BUNCH ARRIVAL TIME MONITOR FOR PAL-XFEL

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Abstract

The X-ray Free Electron Laser project in Pohang Accelerator Laboratory (PAL-XFEL) requires high stability of bunch arrival time, and measurement resolution better than a few femtoseconds. The pickups of the electron Bunch Arrival time Monitor (BAM) for PAL-XFEL have been developed and simulated. The BAM pickups are based on an S-band monopole cavity with two coupling loops. The prototype BAM has been fabricated and installed downstream of the accelerating column at the Injector Test Facility (ITF) for PAL-XFEL. In this paper we will present the recent measurement results on the beam test of the BAM as well as a proposed strategy for developing the BAM for PAL-XFEL.

INTRODUCTION

PAL-XFEL requires high stability of bunch arrival time, and measurement resolution of bunch arrival time less than a few femtoseconds. The cavity type (monopole mode) BAM pickup is applied, which allows the detection of the bunch arrival time with a few femtoseconds. The BAM pickups are based on an S-band monopole cavity (LCLS type) with two coupling loop antennas. Figure 1 shows the geometry of the prototype BAM for PAL-XFEL. The prototype BAM

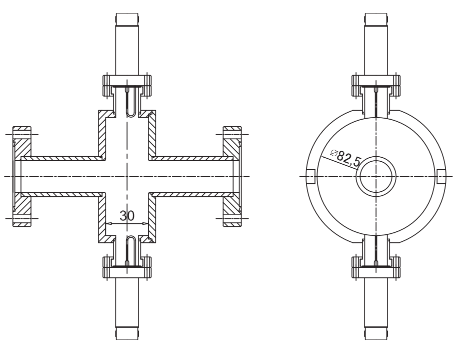

Figure 1: Prototype BAM geometry for PAL-XFEL.

pickup has been developed and installed downstream of the accelerating column at ITF [1] for PAL-XFEL. Figure 2 shows the photograph of the prototype BAM. The prototype BAM was tested for S-parameters and the results were compared to simulations. CST Microwave Studio is used to compute. Table 1 shows the resonance frequencies and their obtained quality factors. For the signal processing, the LLRF system is employed. Because the LLRF PAD is similar to electronics of the BAM. In the LLRF system, the RF signal is downconverted to the Intermediate Frequency (IF) signal while keeping the information of the preserved signal. The IF signal is sampled using by 16 bit Analog to Digital Converter (ADC) at a constant sampling rate of 238 MHz.

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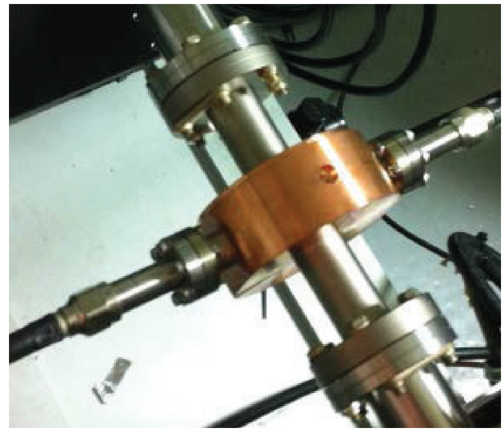

Figure 2: Photograph of the prototype BAM.

Table 1: BAM Pickup Parameters

Parameter	Value	Unit
Operating Frequency	2,823	MHz
Coupling Coefficient	0.1	
Quality Factor	10,000	

More detail on the LLRF system will be found in Ref. [2]. For the RF system, the RF frequency is 2,856 MHz, the LO frequency is 2,826.25 MHz, and then the IF frequency is 29.75 MHz. There frequencies are not well matched to the prototype BAM pickup.

