A new method to measure fast beam transverse size and position in storage ring

Chaocai Cheng
Beam Instrumentation Group
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中国科学技术大学
国家同步辐射实验室
National Synchrotron Radiation Laboratory, University of Science and Technology of China

Outline

- Logarithm processing technique
- Scheme of low speed mode based on Libera Photon
- Scheme of high speed mode based on oscilloscope
- More steps to be continued

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Why we propose this method?

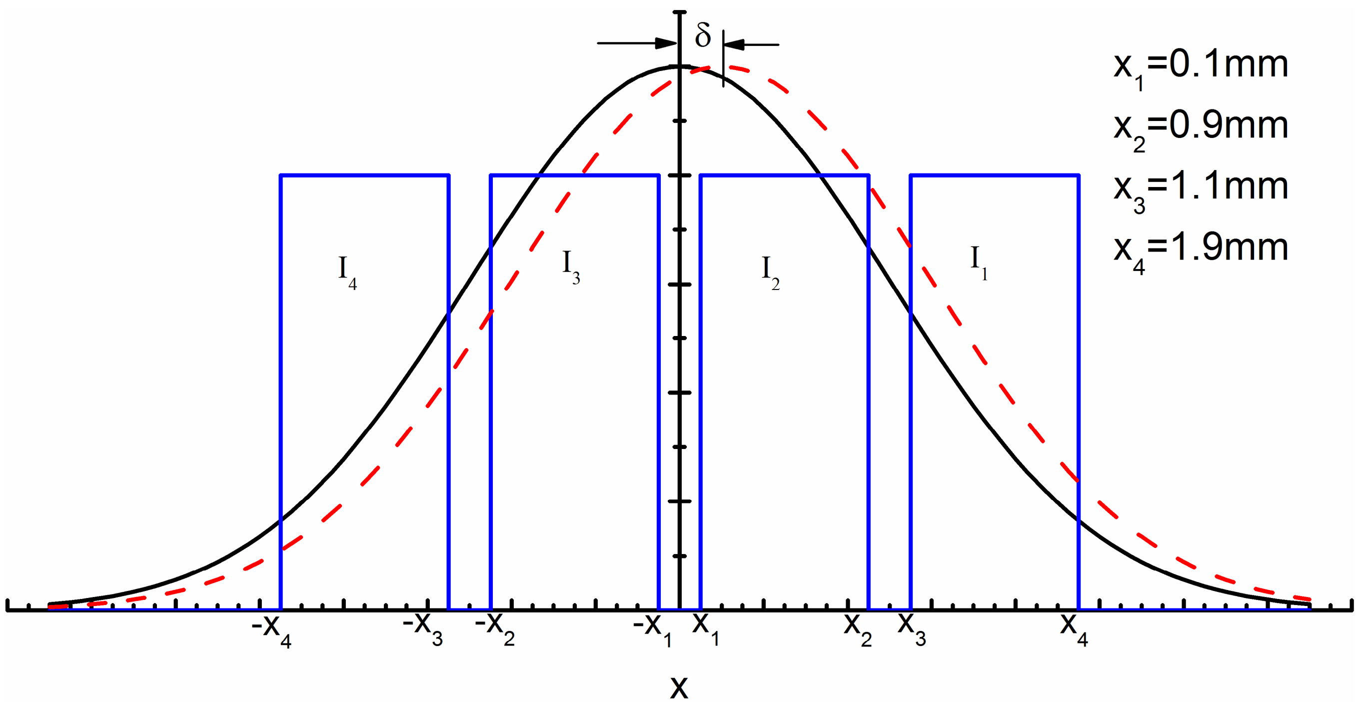
- Improving performance and commissioning instability of the storage ring, it's necessary to study the beam dynamics, beam-beam interaction, etc.
- General method is Gaussian fitting which needs multiple channels to be sampled in parallel. As a result, costs and complexity are hugely increased.
- The method needs only four electrode signals from an MAPMT to extract beam profile.

Logarithm processing algorithm

According to particle accelerator physics, we assume synchrotron light intensity distribution function as:

$$\Phi(x) = \Phi_0 e^{-\frac{(x-\delta)^2}{2\sigma^2}}$$

Based on the assumption of Gaussian distribution, we can get the synchrotron light distribution at MAPMT.



Ideal case

Photocurrent from four channels can be expressed by the subtraction of two error functions.

$$\begin{cases} I_1 = \int_{x_3}^{x_4} \Phi(x)dx = I_0\left[erf(\frac{x_4-\delta}{\sqrt{2}\sigma}) - erf(\frac{x_3-\delta}{\sqrt{2}\sigma}) \right] \\ I_2 = \int_{x_1}^{x_2} \Phi(x)dx = I_0\left[erf(\frac{x_2-\delta}{\sqrt{2}\sigma}) - erf(\frac{x_1-\delta}{\sqrt{2}\sigma}) \right] \\ I_3 = \int_{-x_2}^{-x_1} \Phi(x)dx = I_0\left[erf(\frac{-x_1-\delta}{\sqrt{2}\sigma}) - erf(\frac{-x_2-\delta}{\sqrt{2}\sigma}) \right] \\ I_4 = \int_{-x_4}^{-x_3} \Phi(x)dx = I_0\left[erf(\frac{-x_3-\delta}{\sqrt{2}\sigma}) - erf(\frac{-x_4-\delta}{\sqrt{2}\sigma}) \right] \end{cases}$$

$$\Downarrow$$

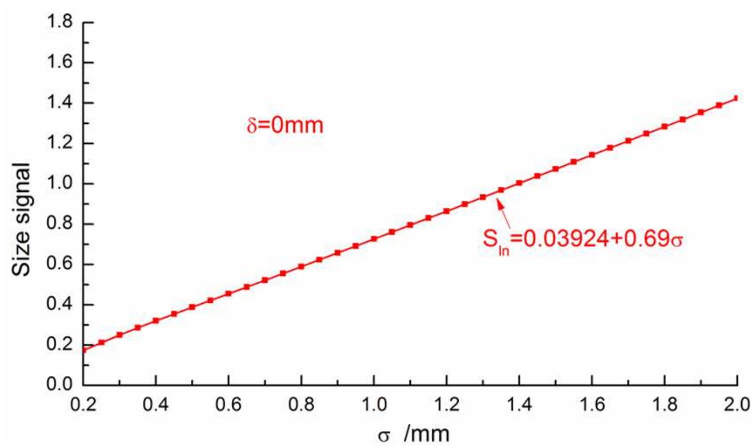
In ideal condition when the four continuous channel electrodes have the same response characteristic.

