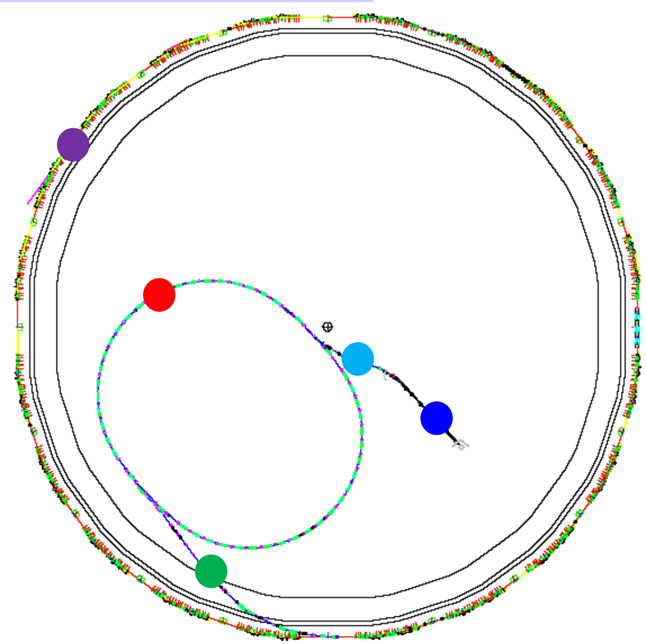
Sensors layout in SXFEL & SSRF



- 2 ICT @ Injector
- 2 ICT @ LINAC
- 3 ICT @ Undulator

- Bunch charge at important nodes
- Calibrate BPMs
- Evaluate transfer efficiency
- As a tool for acceptance of facility

- 1 ICT @ Linac
- 1 ICT @ LTB transfer line
- 1 ICT @ BTS transfer line
- 1 DCCT @ Booster
- 1 DCCT @ Ring

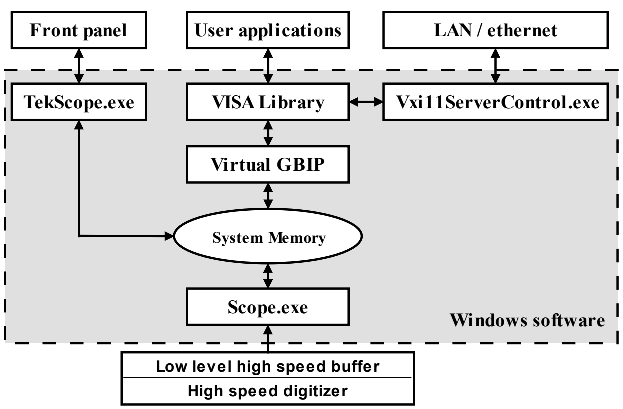


- Transfer efficiency could be fully evaluated with this configuration

Scheme of SXFEL & SSRF

Embedded Soft-IOC

- Bandwidth: 600MHz
- Sampling rate: 5GSA/S
- Resolution: 10 bit



Software diagram of oscilloscope

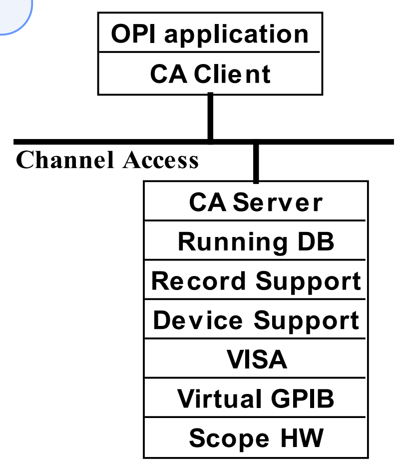


Diagram of embedded IOC

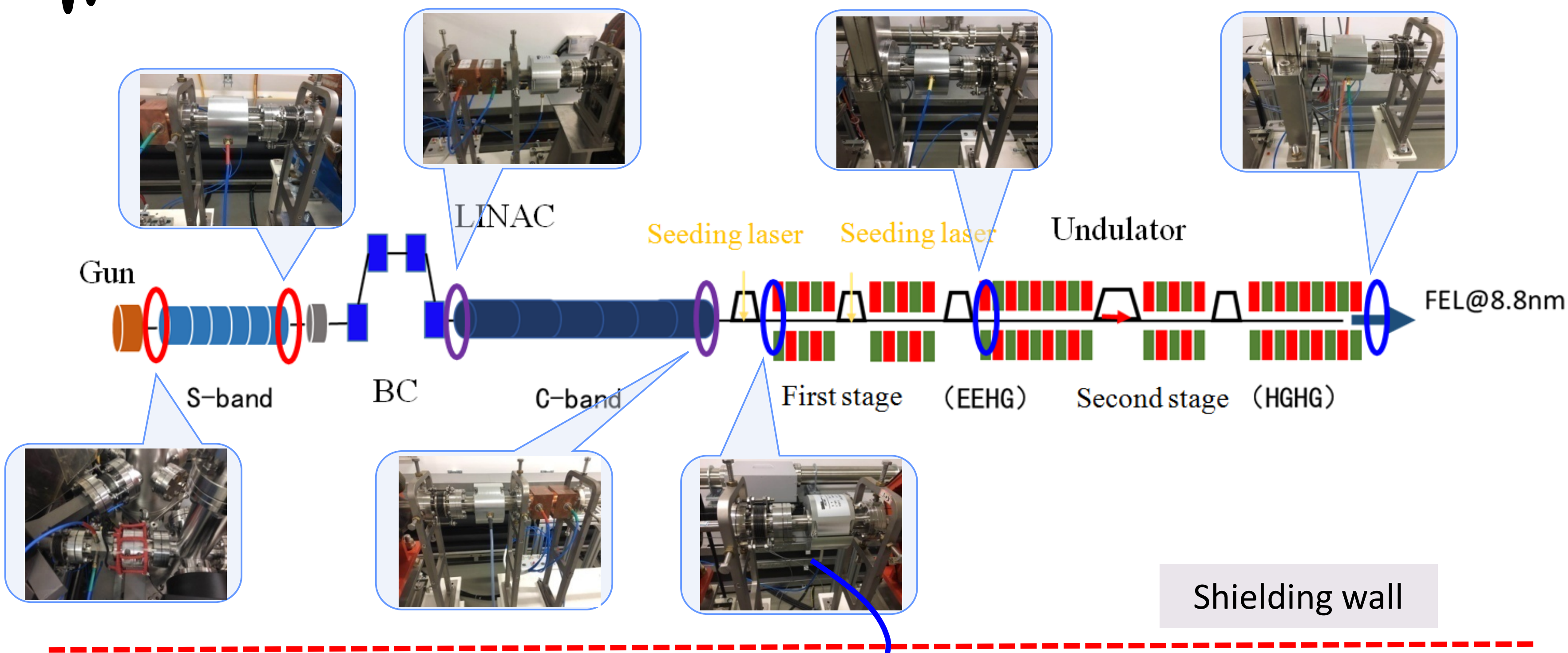
How to reduce the impacts ?