SIGNAL PROCESSING

The schematic diagram of the signal processing is shown in Fig. 3. RF signal is firstly converted to IF signal and then directly digitized. If reference signal, $y_{\mathrm{Ref}}(t)$ and raw BAM signal, $y_{\mathrm{BAM}}(t)$ are:

$$\begin{aligned} y_{\mathrm{Ref}}(t) &= A_{\mathrm{Ref}}(t)\sin(\omega_{\mathrm{Ref}}(t) - \phi_{0,\mathrm{Ref}}), \\ y_{\mathrm{BAM}}(t) &= A_{\mathrm{BAM}}(t)\cos(\omega_{\mathrm{BAM}}(t) - \phi_{0,\mathrm{BAM}}), \end{aligned}$$

then IF signal, $y_{\mathrm{IF}}(t)$ can be written as:

$$y_{\mathrm{IF}}(t) = A_{\mathrm{IF}}(t)\cos(\omega_{\mathrm{IF}}(t) - \phi_{0,\mathrm{IF}}).$$

By using digital modulation the in-phase component, $I_{\mathrm{IF}}(t)$ and the quadrature-phase component, $Q_{\mathrm{IF}}(t)$ of the IF signal can be written as:

$$I_{\mathrm{IF}}(t) = \frac{A_{\mathrm{IF}}(t)}{2}\cos(\phi_{0,\mathrm{IF}}),\ Q_{\mathrm{IF}}(t) = \frac{A_{\mathrm{IF}}(t)}{2}\sin(\phi_{0,\mathrm{IF}}). \tag{1}$$

From Eq. 1, the amplitude, A_{IF} and the phase, $\phi_{0,\mathrm{IF}}$ can be calculated as:

$$A_{\mathrm{IF}}(t) = 2\sqrt{I_{\mathrm{IF}}^2 + Q_{\mathrm{IF}}^2},\ \phi_{0,\mathrm{IF}} = \tan^{-1}\frac{Q_{\mathrm{IF}}}{I_{\mathrm{IF}}}.$$

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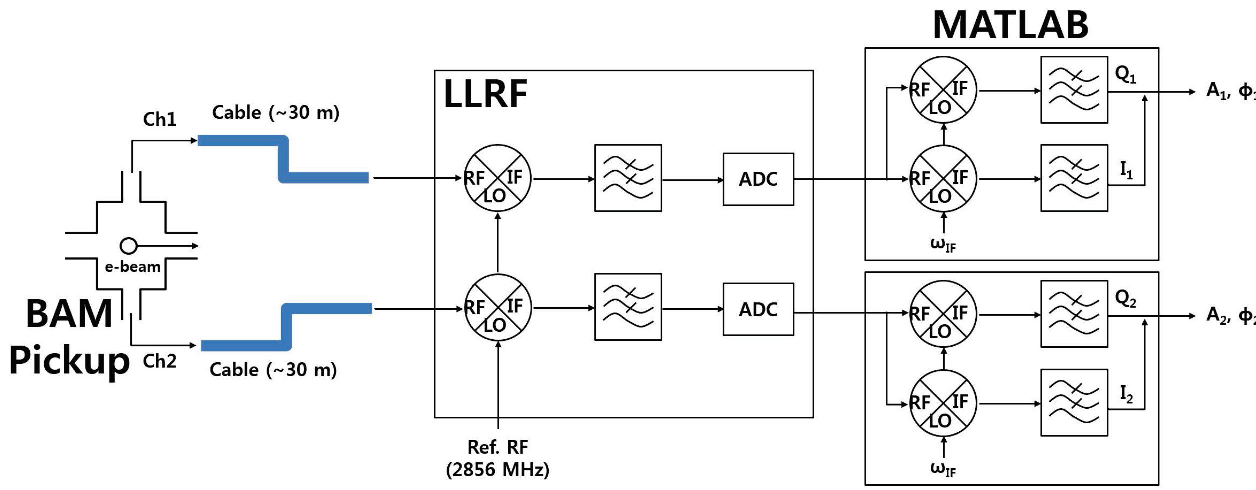

Figure 3: Schematic diagram for signal processing.

For down conversion and digital sampling, we used the LLRF system. MATLAB is used for digital signal processing. Figure 4 shows BAM signal processing data for 200 pC bunch charge. A 16 bit ADC can represent 65,536 (2^{16}) discrete voltage levels. Figure 4 a) shows the amplitude for one of the two pickup electrodes. In this figure the maximum voltage is about 4,096 (2^{12}) peak to peak. This value is so small because input voltage of ADC of the LLRF system is not matched to the voltage due to the prototype BAM pickup.

Using MATLAB simulation we have calculated BAM resolution as a function of signal error as shown in Fig. 5. In this figure, we can find that the resolution is proportional to BAM signal voltage.