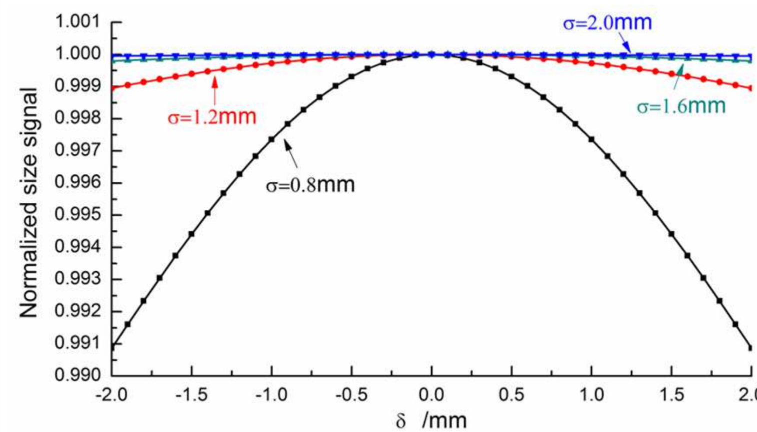
$$\begin{cases} S_{\ln}(\sigma,\delta) = \left(\frac{1}{\ln(I_2)+\ln(I_3)-\ln(I_1)-\ln(I_4)} \right)^{1/2} = \left(\ln\frac{I_2 I_3}{I_1 I_4} \right)^{-1/2} \\ P_{\ln}(\sigma,\delta) = \frac{\ln(I_1)+\ln(I_2)-\ln(I_3)-\ln(I_4)}{\ln(I_2)+\ln(I_3)-\ln(I_1)-\ln(I_4)} = \frac{\ln\frac{I_1 I_2}{I_3 I_4}}{\ln\frac{I_2 I_3}{I_1 I_4}} \end{cases}$$

Ideal case

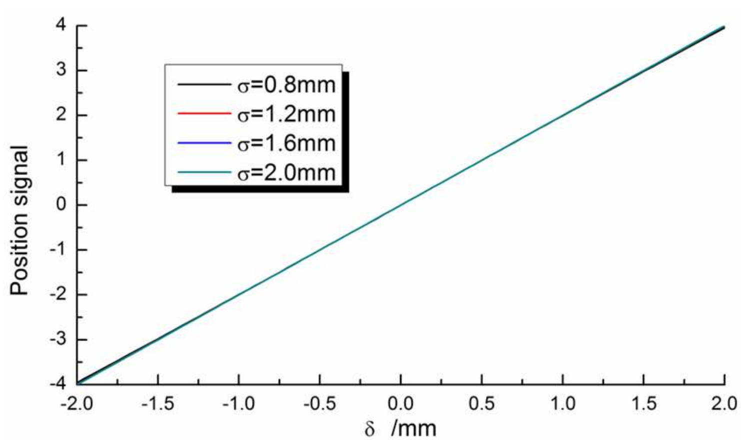
When δ=0mm and σ=0.2-2mm, $S_{ln}(\sigma)=0.03924+0.69\sigma$.

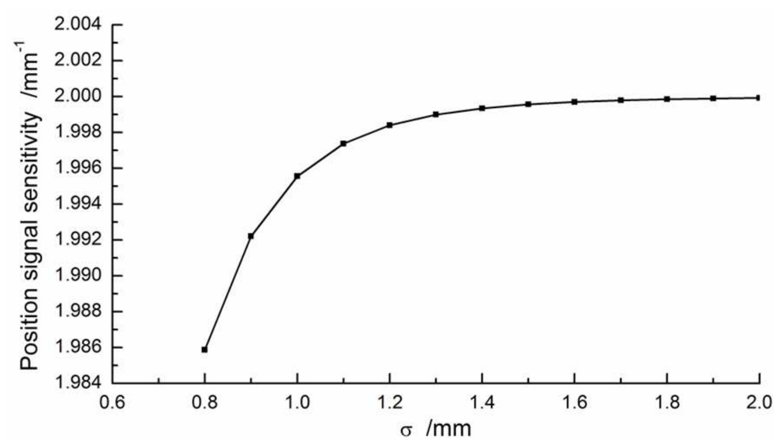
When σ=0.8-2mm, position δ has an effect on normalized ideal size signal within 1%.





When σ=0.8-2mm, position signal has a good linear relation with position, and size has an impact on position signal sensitivity within 1%.





Non-ideal case

Given the channel inconsistency, we introduce the channel gain factor g_i(i=0,1,2,3)

$$\begin{cases} \hat{S}_{\ln}(\sigma,\delta)=\left(\ln\dfrac{\hat{I}_2\hat{I}_3}{\hat{I}_1\hat{I}_4}\right)^{-1/2}=\left(\ln\dfrac{g_2g_3}{g_1g_4}+\ln\dfrac{I_2I_3}{I_1I_4}\right)^{-1/2} \\ \hat{P}_{\ln}(\sigma,\delta)=\dfrac{\ln\dfrac{\hat{I}_1\hat{I}_2}{\hat{I}_3\hat{I}_4}}{\ln\dfrac{\hat{I}_2\hat{I}_3}{\hat{I}_1\hat{I}_4}}=\dfrac{\ln\dfrac{g_1g_2}{g_3g_4}+\ln\dfrac{I_1I_2}{I_3I_4}}{\ln\dfrac{g_2g_3}{g_1g_4}+\ln\dfrac{I_2I_3}{I_1I_4}} \end{cases}$$