Motivation

Sampling the ICT waveform and try to use digital signal processing algorithm to remove Interfered noise

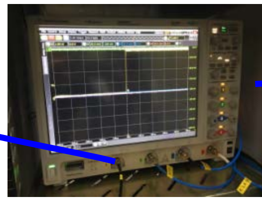
- Digital oscilloscope as the DAQ to quantify the original ICT output waveform
- Embedded IOC is adopted to obtain the original oscilloscope data
- Can be worked well under the data refresh rata of 10 Hz

System setup in SXFEL



	Test facility	User facility
Beam energy	0.84 GeV	1.6 GeV
Bunch charge	~500 pC	~150 pC
Repetition rate	10 Hz	50 Hz
FEL wavelength	8.8 nm	2 nm

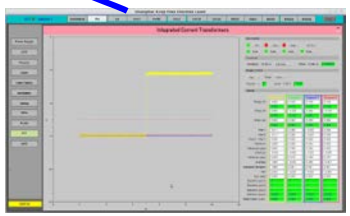
Cable



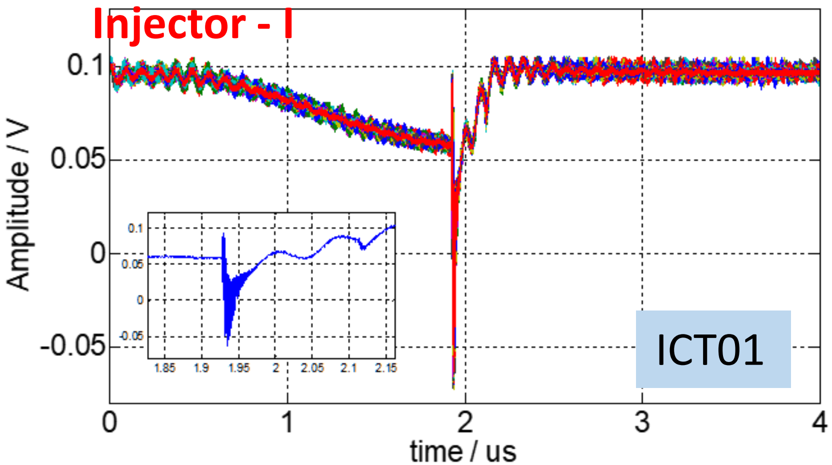
2 oscilloscope embedded Soft-IOC for 7 ICTs

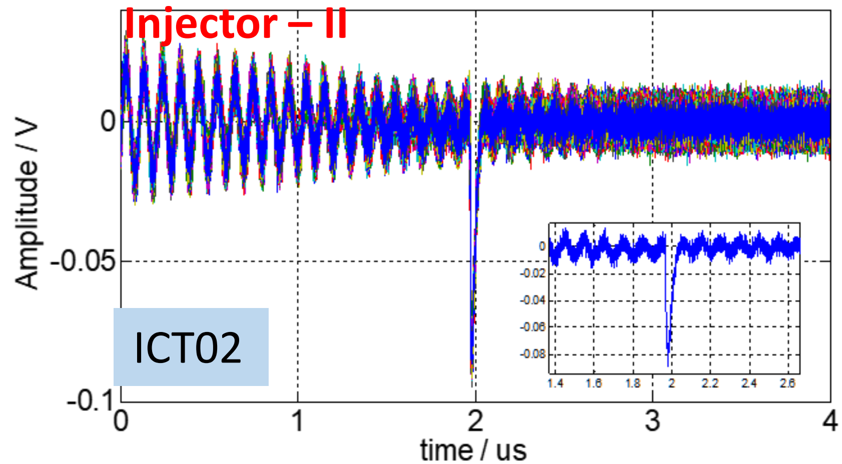
Ethernet

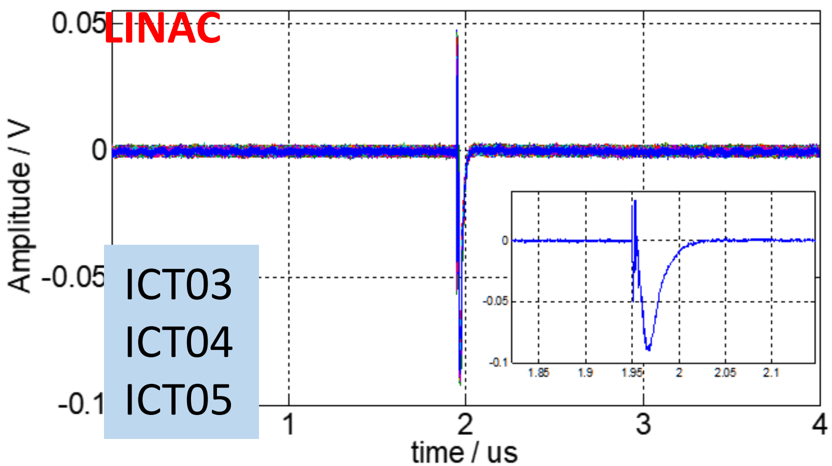
edm panel (Control Room)

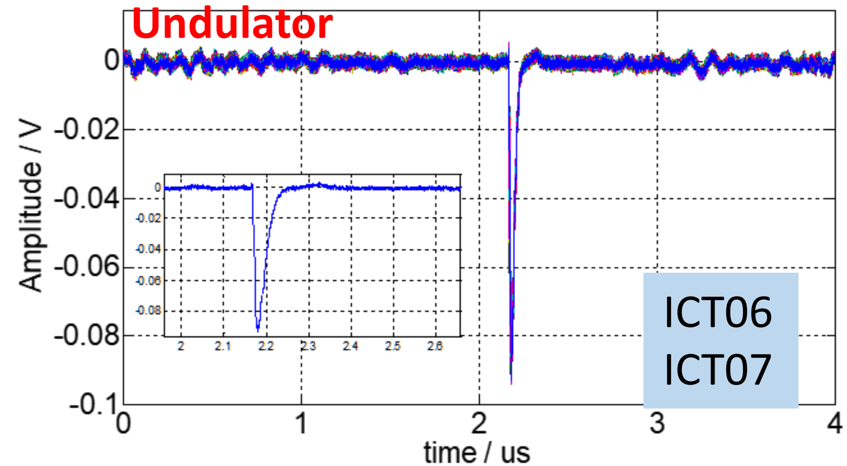


ICT waveform









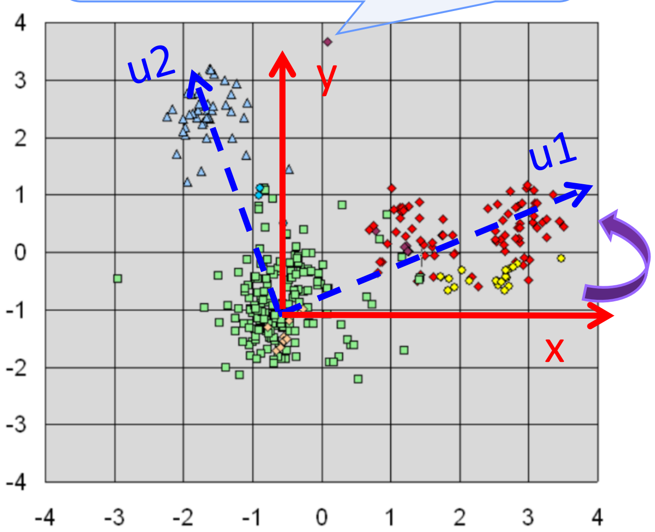
How to process?

