HIGH-PRECISION ELECTRONICS FOR SINGLE PASS APPLICATIONS

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Abstract

Monitoring and subsequent optimization of electron Linacs and transfer lines requires specific instrumentation for beam position data acquisition and processing. Libera Single Pass E is the newly developed instrument intended for position and charge monitoring in classical and multi-mode operation Linacs. Development, initial measurements and verification of the instrument performance were conducted in the Instrumentation Technologies laboratories, followed by characterization measurements of the unit carried out at the KEK Linac facility.

INTRODUCTION

Libera Single Pass E is a result of successful collaboration between KEK Linac and Instrumentation Technologies. The KEK 8-GeV Linac injects electron and positron beams with different characteristics into four storage rings: KEKB high-energy ring (HER), KEKB low-energy ring (LER), Photon Factory (PF) and PF-AR. The performance of these machines depends on the injection quality [1]. The BPM system therefore has to provide continuous high-precision monitoring of position for various beam species. It needs to support a wide dynamic range of charge, i.e. charges vary from 0.1 nC to 10 nC. Furthermore, the BPM must auto-detect and further conduct either single-bunch processing or individual processing of two consecutive bunches which are 96.2885 ns apart.

Based on external event announcing, Libera Single Pass E (see Fig. 1), adapts to the beam charge and pattern. It can process various beam structures (single bunch, narrow dual bunch, trains, continuous wave) with large dynamics (over 40 dB). Libera Single Pass E system is based on uTCA modular technologies with IPMI platform management. The system is therefore developed on multiple AMC modules, with each module covering different functionalities.

Figure 1: Libera Single Pass E front panel.

The user can access the functions implemented in the Libera Single Pass E unit through a control system interface, called the Measurement and Control Interface (MCI). This interface was developed to facilitate the integration of Libera Single Pass E into the accelerator's control system software.

CONTROL SYSTEM INTEGRATION

On the top layer, Libera Single Pass E provides the MCI with a development package and Command Line utilities for open interaction in different control systems. On top of the MCI, various adaptors to different control systems can be implemented (EPICS, Tango, etc.). The EPICS interface is part of the standard software package.

EVENT RECEPTION

Libera Single Pass E [3] detects the events announced by the accelerator timing system in order to set the data processing parameters optimally for the expected bunch structure. It enables event reception via the optics/wire event reception in the event receiver module (EvRx) or alternatively via external interfaces (EPICS protocol event generator) [6].

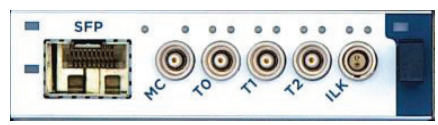

Figure 2: Event receiver module.

The EvRx (see Fig. 2), module receives the optical signal through the SFP transceiver and identifies and extracts the 16-bit event code. Once the code has been extracted, the module decodes the event identification code and triggers specific functions at low latency.

DATA PROCESSING

The data processing is initiated by the external event signal. The short signal from the detector is first shaped by the analog front-end filtering, designed in relation to the accelerator parameters.

Through the configuration of various software parameters, Libera Single Pass E offers processing of various beam types (flavors). After the hardware trigger signal which announces the arrival of the bunch, the search of the bunch signal is started. The bunch signal is detected in comparison with the threshold parameter, then a useful part of the signal is defined with the pre-trigger and post-trigger parameters. The sum of the pre-trigger and post-trigger defines the processing window. The signal energy is calculated from the signal as defined by the processing window. After calculating the four signal amplitudes – Va, Vb, Vc and Vd – the beam position is calculated using formulas for X and Y. Four options can be used for position calculation:

- Diagonal pickup orientation – Linear formula
- Diagonal pickup orientation – Polynomial formula (3^{rd} order)

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- Orthogonal pickup orientation – Linear formula
- Orthogonal pickup orientation – Polynomial formula (3rd order):

$$X = X_{OFFSET} + \sum_{ij=0}^{3} K_{Xij} \left(\frac{(V'_A - V'_C)}{(V'_A + V'_C)} \right)^i * \left(\frac{(V'_B - V'_D)}{(V'_B + V'_D)} \right)^j$$

$$Y = Y_{OFFSET} + \sum_{ij=0}^{3} K_{Yij} \left(\frac{(V'_A - V'_C)}{(V'_A + V'_C)} \right)^i * \left(\frac{(V'_B - V'_D)}{(V'_B + V'_D)} \right)^j$$

In the case of longer beam structures, similar data processing is used, based on the appropriate signal windowing [3]. The data calculation is initiated by the external trigger event and is automatically stopped after the bunch structure is over. The decimated batch of data is available for transmission to the control system. In the case of continuous wave operation, the unit continuously processes and outputs the stream of decimated beam position data.