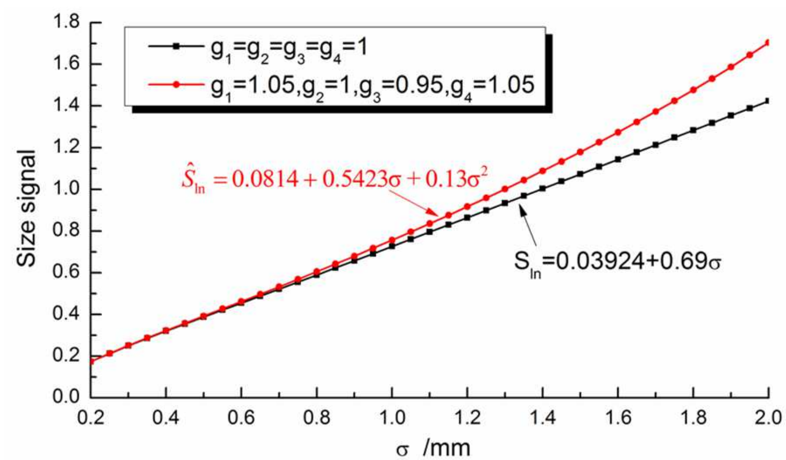
We define $d_s=\ln\dfrac{g_2g_3}{g_1g_4}, d_p=\ln\dfrac{g_1g_2}{g_3g_4}$ And the approximation $S_{\ln}(\sigma,\delta)\approx S_{\ln}(\sigma), P_{\ln}(\sigma,\delta)\approx P_{\ln}(\delta)$

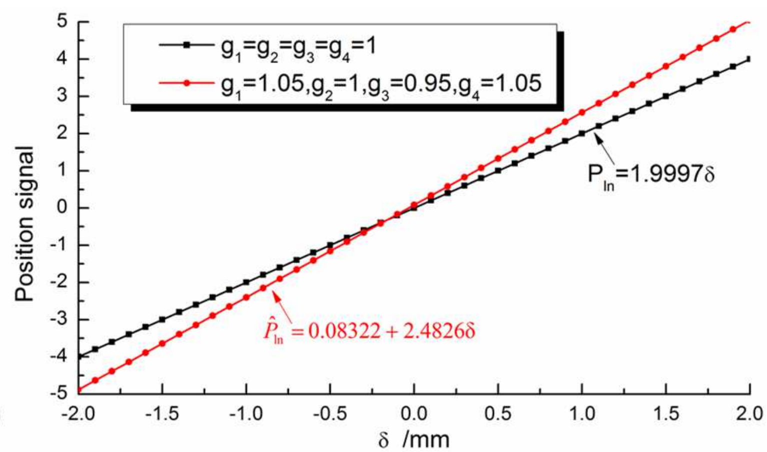
Then we can get
$$\begin{cases} \hat{S}_{\ln}(\sigma,\delta)\approx S_{\ln}(\sigma)\left[1+\tilde{d}_sS^2{}_{\ln}(\sigma)\right]^{-1/2} \\ \hat{P}_{\ln}(\sigma,\delta)\approx P_{\ln}(\delta)\left[1+\tilde{d}_sS^2{}_{\ln}(\sigma)\right]^{-1}+\tilde{d}_pS^2{}_{\ln}(\sigma)\left[1+\tilde{d}_sS^2{}_{\ln}(\sigma)\right]^{-1} \end{cases}$$

Modified size and position signal can be expressed as
$$\tilde{S}_{\ln}(\sigma,\delta)=\left(\ln\dfrac{\hat{I}_2\hat{I}_3}{\hat{I}_1\hat{I}_4}-\tilde{d}_s\right)^{-1/2},\quad \tilde{P}_{\ln}(\sigma,\delta)=\dfrac{\ln\dfrac{\hat{I}_1\hat{I}_2}{\hat{I}_3\hat{I}_4}-\tilde{d}_p}{\ln\dfrac{\hat{I}_2\hat{I}_3}{\hat{I}_1\hat{I}_4}-\tilde{d}_s}$$

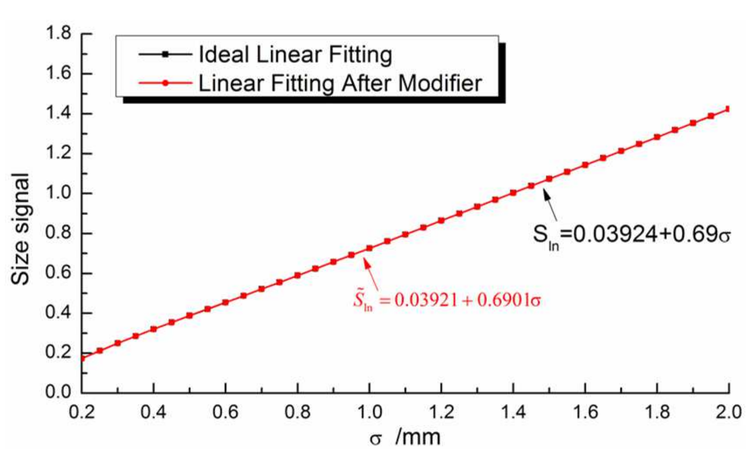
Example

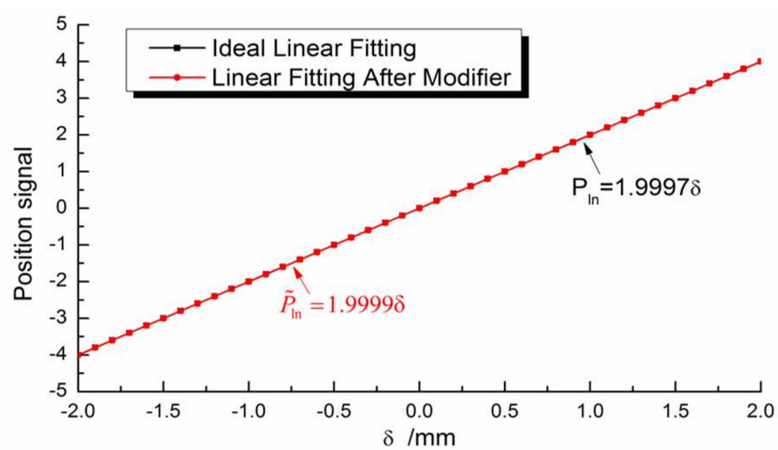
We assume g_1=1.05, g_2=1, g_3=0.95, g_4=1.05, then $\tilde{d}_s$=-0.1489, $\tilde{d}_p$ =0.05129.
Size signal presents huge non-linearity with beam size σ but position signal has a good linear relation with position even there exists channel difference.