Data processing

Principle Components Analysis

■ **PCA** is a statistical procedure that uses an **orthogonal transformation** (coordinate transformation) to convert a set of observations of possibly **correlated variables** into a set of values of **linearly uncorrelated variables**.

Converts related 2D data into 1D linearly uncorrelated data



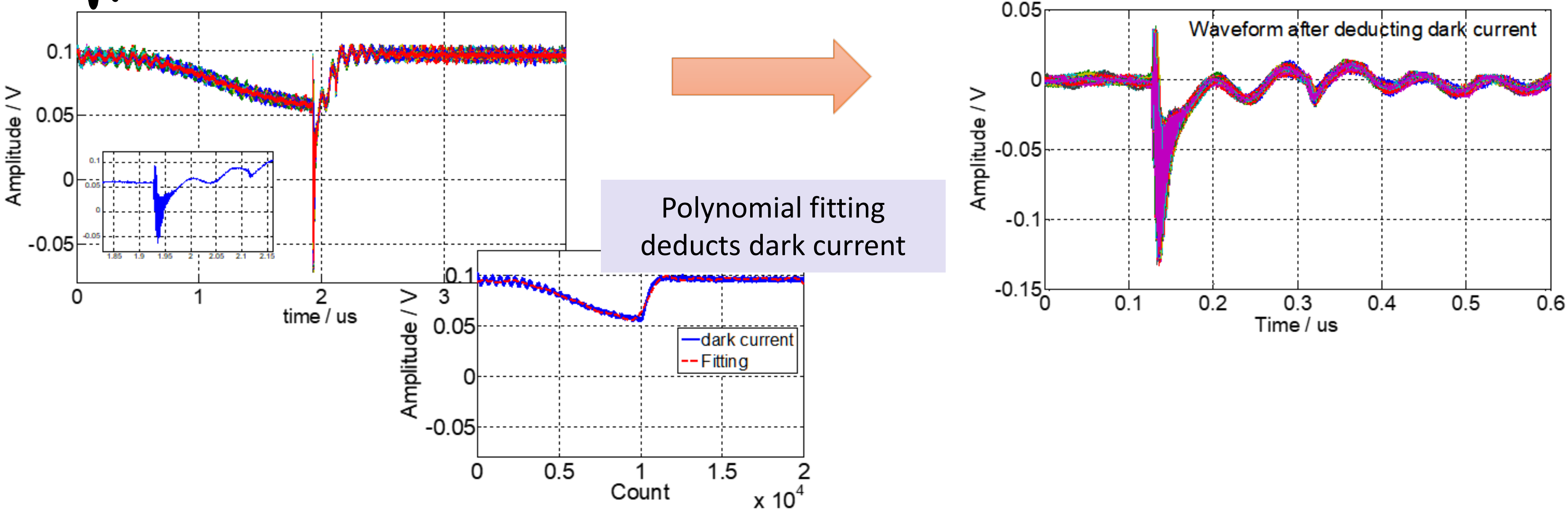
$$V(t) = \Sigma_m C_m V_m(t) + C_{noise} V_{noise}(t)$$

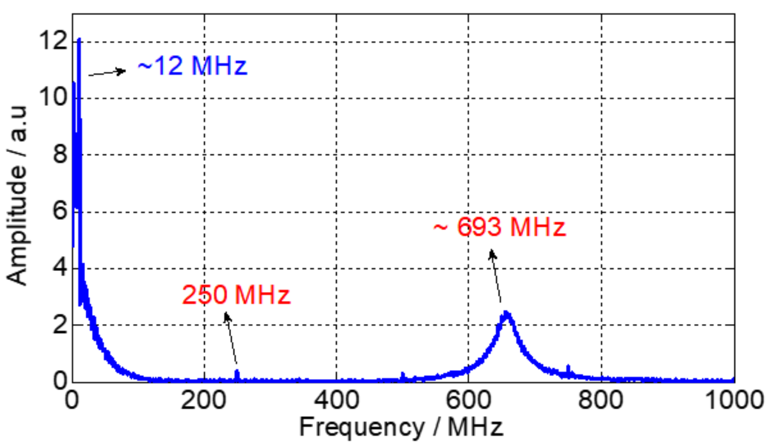
- **Spatial vector**: indicate the variance in the amplitude during the measurements
- **Noise mode**: uncorrelated to the object of study
- **Temporal vector**: time evolution properties (resonant frequency, damping ratio, etc)
- Can be used to determine the physical source of the mode

Need more data samples

The signal can be decomposed into the form of the **sum** of multiple **linearly uncorrelated** variables