STANDARD UNIT PERFORMANCE

Measurement performance mostly depends on the Libera front-end configuration [2]. Its parameters are set in accordance with other accelerator parameters. The standard type of Libera Single Pass E implements 500 MHz SAW filters with 10 MHz bandwidth. At normal beam charges, the position measurement resolution is close to 1 µm for a single-bunch beam structure (see Fig. 3).

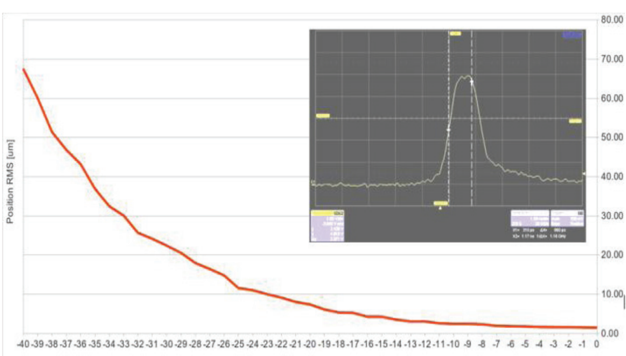

Figure 3: Measurement performance versus input signal level (0 dBFS = 5 V peak).

KEK LINAC TYPE UNIT EVALUATION

In addition to the standard unit requirements, the KEK Linac custom Libera Single Pass E was further required to process two consecutive bunches, the separation between them being 96.2885 ns. It differs from the standard unit in the equipment of the front end: the signal filtering has to be designed in such a way that the filter response to the first bunch does not have a significant overlap with the filter response to the second bunch. The unit can measure the individual bunch position with the resolution close to 2 µm. A typical filter response of the two-bunch signal after the AD conversion is shown in Figure 4.

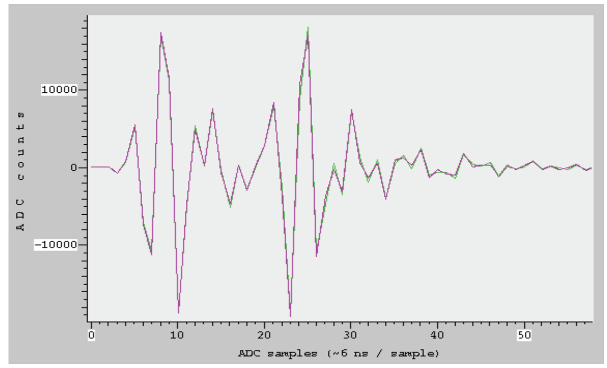

Figure 4: ADC raw signal – 2-bunch input signal.

Filter Response Overlapping Effect Test

The response of the SAW filter on the pulsed signal usually consists of the main intense overshoot followed by a couple of lower oscillations. As bunches in the KEK Linac are only ~96 ns apart, it is necessary that the filter response to the first bunch has only a minimal overlap with the second one. To quantify the impact, we moved the X position of the first bunch in the range from −2.25 mm to 2.25 mm and monitored the change of position measured for the second bunch. The laboratory test setup presented in Figure 5 was built in such a way that two equal chains were used for the signal generation in one measuring plane – Ch_A and Ch_C. The amplitude of the first bunch and the second were set to be equal within 1%. The position of the first bunch was changed by changing the 4 dB attenuator in both chains. The delay between the two consecutive bunches was accurately set to 96.2885 ns.

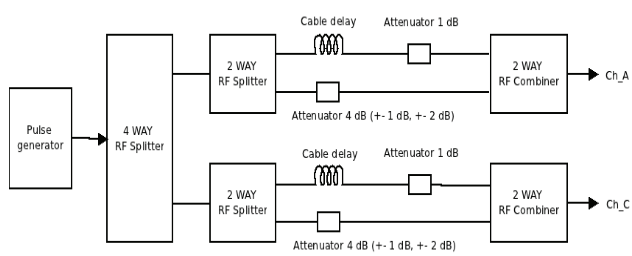

Figure 5: Laboratory test setup.

Only a minor effect on the second bunch position measurement was obtained as a consequence of the filter response overlap. With the first bunch movement from −2.25 mm to 2.25 mm, the second bunch position moved from −77.2 µm to 77.8 µm (see Fig. 6) in a linear manner. The measured impact of the first bunch position on the second one was 3.44% in the worst simulated case.