After being revised, modified size and position signals are almost consistent with theoretical simulation result.





Layout on the optical bench

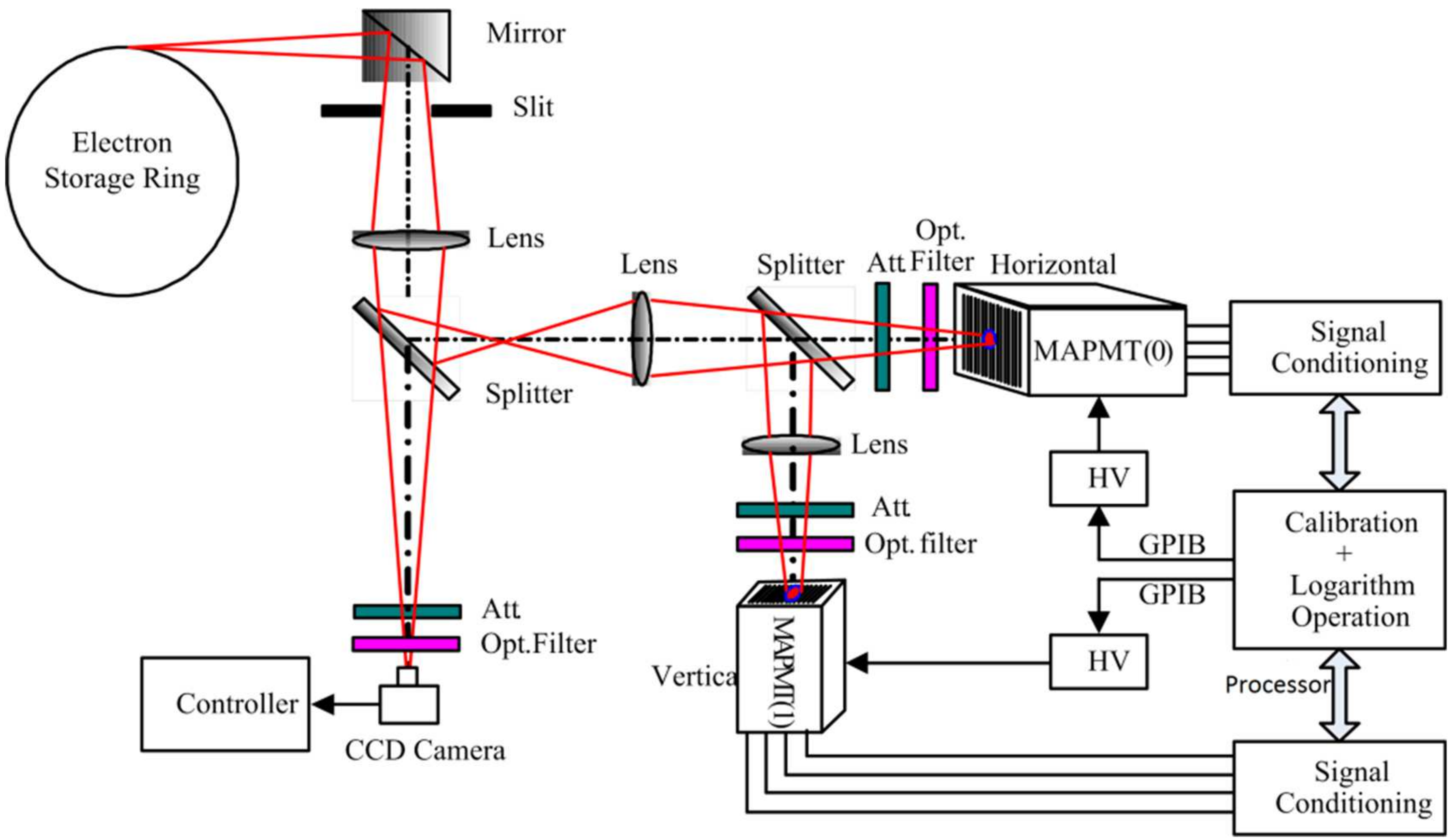
HLS II storage parameters

Energy	800MeV
Circumference	66.13m
RF frequency	204MHz
Harmonic numbers	45
Revolution frequency / Period	4.534MHz/220ns
Transverse tunes (hor. / ver.)	4.44/2.36
Emittance	36nm.rad
B8 source point σ_x/σ_y	225μm/52.6~115μm

The synchrotron light beam size at the beam diagnostic beamline is 225μm and 52.6-115μm in horizontal and vertical direction in consideration of different coupling factor with 1% and 5%.

At the moment, synchronous light from B8 source point has four applications. One is used for Streak camera, one for CCD camera and other two for MAPMTs. The two MAPMTs are installed horizontally and vertically respectively to measure transverse beam profile in both directions.

Beam size at the image of horizontal MAPMT is amplified by ×6 times and vertical MAPMT by ×12 times.



HV is supplied by PS350 controlled by GPIB interface. They can be sampled by high-speed data acquisition device such as oscilloscope or dedicated digital signal processor. Or photocurrents can be directly sampled by current signal acquisition device such as multimeter and Libera Photon.

