The removal of interference noise of ICT using PCA method

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Outline

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

- 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
## Methods of measuring bunch charge

<table>
<thead>
<tr>
<th>Methods</th>
<th>Faraday cup</th>
<th>DCCT</th>
<th>ICT</th>
<th>BPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
<td>Intercepting low current absolute measure</td>
<td>Non-intercepting DC current absolute measure</td>
<td>Non-intercepting Ultrafast short pulse absolute measure</td>
<td>Non-intercepting High resolution Relative measure</td>
</tr>
<tr>
<td>Measured parameters</td>
<td>Pulse current Long/short pulse waveform</td>
<td>Beam lifetime DC current</td>
<td>Impulse charge</td>
<td>Pulse current Bunch by bunch current DC current</td>
</tr>
<tr>
<td>Time response</td>
<td>ns ~ us</td>
<td>DC ~ ms</td>
<td>ps ~ ns</td>
<td></td>
</tr>
<tr>
<td>Applications</td>
<td>storage ring LINAC/transfer line</td>
<td>storage ring Booster</td>
<td>LINAC transfer line</td>
<td>storage ring LINAC/transfer line</td>
</tr>
</tbody>
</table>

*Image 1: Example of a Faraday cup.*
*Image 2: Example of a DC current transformer.*
*Image 3: Example of an ICT.*
*Image 4: Example of a BPM.*
Typical usage

- 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

- 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

\[
V_{out} = \frac{i_{beam}}{5} \times \frac{1}{2} \times 50\Omega
\]

\[
Q_{beam} = \int i_{beam} \, dt
\]

\[
= \int \frac{5 \times 2 \times V_{out}}{50\Omega} \, dt
\]

Diagram of ICT
**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: \( \sim \) kHz
- Easy to be interfered by external noise
- Noise signal will be also integrated in the output results

\[ \text{Tw} \pm \sim \text{MHz} \]
**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

The pulse charge by summing the two integrators will larger than normal
Sensors layout in SXFEL & SSRF

- Gun
- LINAC
- First stage (EEHG)
- Second stage (HGHG)
- Seeding laser
- Seeding laser
- Undulator
- FEL@8.8nm

0 2 ICT @ Injector
0 2 ICT @ LINAC
0 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

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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 rate of 10 Hz

Software diagram of oscilloscope

Diagram of embedded IOC

- Bandwidth: 600MHz
- Sampling rate: 5GSA/S
- Resolution: 10 bit
System setup in SXFEL

<table>
<thead>
<tr>
<th>Test facility</th>
<th>User facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>0.84 GeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>~500 pC</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>FEL wavelength</td>
<td>8.8 nm</td>
</tr>
</tbody>
</table>
ICT waveform

**How to process?**
Data processing
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.

\[ V(t) = \sum_m C_m V_m(t) + C_{\text{noise}} V_{\text{noise}}(t) \]

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

The signal can be decomposed into the form of the sum of multiple linearly uncorrelated variables.
Case 1: ICT in Injector

- 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.

**Polynomial fitting deducts dark current**
Case 1: ICT in Injector - 1

- Three modes higher than noise level
- Mode 1 is mainly contributed by ICT
- Mode 2 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

- **Total samples**: 500
- **Average**: 556 pC
- **STD**: 11 pC

\[
\frac{11}{556} = 2\% 
\]

**After PCA**

- **Total samples**: 500
- **Average**: 482 pC
- **STD**: 3.5 pC

\[
\frac{3.5}{482} = 0.7\% 
\]

**Digital filtering**

- **Total samples**: 500
- **Average**: 473 pC
- **STD**: 9 pC

\[
\frac{9}{473} = 1.9\% 
\]

### 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
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

- 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%
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).
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

**XILINX**
- Bandwidth: 1.2GHz
- Sampling rate: 1GSA/S
- Resolution: 14 bit
- KINTEX7 FPGA
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Thanks for your attention

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