An on-line data acquisition system of oscilloscope-embedded input/output controller for cavity BPM measurement

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Abstract Cavity beam position monitor (BPM) is widely used in a precise electron beam position measurement. Based on high performance oscilloscope-embedded EPICS input/output controller, we developed an on-line cavity BPM signal processing system for fast data acquisition solution when designing a cavity BPM. Also, methods for extracting the position information from cavity pickup signals and calibration algorithm are included in this solution.

Key words Cavity, Embedded input/output controller, On-line acquisition, Signal processing, Fast Fourier transform

1 Introduction

Coincidence between electron and photon beam is of significance for the Free Electron Laser Facility based on Self-Amplified Spontaneous Emission (SASE). So cavity beam position monitor (BPM) using TM_{110} (dipole) and TM_{010} (monopole) cavities is introduced to measure electron beam position precisely[1,2]. In order to evaluate the performance of BPM sensor in prototype stage a signal processing system for cavity BPM[3] offers plug and play and RF-front end free capabilities was introduced. This solution is to use a wideband Tektronix DPO oscilloscope to receive pickup signals from cavity output ends, and digitize it at high sampling rate. The raw waveform data are stored in a large memory buffer of oscilloscope and processed by an algorithm mainly involving FFT and peak searching. Beam positions extracted are stored in EPICS running database, and shared by users via EPICS Channel Access protocol. This solution works just in wideband situation, rather than narrowband situation for traditional electronics. It makes system suitable for different cavities with different resonant frequencies.

2 Basic concepts of cavity BPM

The TM_{110} and TM_{010} modes as fundamental oscillation will be excited when a bunch of particle beam transits a cavity (a circular cylinder with $L < 2.1R$ in usual case). The amplitude of TM_{110} mode has a strong linear dependence on transverse offset of the beam relative to the electrical center of the cavity (Fig.1). So extracting position information from the cavity BPM mainly refers to the TM_{110} mode[4].

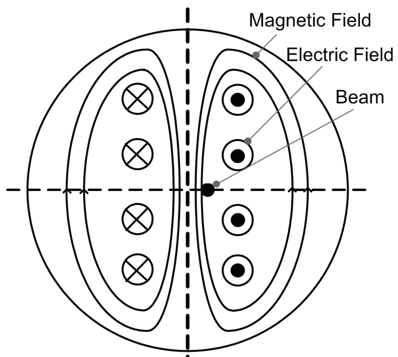

Fig.1 TM_{110} mode fields. The amplitude has a strong linear dependence on transverse offset of the beam.

The TM_{010} mode, which is proportional to the bunch charge, is unaffected by the beam offset. For a cavity employing the TM_{110} mode, when a beam with bunch charge (q) and length (σ_z) is passing through the

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cavity on a trajectory which is parallel to the center axis by an offset in transverse plane, the signal voltage responded by cavity with oscillation and decay can be expressed as[6]

$$V_x(t) = V_{\mathrm{out},x}\ \mathrm{e}^{-t/(2\tau)}\ \sin(\omega t)$$
$$V_y(t) = V_{\mathrm{out},y}\ \mathrm{e}^{-t/(2\tau)}\ \sin(\omega t) \qquad (1)$$

where, V_{out} is peak voltage of output signal, τ is damping time of the channel, ω is resonance frequency of cavity, and t is the sampling time.

Assuming a digitizer applied to acquire the output signal, the digitized waveform in a given channel can be described by Eq.(2).

$$V(t) = V_0 + A\mathrm{e}^{-(t-t_0)/(2\tau)}\ \sin[\omega(t-t_0) + \varphi] \qquad (2)$$

where, V_0 is the DC baseline of digitizer, A is peak voltage of acquired waveform that represents the magnetic field amplitude, φ is the initial phase of the acquired waveform that represents the trigger delay, and t_0 is the time when the bunch passes through the apparatus.

Two typical digitized waveforms data employing $\mathrm{TM_{110}}$ mode for horizontal and vertical directions obtained at 6-GHz bandwidth and 25-Gsps are shown in Fig.2.

In this case V_0 was determined by calculating the mean of acquired samples before the pulse transited. After fitting the value of A and φ, the τ and ω for a given channel could be determined by calibration.

For $\mathrm{TM_{110}}$ mode, the value of A is proportional to the product of bunch charge q and the value of beam offset (***x*** and ***y***) within the cavity. So the signal of reference cavity employed $\mathrm{TM_{010}}$ mode (Fig.3) which is insensitive to beam offset is used to remove the variation effect of bunch charge q and normalize the amplitude A from $\mathrm{TM_{110}}$ cavity.