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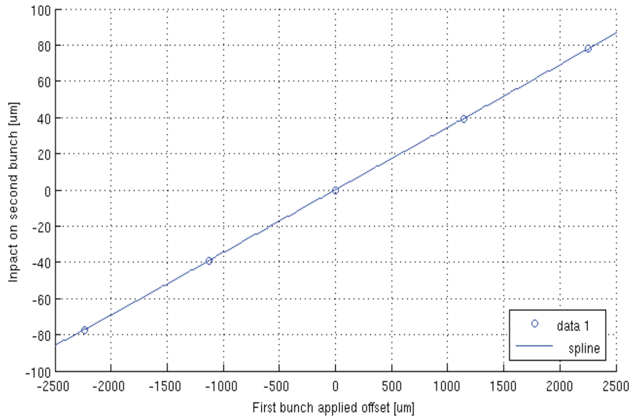

Figure 6: Filter response overlapping effect on the second bunch position.

In the accelerator, the goal is to have both consecutive bunches well aligned – the expected misalignments are of few micrometers. The filter response overlapping effect on position measurement is acceptable.

Phase Alignment vs. Performances

The filtering response of the KEK Linac custom front end is short. Thus the phase alignment of the four signals plays an important role in achieving the desired measurement performance. For this purpose the front end in the Libera includes software-controlled phase shifters that make phase calibration quick and effective. The benefit of the precise phase alignment was evaluated at the KEK Linac laboratory [4]. The influence of the phase alignment on the position measuring resolution is presented in Figure 7. In the experiment, channel C was fed with a fixed value, while the channel A (CHA) input was varied in the range from 0 to 180° over 4,000 steps.

With the best phase alignment, the position measurement resolution approaches 2 μm.

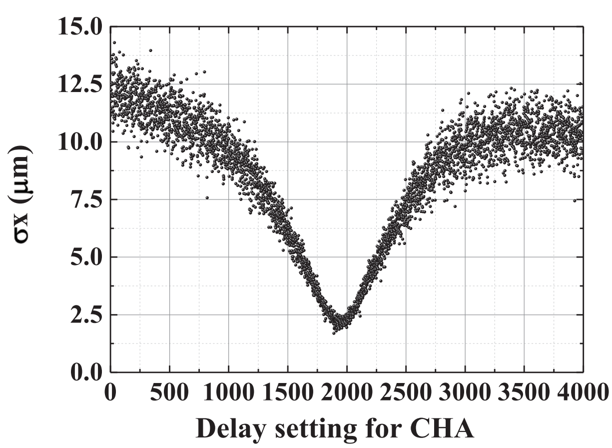

Figure 7: Measuring resolution vs. phase alignment.

Performance Evaluation on the Beam

The crucial requirement for the KEK Linac BPM is the measuring accuracy and resolution. The latter is required to be less than 10 μm, measured on the beam in the actual KEK Linac environment using the so-called "3BPM method" [5]. With this method, the position resolution can be obtained by measuring the correlation of three BPM readings. Synchronous beam position measurement was performed on BPM-1, BPM-2 and BPM-3. The beam charge during the beam test was 0.3 nC. The beam was steered to different positions by correctors which are located upstream of BPM-1. During this measurement, five different beam positions in the range within ±2 mm were used, with 400 BPM readings acquired at each of them.

Beam orbit measurement along the KEK Linac during the 3-BPM test is presented in Figure 8. Here horizontal orbit (top), vertical orbit (middle) and beam charge (bottom) are shown. The green coloured line means the reference orbit along the KEK Linac, using the nominal steering magnet setting. The blue line presents the position measurement after the beam steering. Three adjacent BPMs (coloured in light green) are used in the 3-BPM experiments [4].

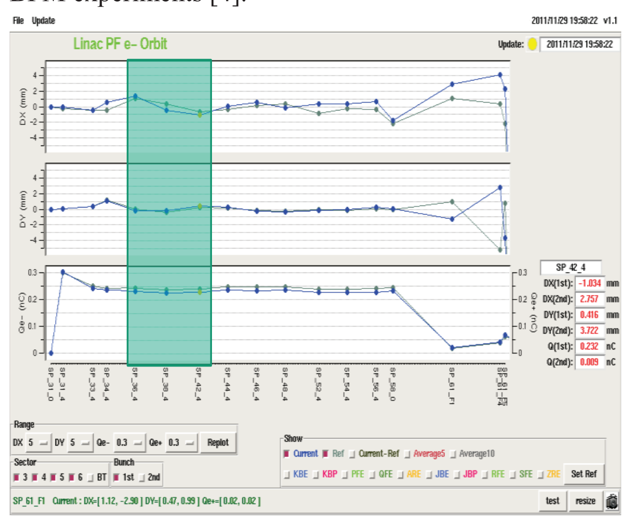

Figure 8: Beam orbit along the KEK linac.