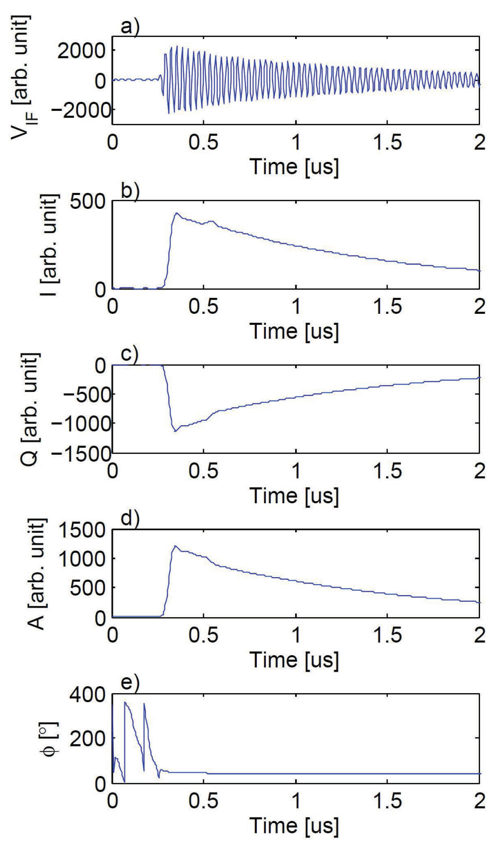

Figure 4: BAM signal processing data for 200 pC bunch charge; a) IF raw data, c) I data, d) Q data, e) amplitude data, and f) phase data.

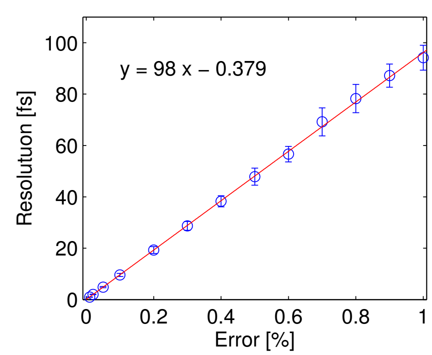

Figure 5: BAM resolution as a function of the signal error. The solid line represents a linear fit.

MEASUREMENT

The prototype BAM was installed at ITF and then tested with an electron beam. An RF signal is generated when an electron beam passes through the BAM cavity. The RF signal is collected with two pickups at the cavity cylindrical wall. The signals are processed using two channels of the LLRF system installed at the first RF station.

Charge dependence of BAM resolution is measured. By measuring the arrival-times with both pickup electrodes, the BAM resolution can be determined. The dependence of BAM resolution on bunch charge is shown in Fig. 6. Between 300 and 100 pC BAM resolution becomes worse slowly from 14.8 fs to 40.8 fs. Below 100 pC degradation is faster and at 20 pC it reaches 247 fs. The BAM resolution with bunch

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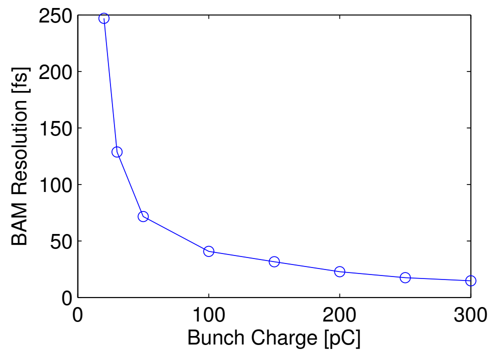

Figure 6: BAM resolution dependence on the charge.

charge of 200 pC is 22.8 fs. In this figure, BAM resolution is inversely proportional to bunch charge.

Using both timing systems (RF timing system and Optical timing system), long term stability test is performed. A long term bunch arrival time measurement with RF timing system is shown in Fig. 7. In this measurement the bunch charge is 200 pC, beam energy is 70 MeV. Figure 7 a) represents the beam arrival time variations measured by BAM. Figure 7 b)