Because the bunch train is running in a preset offset trajectory parallel to the center axis of cavity, the tilt angle is considered as zero, and only the absolute offset value of ***x*** and ***y*** should be extracted. Define a normalized position parameter U_i by dividing amplitude of position signal A_i with amplitude of reference signal A_{ref}, the practical beam position V_i can be expressed as Eq.(3).

$$V_i = a_i U_i + b_i,\ U_i = A_i/A_{\mathrm{ref}},\ i = x,y \qquad (3)$$

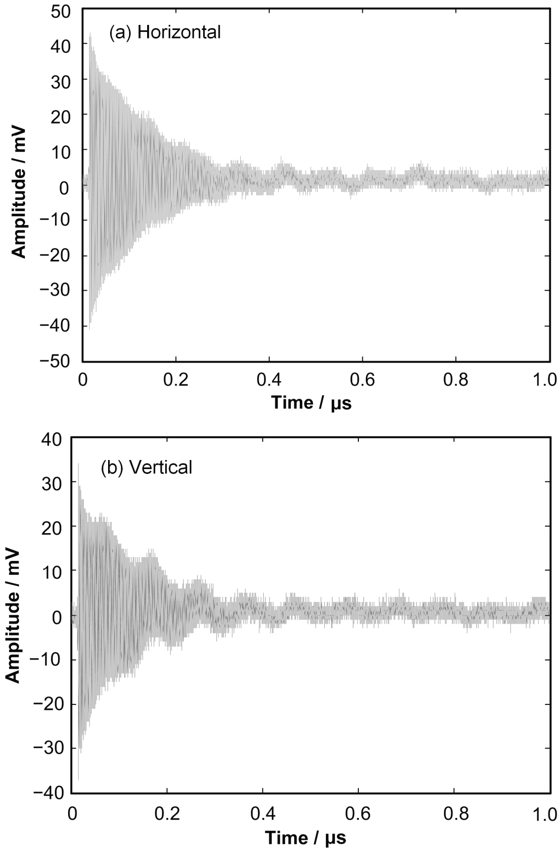

Fig.2 Typical digitized waveforms of $\mathrm{TM_{110}}$ mode at horizontal and vertical directions.

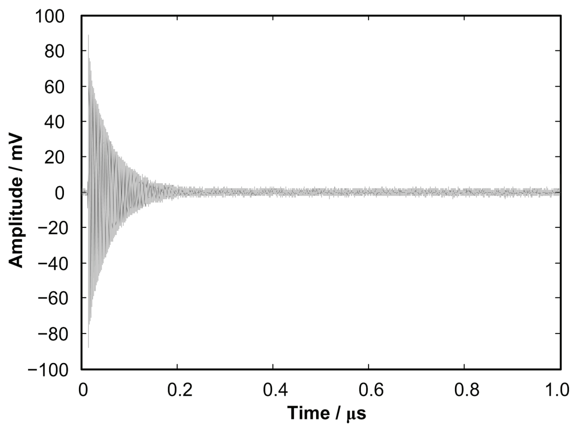

Fig.3 Typical digitized waveforms of $\mathrm{TM_{010}}$ mode. The amplitude is proportional to bunch charge q, and insensitive to the beam offset.

where, a_i is the position scale factor, and b_i is zero drift determined by the calibration procedure. A_i from horizontal and vertical directions of position cavity, and A_{ref} from reference cavity, can be retrieved from Fast Fourier Transform (FFT) of raw waveform data for each bunch. The peak values of spectra represent the A_i and A_{ref}, and the corresponding frequencies represent the resonant frequency of the cavities.

3 Scope embedded EPICS IOC software

Before developing the embedded IOC software, an EPICS environment, which is necessary to compile and run EPICS program, is established using EPICS base software package (Version 3.14.11) and Microsoft Visual Studio2008/C++ (MSVSC++) in the Tektronix DPO70604 oscilloscope (Fig.4).

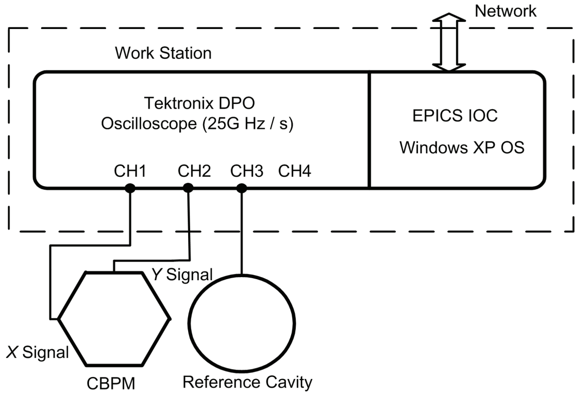

Fig.4 Schematic drawing of the cavity BPM on-line measurement system.