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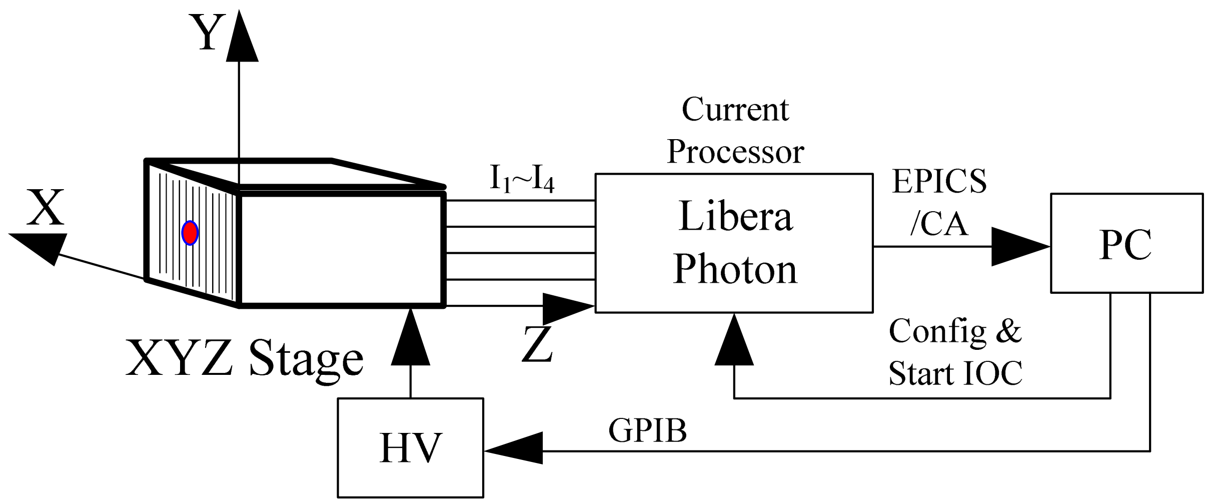
Scheme of low speed mode

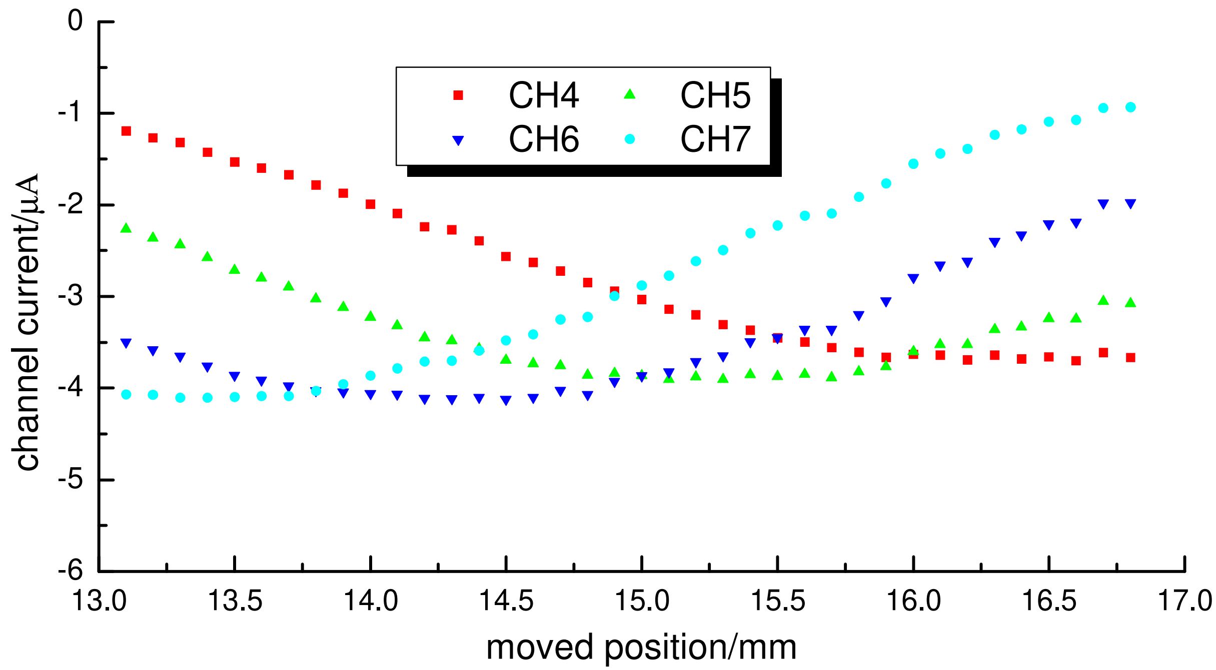
Two MAPMTs are placed on 3-D adjustment station.



Four channel photocurrent signals are measured by Libera Photon and then sent to remote PC by EPICS/CA protocol.

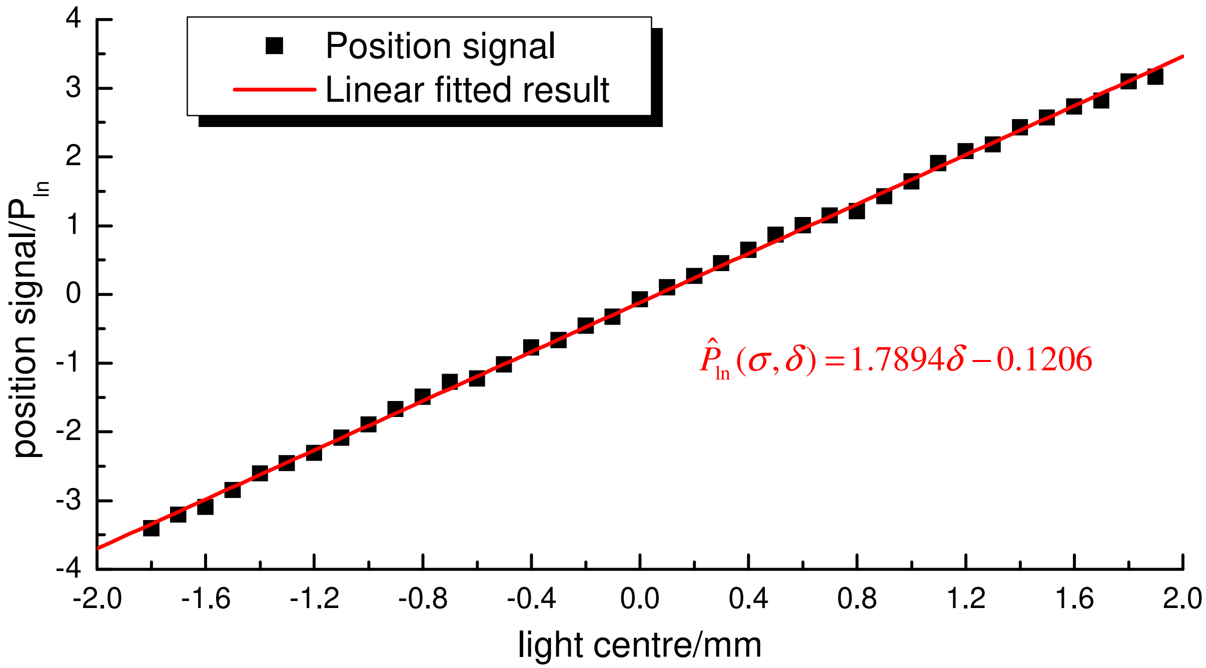
We move the adjustment station to simulate the movement of beam center and assume the beam size remain unchanged in a short time. For horizontal direction, the true beam size is 0.332mm measured by CCD camera filling in 39 bunches in all 45 bunches.