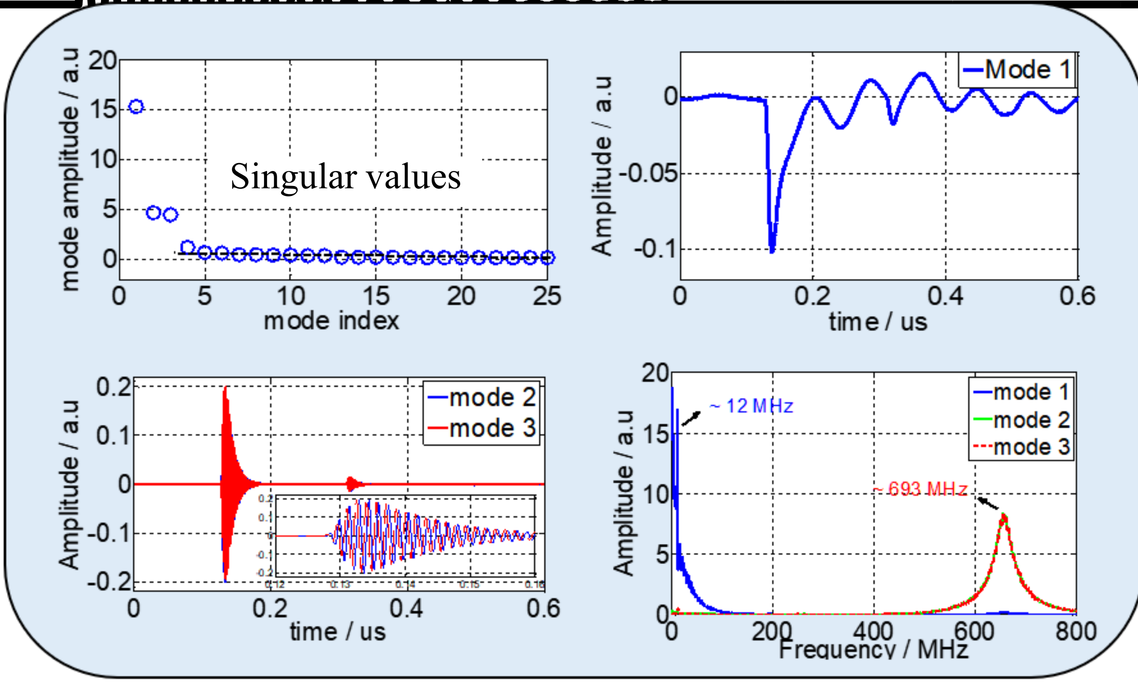
Case 1: ICT in Injector - I



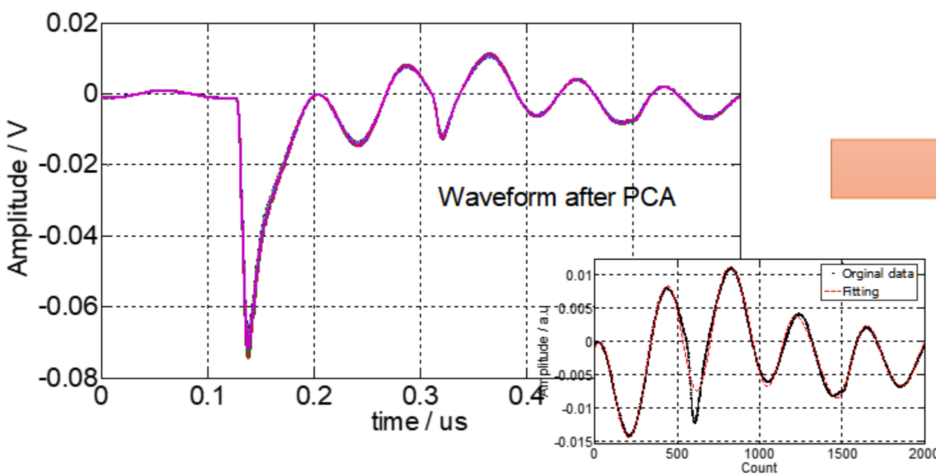


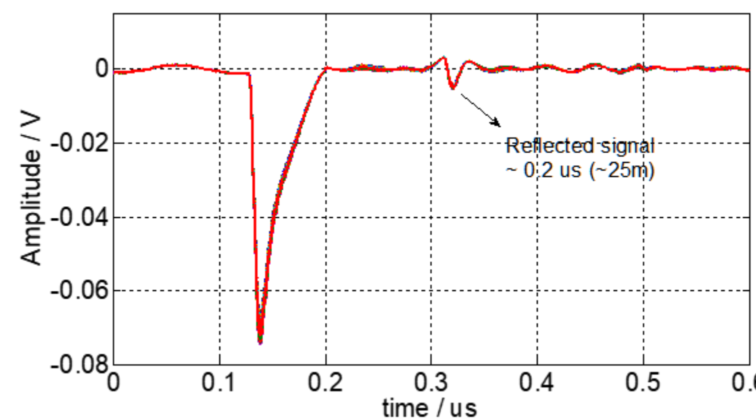
- ICT is interfered by dark current seriously at the outlet of the electron gun
- It will give a wrong result if use the method of analog integration
- Dark current can be obtained by turning off the driver laser and can be removed by **polynomial fitting**
- Disturbed by multiple noise, try to **separate and determine the physical source** of noises

Case 1: ICT in Injector - I



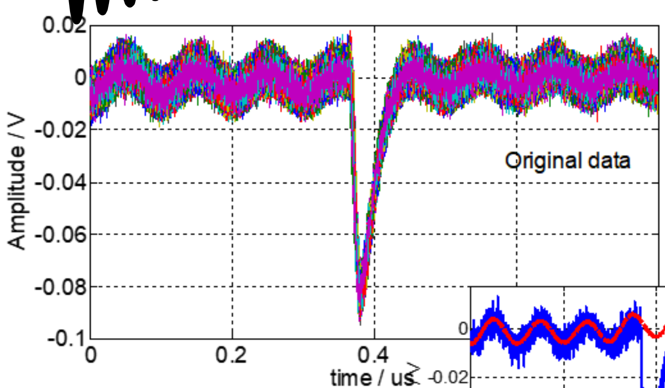
- Three modes higher than noise level
- Mode1 is mainly contributed by ICT
- Mode2 and 3 like the IQ component of a cavity signal
- Physical source has not been determined yet but can provide a direction
- Keep first main mode and convert back to the real space to realize the removal of interference noise

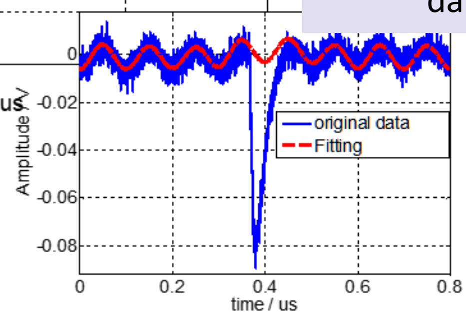




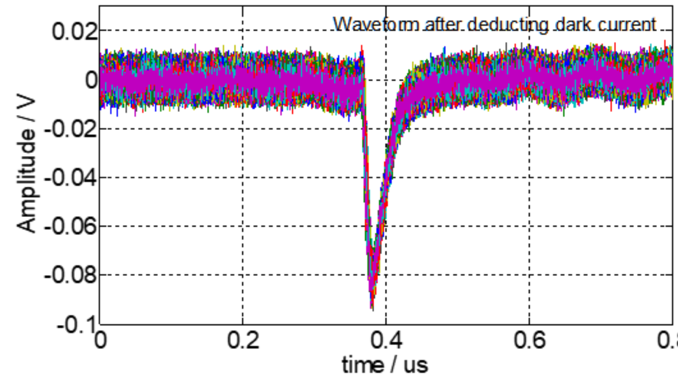
Polynomial fitting deducts low frequency noise