The 3-BPM measurement results in the horizontal and vertical directions are presented in Figure 9 and Figure 10 respectively. In the present measurement, a linear multivariate regression analysis is applied to estimate the beam position at BPM-3 from the measurement results in BPM-2 and BPM-1. Residual distribution of the estimated value and the aforementioned measurements of BPM-3 give the BPM position measurement accuracy [4]. In Figure 11, estimated and measured position on BPM-3 is presented.

Resolutions of 7.06 μm in the horizontal plane and 7.05 μm in the vertical plane were obtained, with the target value for KEK Linac BPM instrumentation being set at 10 μm RMS.

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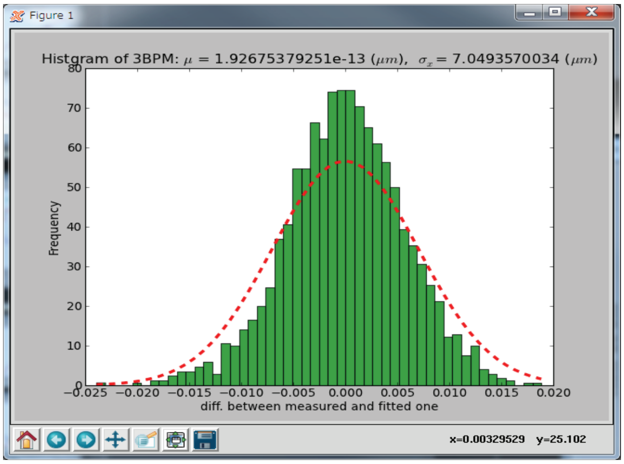

Figure 9: Histogram of residual between the estimated and the measured beam positions (horizontal).

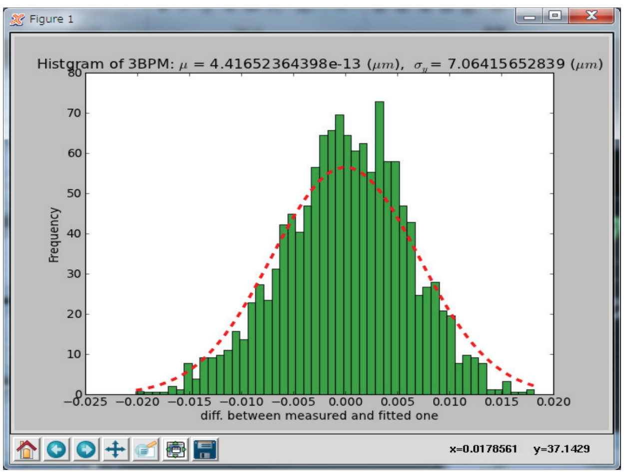

Figure 10: Histogram of residual between the estimated and the measured beam positions (vertical).

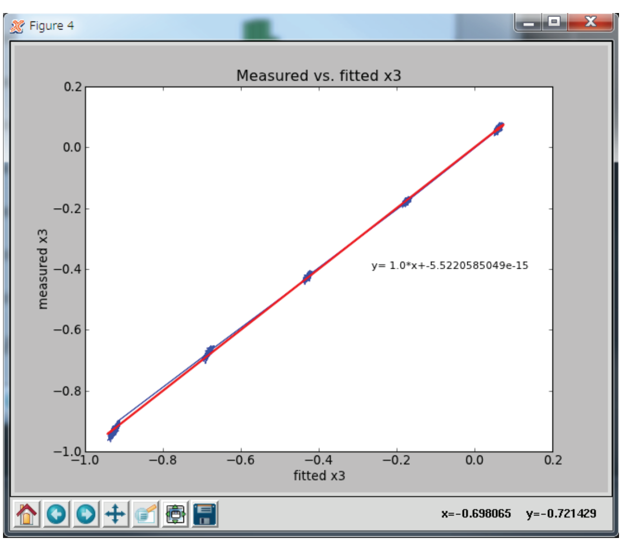

Figure 11: Estimated and the measured beam positions (horizontal).

CONCLUSION

Libera Single Pass E provides position measurement resolution results close to 1 µm for single-bunch beam signals (depending on the front-end configuration). One of the crucial requirements for the KEK Linac BPM is the actual measurement resolution under specific conditions, which must be less than 10 µm for each individual bunch. Position resolution close to 2 µm was achieved in the test setup in the laboratory. Extensive testing was carried out at KEK Linac, where on-the-beam tests of three Libera units gave results with horizontal and vertical resolution well within the specifications. The so-called "3BPM method" gave resolutions of ~7 µm in both planes.

The successful collaboration needs to be emphasized between users (KEK Linac) and development & manufacturing of the instrument (Instrumentation Technologies).

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