Following figure shows how the anode output photocurrent intensity of 4 successive channel of horizontal MAPMT varies with the moved position.



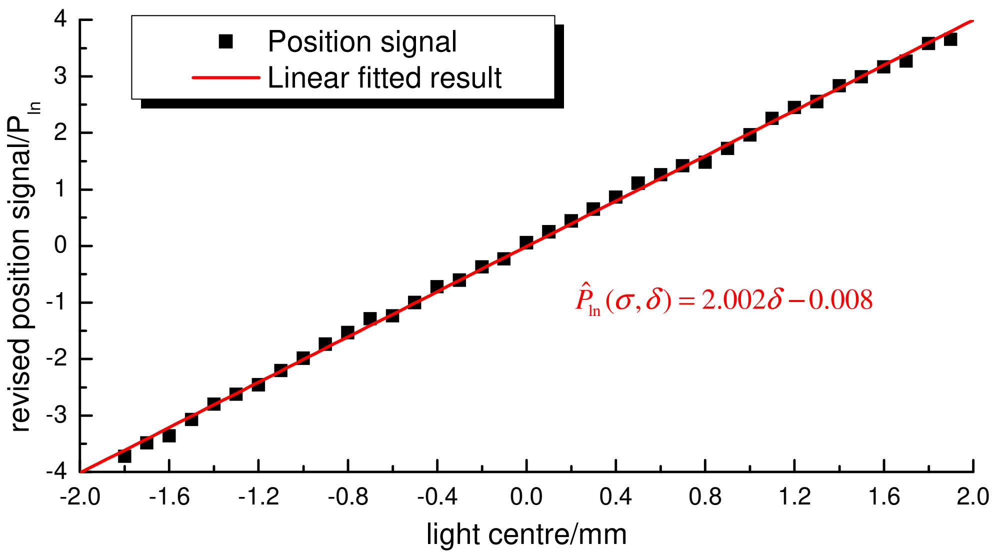
When the adjustment station increases, photocurrent intensity of CH4 and CH5 increases and is just opposite for CH6 and CH7, which roughly indicates the beam spot center is moving from CH7 to CH4. The position of 14.9mm can be thought to the absolute center.

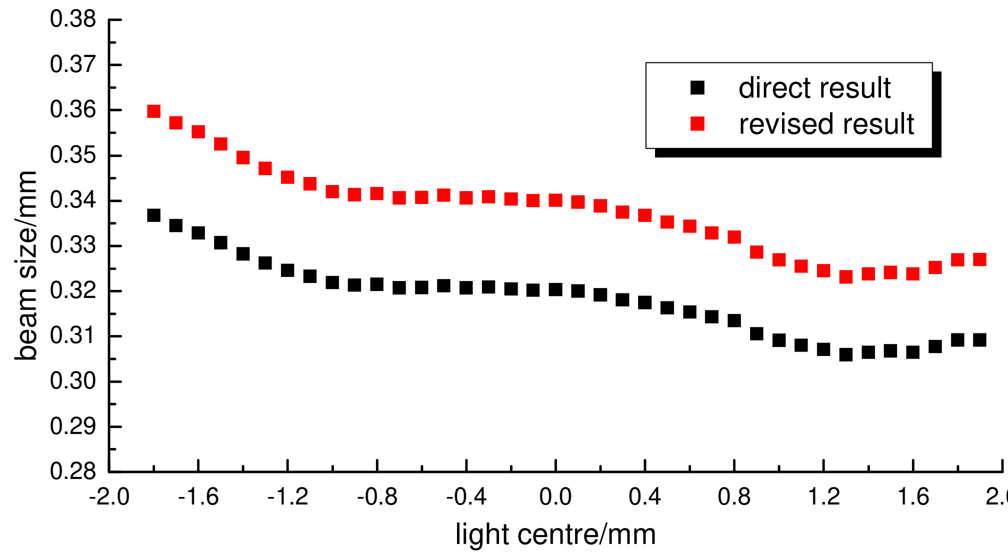
With logarithm processing equation, we can get how the position signal varies with the beam center. Linear fitting shows the slope is 1.7894 and intercept is -0.1206. Indeed simulation result shows that the slope should be about 2.0 and intercept about 0. The difference mainly comes from the channel difference and should be revised.



With slope and intercept obtained in non-ideal case, we can get revised position signal. Linear fitting result shows a very good agreement with the simulation result.

With collection factors $\tilde{d}_s$, we get how actual and revised beam sizes vary with light center. When position increases, beam size decreases overall but keeps almost the same in the range from -0.8mm to 0.1mm. After being revised, the result is closer to CCD result and is more reliable. But it still needs further analysis.