Case 1: ICT in Injector - II



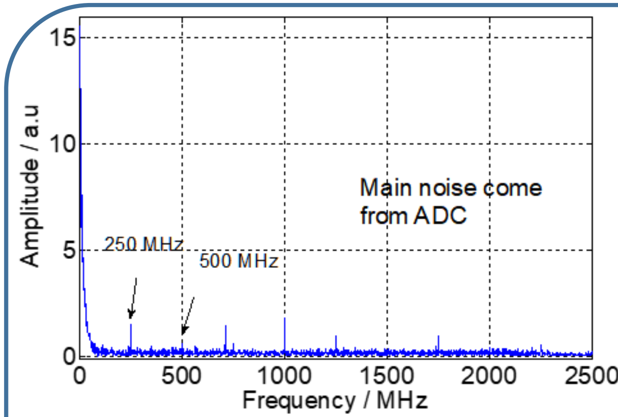


Polynomial fitting deducts dark current

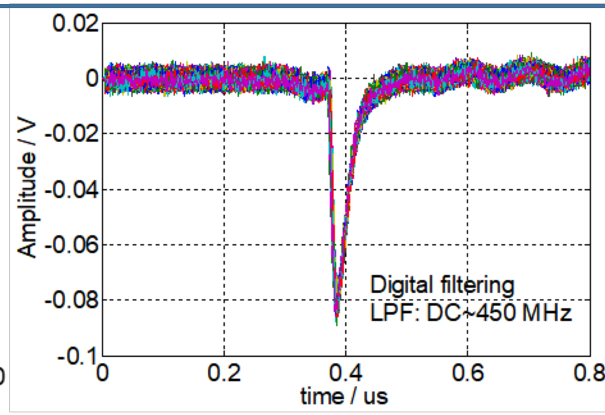


- Interfered by a low frequency signal about 10 MHz
- Can be removed by polynomial fitting
- Main noise come from ADC of oscilloscope
- PCA is more better at improving the quality of signal

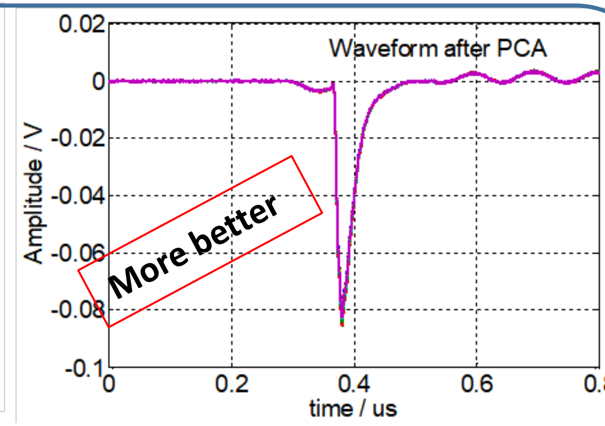
Comparison:



Spectrum after deducts dark current



Waveform after Digital filtering

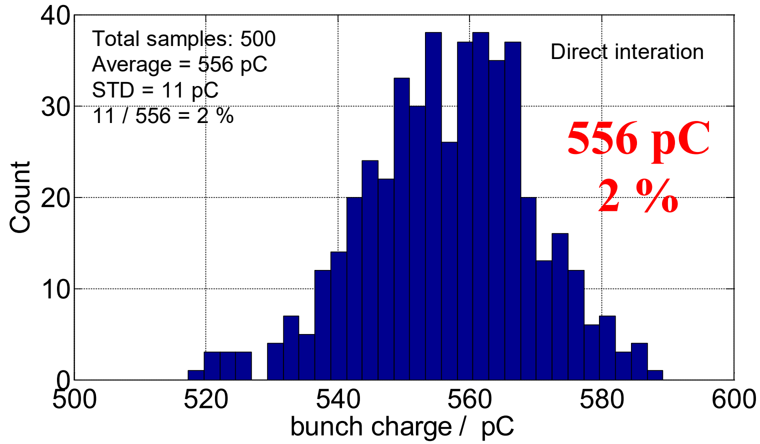


Waveform after PCA

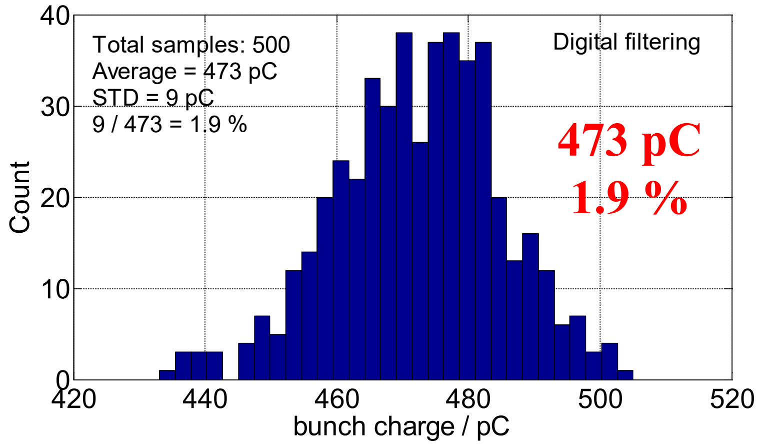
Case 1: ICT in Injector - II

Comparison for three methods

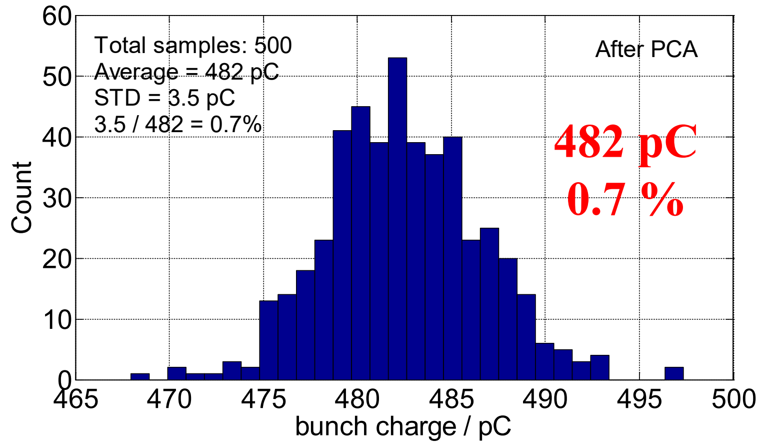
Direct integration



Digital filtering



PCA



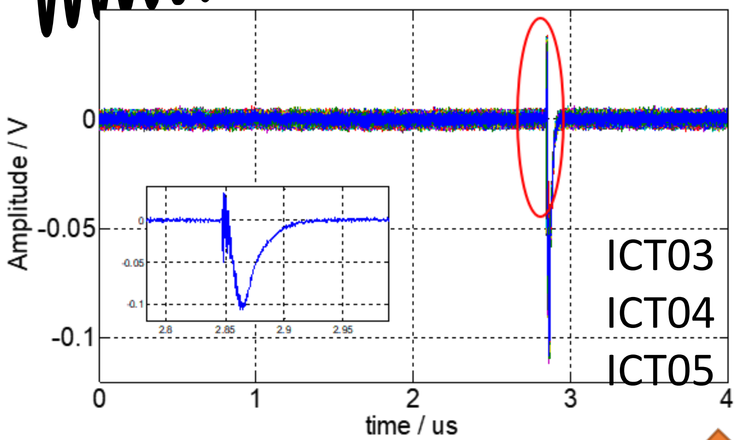
- Direct integration result bigger than others, because the interference signal in integration window is **not an integer number of period**
- Bunch charge resolution was evaluated using two ICTs for **correlation analysis**
- PCA removed a lot of thermal noise, has great benefits for **improving charge resolution**
- This result also illustrates the advantages of processing in the digital domain