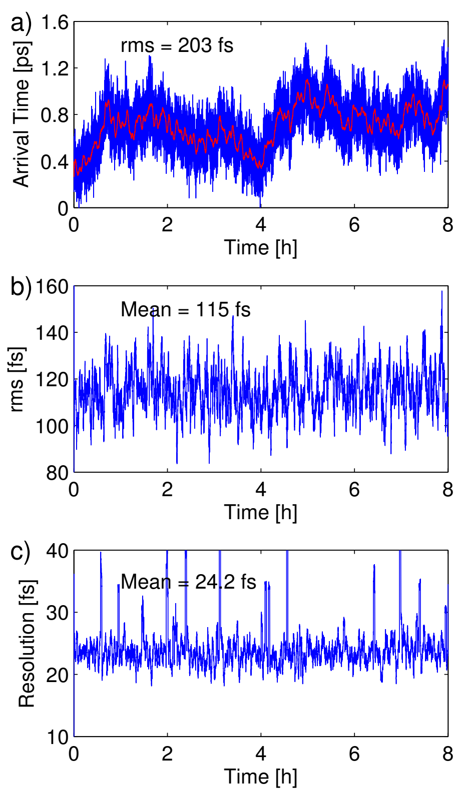

Figure 7: Stability measurement at the bunch charge of 200 pC with RF timing system; a) bunch arrival time, b) bunch arrival time jitter over 100 shots, and c) BAM resolution over 100 shots.

shows the bunch arrival time jitter calculated as deviation of instantaneous arrival time from a smoothed average. The rms jitter is 115 fs and the peak is 158 fs. This jitter accumulates in the gun-laser amplifier and in the transfer line sections following the stabilized laser oscillator. Figure 7 c) represents the resolution of the BAM. The average value of this signal is 24.2 fs. To minimize bunch arrival time jitter, an optical timing system is developed. A long term bunch arrival time measurement with the optical timing system is shown in Fig. 8. In this measurement the bunch charge is

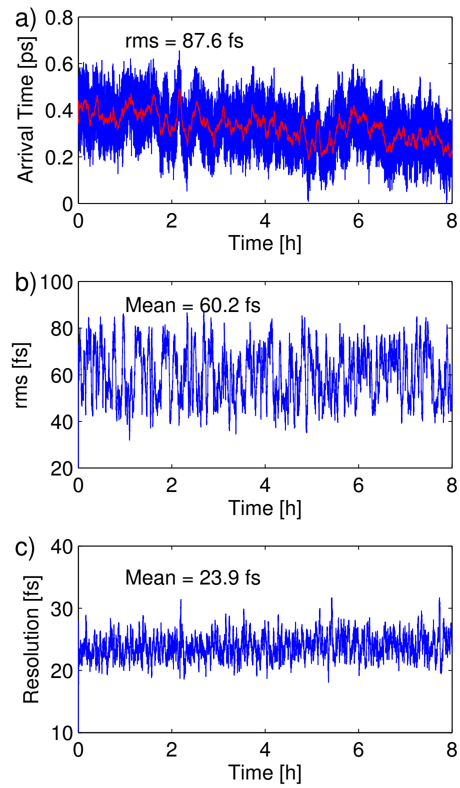

Figure 8: Stability measurement at the bunch charge of 200 pC with optical timing system; a) bunch arrival time, b) bunch arrival time jitter over 100 shots, and c) BAM resolution over 100 shots.

200 pC, beam energy is 70 MeV. Figure 8 a) presents beam arrival time variations measured by BAM. The rms jitter is 60.2 fs and the peak is 85.1 fs. The average value of BAM resolution is 23.9 fs. Initial measurements on long-term stability could be carried out yielding a BAM resolution of around 24 fs over a duration of 8 hours. Comparing the results in Fig. 7 and Fig. 8 the optical timing system is better than the RF timing system.

SUMMARY

In the first BAM measurements the bunch arrival time jitter was 115 fs with the RF timing system and 60.2 fs with

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the optical timing system over a duration of 8 hours without beam feedback. The calculation of BAM resolution was done by using the prototype BAM. In both timing systems the resolution of the BAM is 24 fs. This is larger than the desired value of a few femtoseconds. Probably the main limitation on the BAM resolution with the present setup are the BAM electronics (LLRF system). Studies on the BAM electronics are ongoing. Matching of the input voltage of the ADC will be processed, so that its full 16 bit range can be used independently on the bunch charge. A 16 bit ADC is in progress to improve the resolution and reduce the noise effect at low charge. Also, there are several ideas for improvement of the electronics, which could be implemented as patches. We hope that all these will provide for the required resolution of PAL-XFEL.

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