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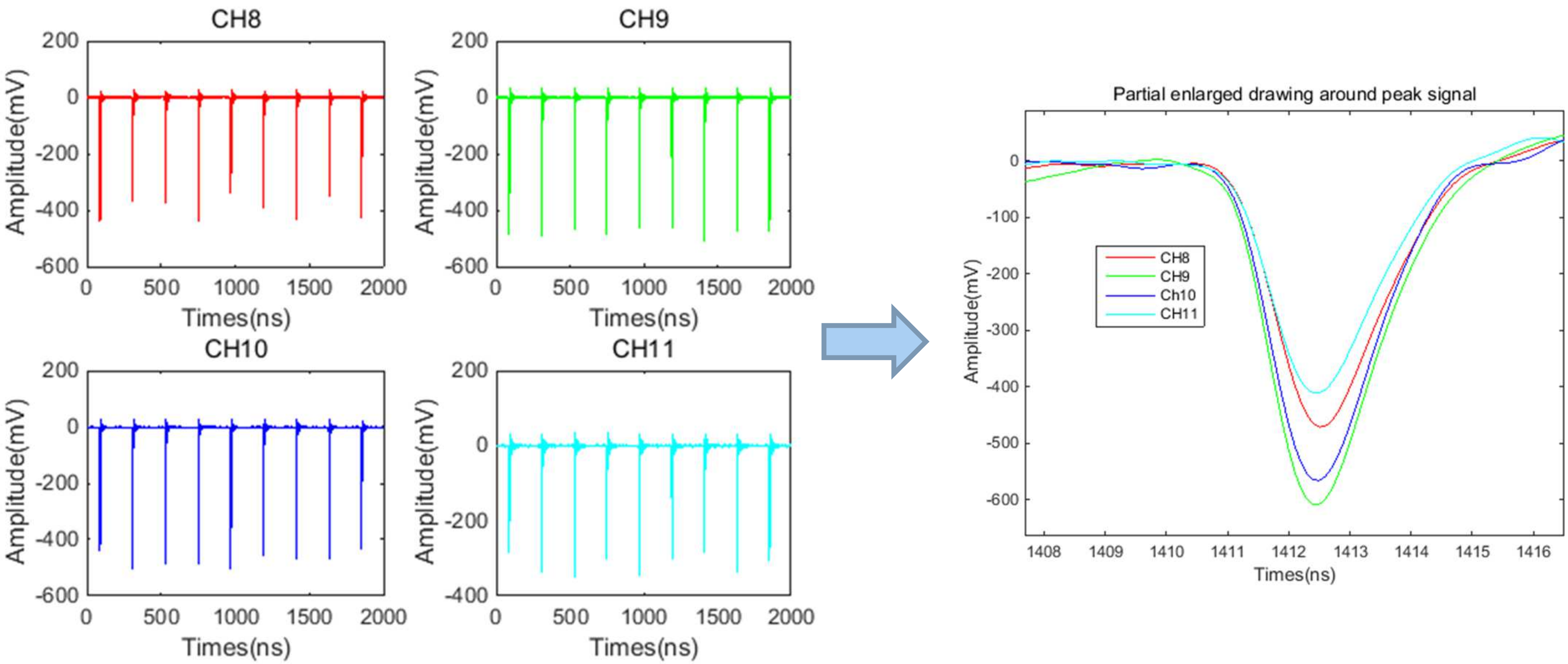
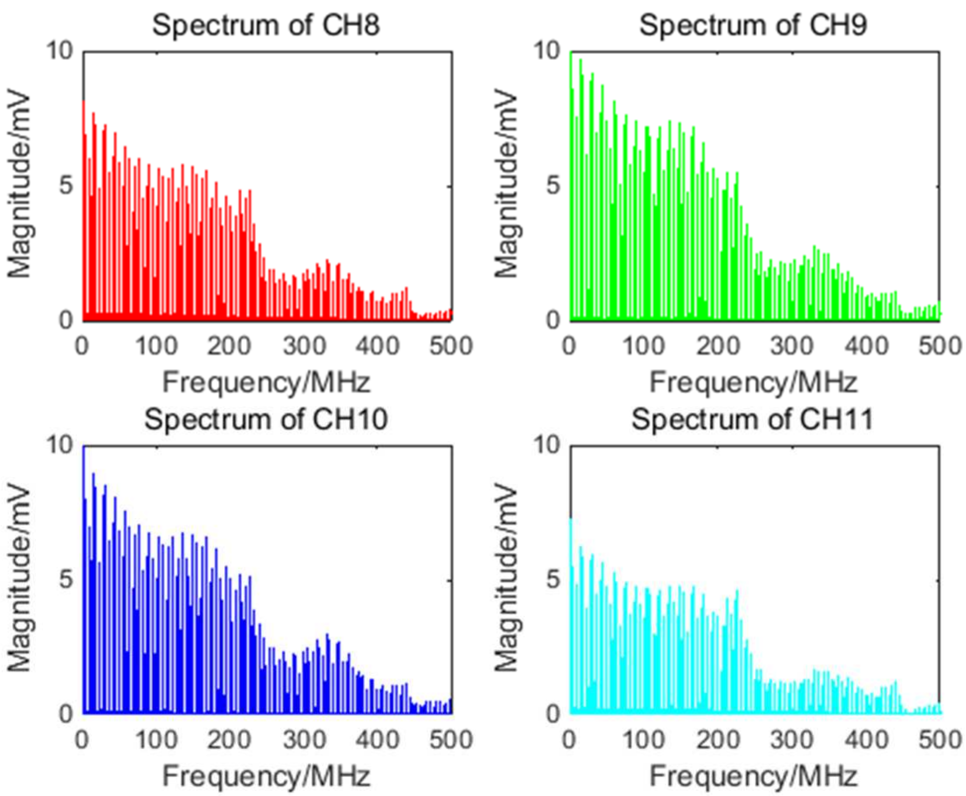
Scheme of high speed mode