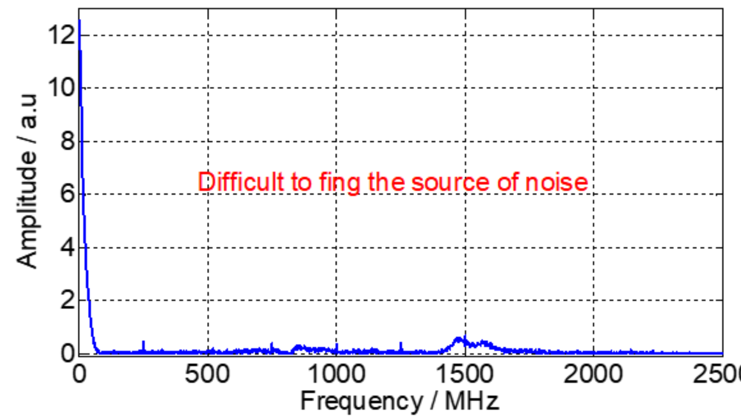
Discussion 1

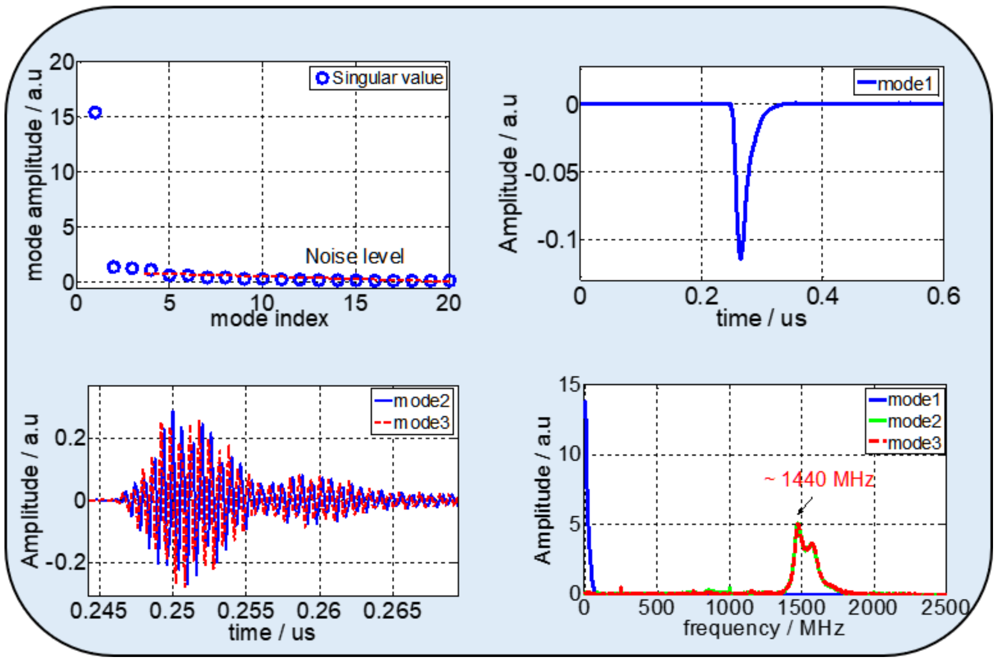
- ICTs located in the injection section are easily to be interfered:
  - For the existence of dark current
    - Come from RF system
    - **In-air ICTs** are purchased and the external shield is designed by ourselves, the **shielding effect may not ideal**
    - Interfered signal about 10 MHz (ICT02) can be shielded by rotating the external shield, this also confirms that the external shield is not ideal

- In-flange ICT will be purchased and do some comparison in SXFEL

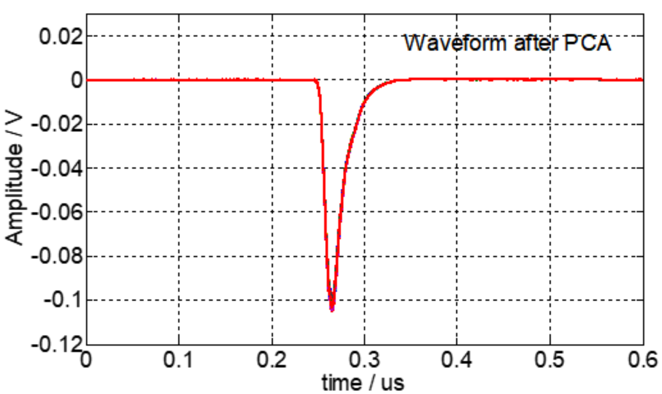
Case 2: ICT in LINAC





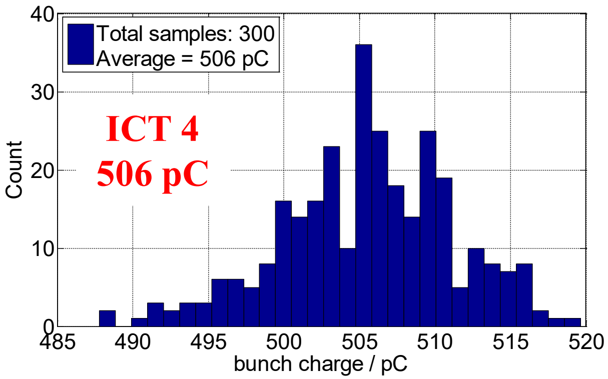


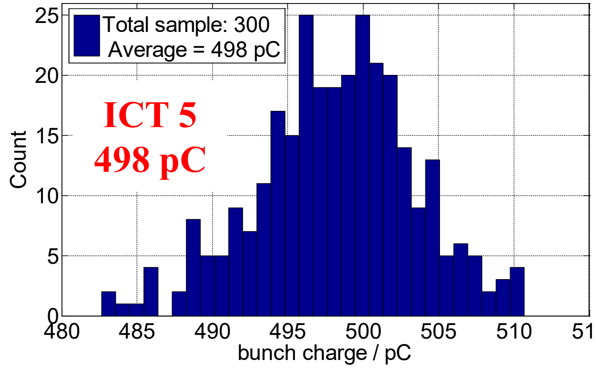
PCA

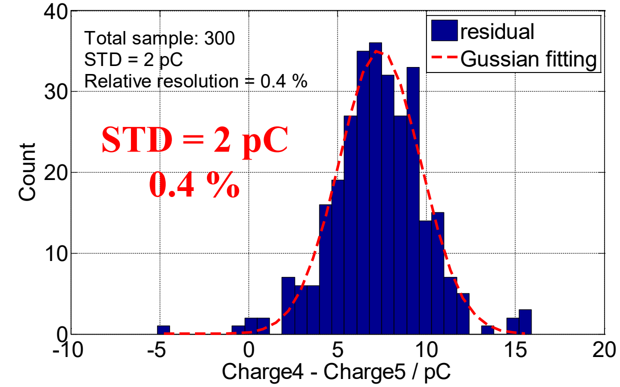


- ICTs in LINAC are mainly interfered by the signal about 1440MHz
- That signal can be separated perfectly