To acquire raw waveform data and extract beam position values, an EPICS IOC instance in the oscilloscope was built on Windows XP platform. The core part of an IOC is runtime database and related driver programs called "record/device/driver support" modules. In "EPICS-speak", database is defined as collection of function blocks called "records", many built-in record types are described in 'dbd' files and instantiated by 'db' files. Database records should be processed by database scanning mechanism[7]. During processing 'db' files, records and device specific routines are called to initialize the record.

The IOC database structure is shown in Fig.5. Three "Waveform" type records were used to acquire and process two positions and one reference cavities signal respectively. Raw data acquisition based on Tek -VISA protocol and FFT calculation were performed in these "Waveform device support" modules. Three "Longin" type records were linked with "Waveform" records to get peak values in spectrum, and pass them to "Calc" records which would calculate the beam position values for each bunch. The "Compress" records were used to build a circular buffer to save the position history data. Users can access the "Compress" records to read the final result.

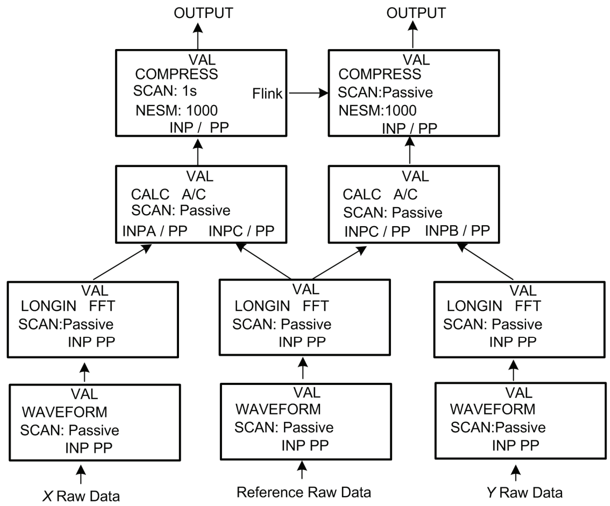

Fig.5 Block diagram of IOC database structure.

To get the relationship between FFT points and resolution, we have simulated a cavity signal raw waveform data of 50 000 points for vertical direction mixed with oscilloscope noise signal. FFT calculation from 500 to 50 000 points was taken to get the corresponding resolution (Fig.6a).

When considering the integrity of decay signal, the length of effective raw data, and the efficiency of FFT radix-2 method, the 8 192 points in the raw data of 50 000 points was used for FFT algorithm (Fig.6b).

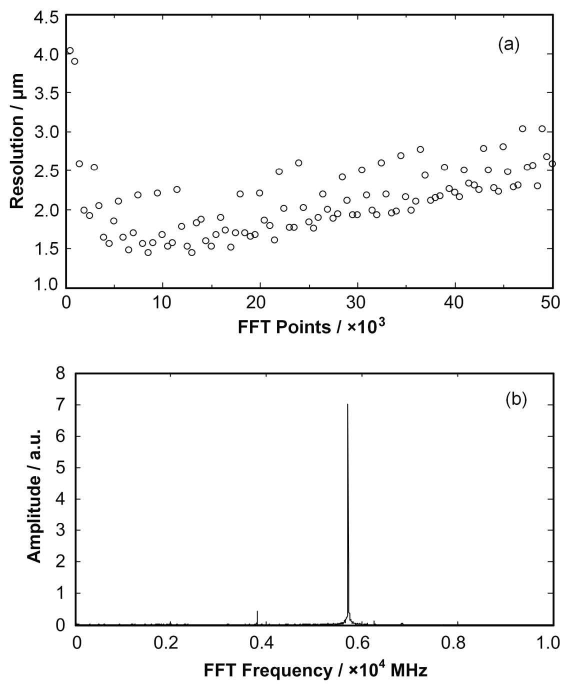

Fig.6 Relationship between FFT points and resolution (a) and FFT for 8 192 points of raw waveform data (b).

4 Preliminary experiment

A cavity BPM, with which the TM_{110} and TM_{010} modes are of the same frequency (5 710 MHz), was built at SINAP[5]. It was used to demonstrate the functionality and performance of the Scope IOC. The DPO oscilloscope was set to 6 GHz bandwidth and 25 Gsps real-time sampling rate. The signals of three output ports at given horizontal and vertical directions, and reference cavity, were sent to three input channels (CH1, CH2, CH3) of the DPO oscilloscope. The data rate of 1 Hz and buffer size of 50 000 points were configured in EPICS database files. The raw waveform data were readout by EPICS database scan mechanism which would trigger on-line data processing. A dedicated C program embedded in EPICS IOC monitored bunch arrival, computed its offsets, and published the results (raw waveform data if needed) via EPICS Channel Access protocol to any interested users.