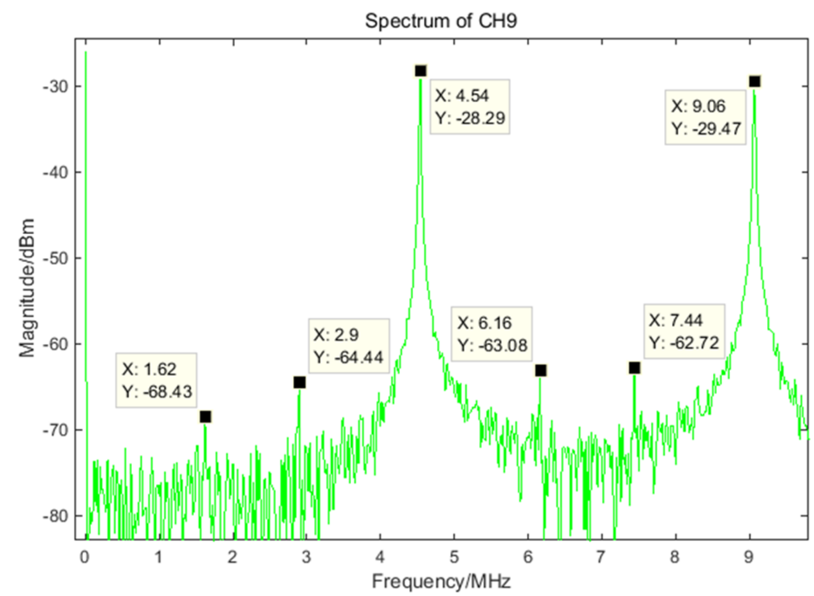
- Filling one bunch in storage ring and bunch interval 220ns.
- Using high-speed oscilloscope DSO9104A to simultaneously sample 4 channel data.
- Sample is synchronized to external revolution frequency resulting from divide-by-45 cavity rf signal, up to 10Ga/s, sample 227 turns with 500,000 points.
- Excite the beam at baseband with swept frequency signal from spectrum analyzer.



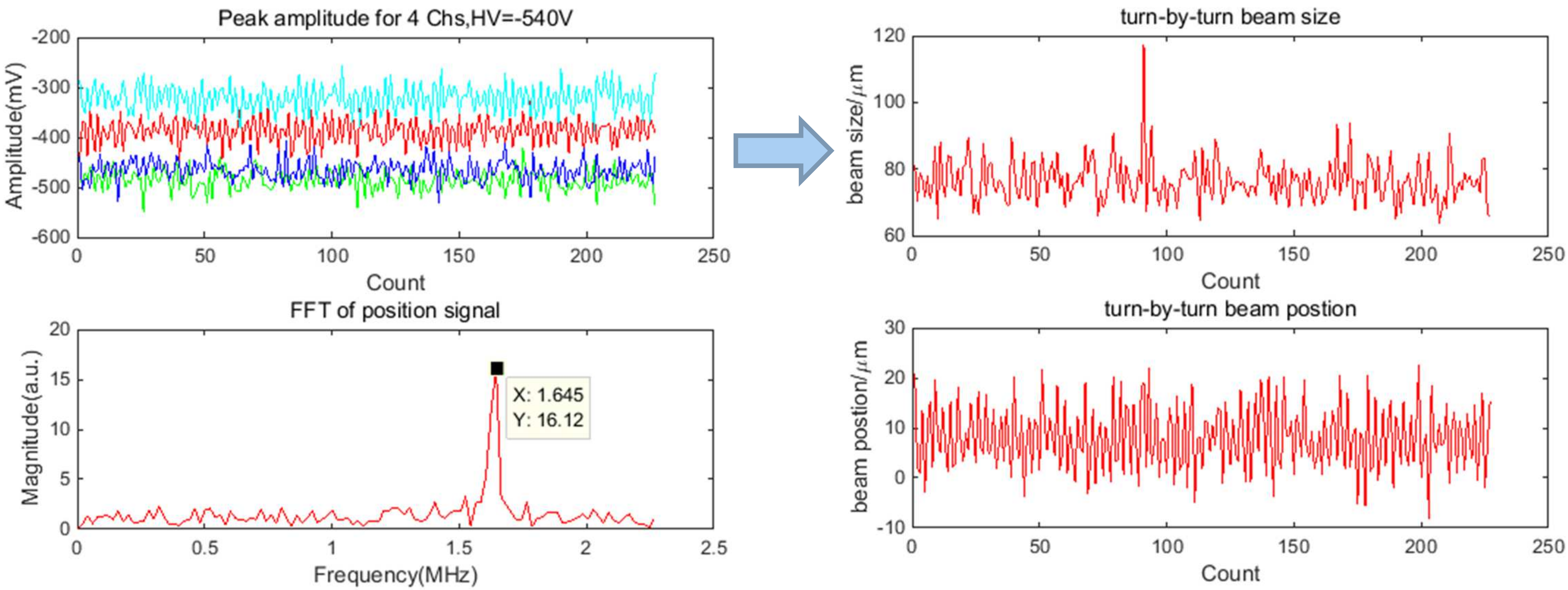
Main harmonic components present at the position of integral multiple of revolution frequency. Amplitude of each harmonic decrease as the frequency increases.

View the first two harmonic components of CH9, convert the y-axis to logarithmic axis, apart from the two frequency components at integral multiple of revolution frequency, we can clearly see vertical synchronous beta oscillation sideband.





- By extracting the peak signal based on peak search algorithm, we can obtain the 227 turns peak value data.
- With the FFT of position signal, we can see a peak signal appears at 1.645MHz corresponding to fractional of vertical tune 0.36.
- The average value of turn-by-turn beam size is 76.4um while CCD result is 70um. Result is larger for about 8%.



Other signal processing technique

We replaced the oscilloscope with Libera Brilliance Plus, and found DDC output data are chaotic so as not to be distinguished. This might be that signal amplitude is rather low at 408MHz which is the center frequency of SAW BPF for our storage ring.

We are now developing our digital signal processor based on NI FPGA and NI ADC adapter module, in which we can define our logic using LabVIEW software.

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- The average anode current of MAPMT is rather low and we only do experiments in single bunch mode at the moment, more bunches will be injected so as to measure bunch difference.
- New high speed and spatial resolution photoelectric detectors are needed to measure transient photon flux or photon density at very frequency up to several hundreds of MHz.
- Time-domain processing method for acquiring signal peak value has a large error once the clock or trigger jitters. And better processing method is in frequency-domain.
- High speed analog-front electronics is required to convert light pulse current signal to voltage signal and then fed to a dedicated digital signal processor based on frequency-domain.

Thanks for your attention.