Case 2: ICT in LINAC

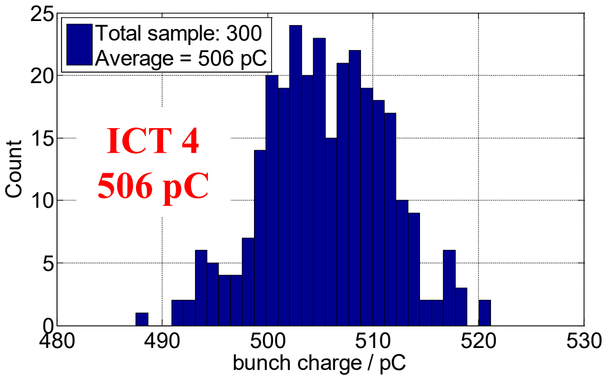


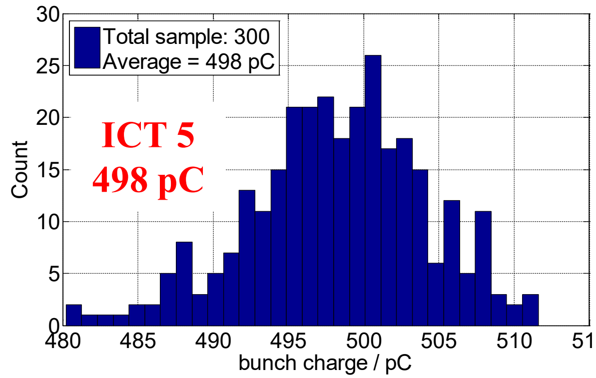


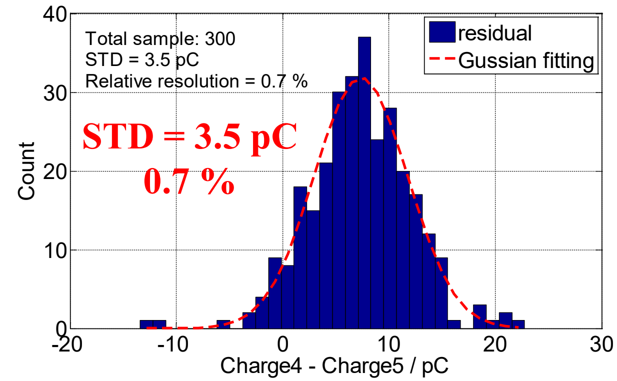


PCA:

- Relative resolution = 0.4 %
- Transfer efficient from LINAC to Undulator about: 498 / 506 = 98.5 %



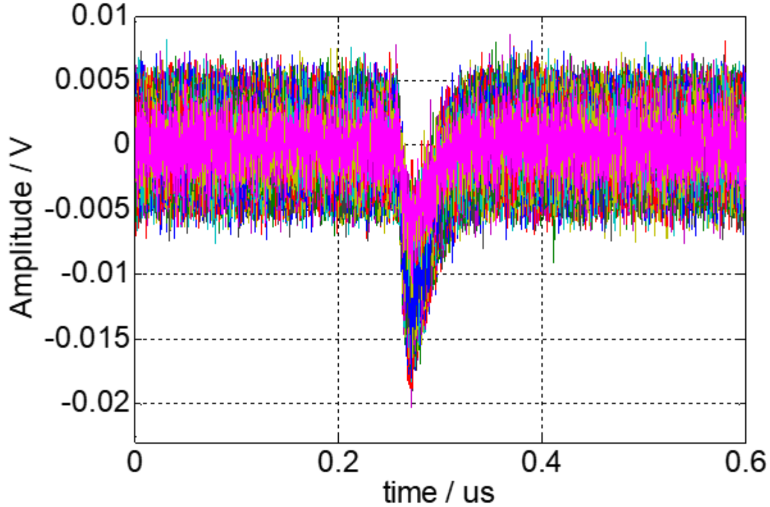


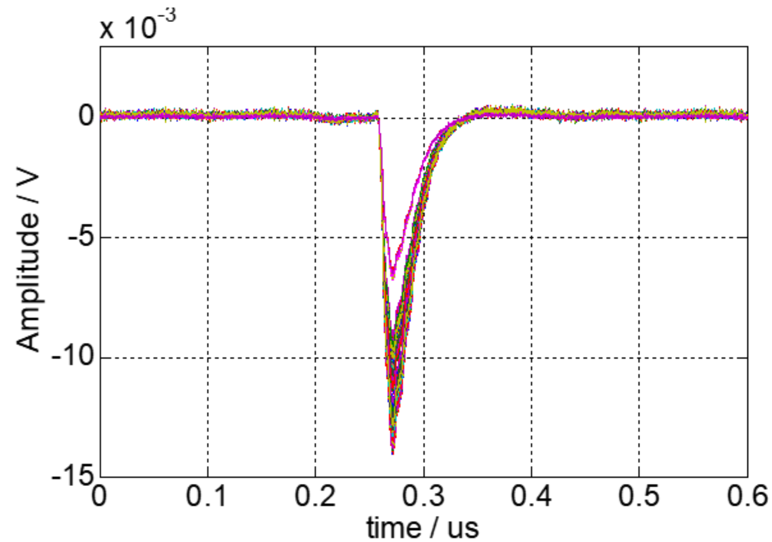


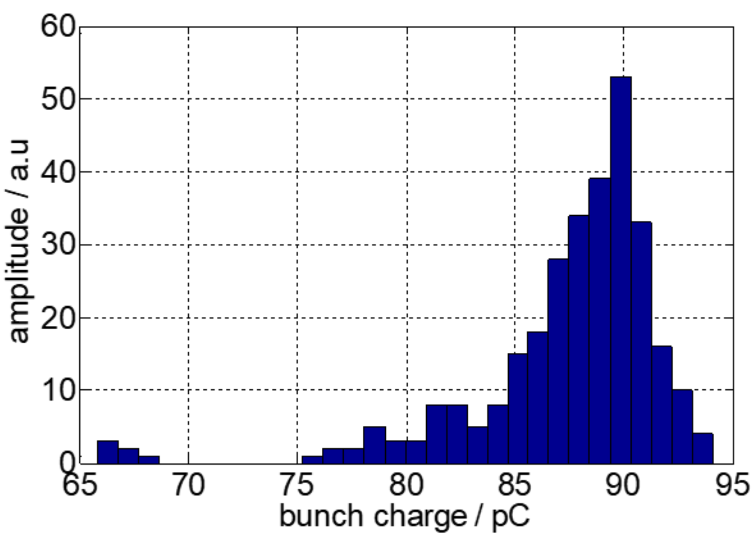
Direct integral:

- Relative resolution = 0.7 %
- Transfer efficient from LINAC to Undulator about: 498 / 506 = 98.5 %