The on-line acquisition system was calibrated by moving the BPM cavity mechanically while fixing the electron beam trajectory to hold the offset at a known amount. Offset from the nominal position to origin center axis (V_i) was related to the IOC-normalized output value (U_i) in Eq.(4). Totally, 11 nominal positions were obtained by moving the cavity in a distance of 5 mm from center axis of the cavity, in 0.5-mm steps of 2-μm accuracy. Output counts of 20 bunches were acquired using the on-line acquisition system and stored in EPICS IOC each step. The average counts of the beam offsets were used to calculate scale factors. The scale factors for both directions were derived by off-line linear fittings (Fig.7). The large error bar of normalized position was due to the changes in beam bunch position and charge, and the deviations in horizontal and vertical directions were inconsistent with the symmetry of cavity cross-section. These suggest that the position sensitive cavity might be affected by reference cavity signal nearby. However, this was not proved strictly in the experiment.

After the scale factor calibration, the C program embedded IOC was modified by the fitting coefficients in Fig.7. Then, the beam bunch positions could be acquired directly from IOC by keeping the cavity unmoved, calculating the ***x*** and ***y*** data, recording them in IOC, and counting 800 beam bunch positions. The results are shown in Fig.8.

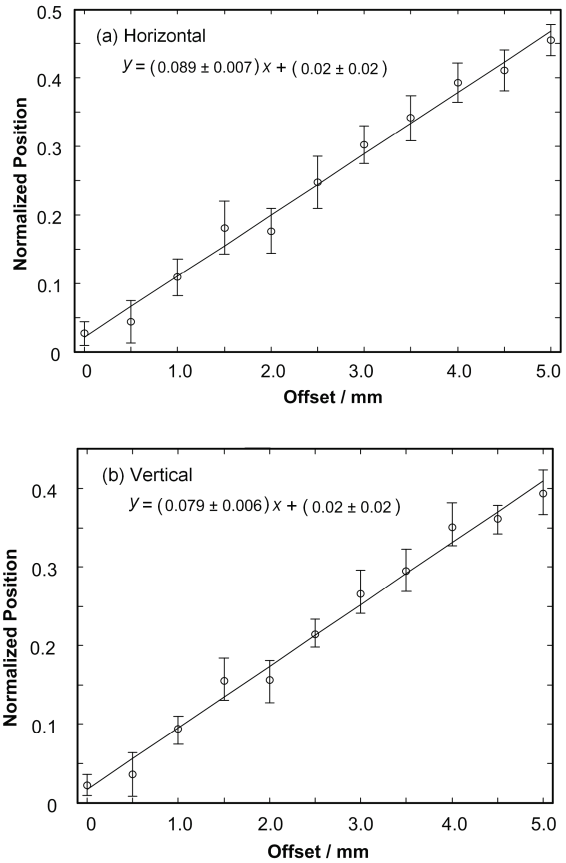

Fig.7 The scale factors for horizontal and vertical directions of the BPM.

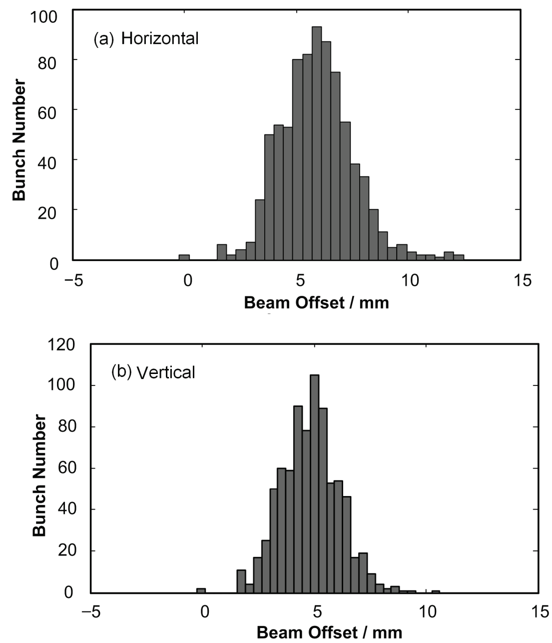

Fig.8 Data distribution in horizontal and vertical directions.

5 Conclusions

The embedded EPICS IOC in the Tektronix DOP oscilloscope was introduced as a cavity BPM signal processor offering plug and play capability. This RF front-end free solution is useful for cavity BPM designer to make a fast and direct performance evaluation in prototype stage. In the preliminary beam experiment, the basic functionality and calibration procedure were demonstrated. But changes in beam position and charge resulted in a large jitter of measured beam position. It makes evaluation of the system resolution undoable. More precise beam experiments need to be done in the future.

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