Low charge / Low SNR







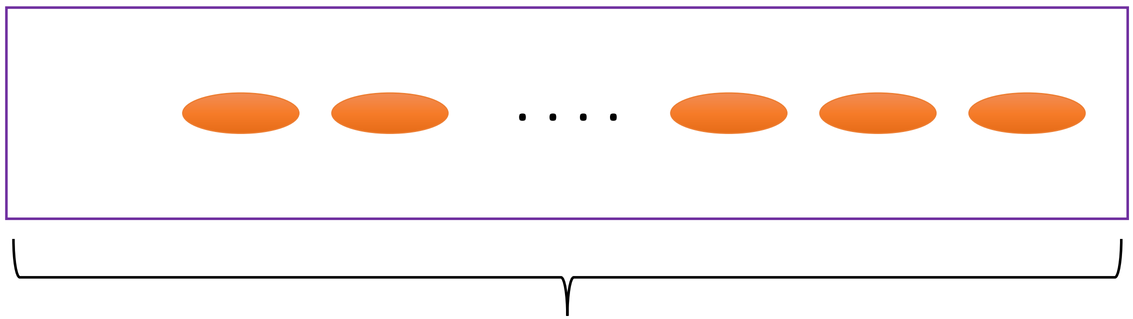
- PCA method has a significant effect on improving signal quality at low SNR
- It will bring more benefits to the SXFEL user facility in the future (bunch charge : ~150 pC)

Summary

- ICT is easily interfered by noise, analog integration to calculate bunch charge may have a large error in some cases
- Digital oscilloscope embedded Soft-IOC to obtain the original ICT data and processed in digital domain was used in SXFEL and SSRF
- ICTs in SXFEL are easily interfered, the possible reason is the shielding effect of the external shield designed by ourselves is not ideal
- PCA method has a good effects on the separation and removal of noise pattern which independent with the charge. It can not only analyze the source of noise but also can achieve higher charge resolution
- The sources of the noises separated by PCA has not been fully confirmed, need to discuss with the FEL physics group
- PCA has a significant effect on improving signal quality at low SNR, It will bring more benefits to the SXFEL user facility in the future (bunch charge : ~150 pC)

Next Work

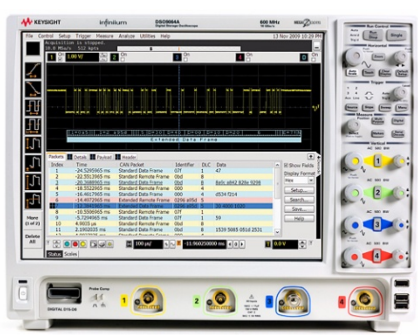
- **In-flange ICT** will be purchased for testing in SXFEL
- Using **higher resolution data acquisition system** to get higher charge resolution
- To realize the **online processing** of PCA method



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

Embedded Soft-IOC

- Bandwidth: 600MHz
- Sampling rate: 5GSA/S
- Resolution: 10 bit



- Bandwidth: 1.2GHz
- Sampling rate: 1GSA/S
- Resolution: 14 bit
- KINTEX7 FPGA

Acknowledge

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Thanks for your attention

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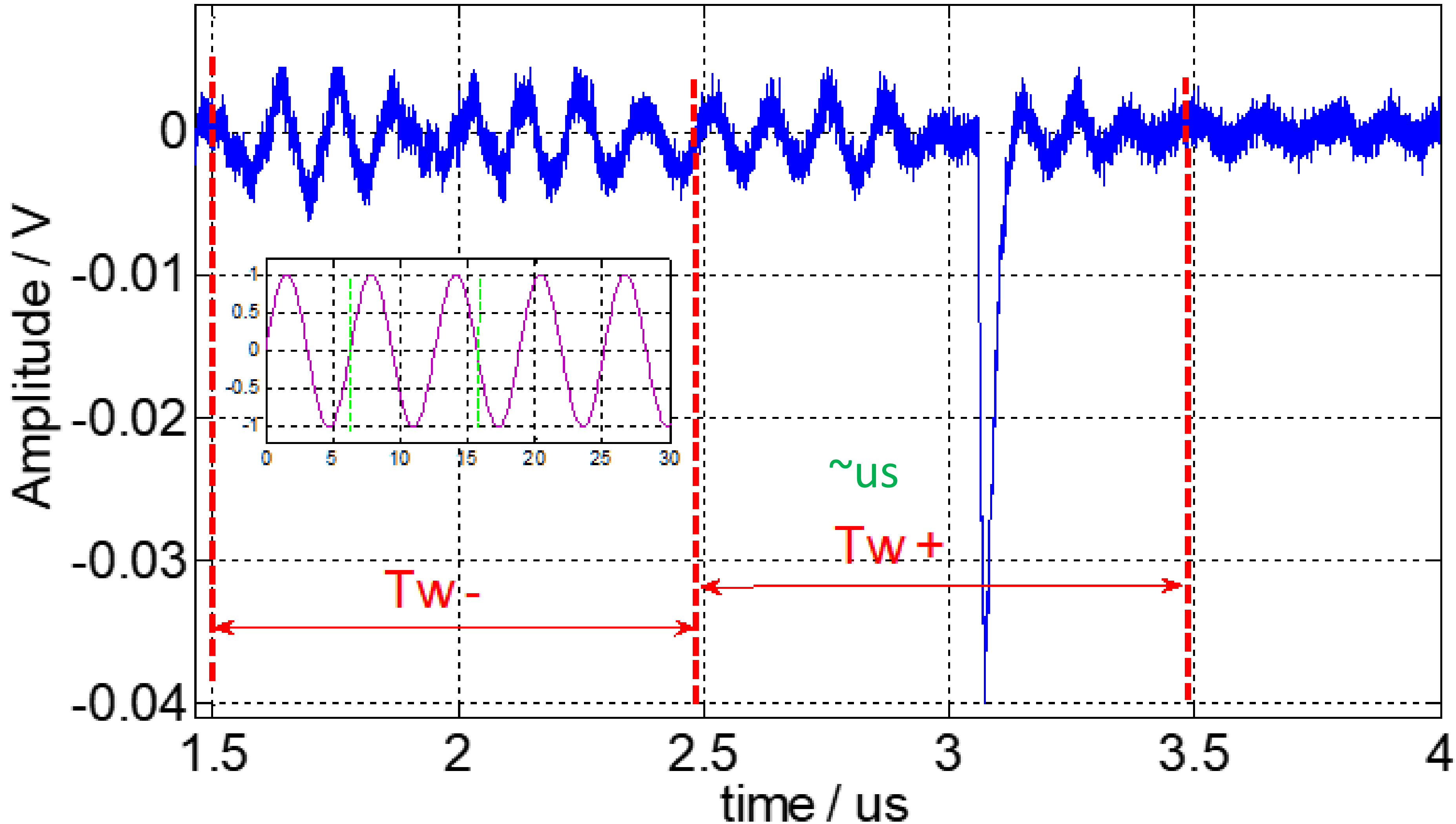
Shanghai Institute of Applied Physics, Chinese Academy of Sciences



0
-0.01
-0.02
-0.03
-0.04
Amplitude / V
1.5
2
2.5
3
3.5
4
time / us
~us
Tw-
Tw +
1
0.5
0
-0.5
-1
0
5
10
15
20
25
30