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ELECTRO-OPTIC MODULATOR BASED BEAM ARRIVAL TIME MONITOR FOR SXFEL*

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Abstract

Beam arrival time monitor (BAM) is an important tool to investigate the temporal characteristic of electron bunch in free electron laser (FEL) like Shanghai soft X-ray Free Electron Laser (SXFEL). Since the timing jitter of electron bunch will affect the FEL's stability and the resolution of time-resolved experiment at FELs, it is necessary to precisely measure the electron bunch arrival time so as to reduce the timing jitter of the electron bunch with beam based feedback. The beam arrival time monitor based on electro-optic modulator (EOM) is already planned and will be developed and tested at SXFEL in the next three years. Here the design and preliminary results of the EOM based beam arrival time monitor will be introduced in this paper.

INTRODUCTION

As China's first X-ray free electron laser (FEL) facility, SXFEL has finished the infrastructure and installation, right now is under commissioning. The main parameters of SXFEL are listed in table 1.

Table 1: Main Parameters of SXFEL

parameter	value
Wavelength	3-9 nm
length	~300m
FEL principle	HGHG, EEHG
Beam energy	840 MeV
Peak current	500A
Normalized emittance	1.5mm.rad
Bunch length(FWHM)	500 fs

The SXFEL is a test facility for various external seeding modes, such as HGHG and EEHG. External seeding lasers are required for the generation of fully coherent radiation pulse. For seeded FEL, large timing jitter and drift of the electron bunch will affect the synchronization between the electron bunch and seed laser, then consequently reduce the stability of the output radiation. To reduce the timing jitter of the electron bunch with beam based feedback, it is necessary to precisely measure the electron bunch arrival time at different locations through the entire FEL facility. The Beam arrival time monitor (BAM) based on phase cavity and RF phase detecting technology has already been tested at SXFEL and obtained the 67.7 fs arrival time resolution [1], while efforts are ongoing to improve the resolution. Meanwhile, to achieve better bunch arrival time resolution, the electro-optic modulator (EOM) based beam arrival time monitor scheme originated from DESY [2-3] is also planned for SXFEL and will be developed and tested at SXFEL in the next three years. In this paper, we present the design of the EOM based beam arrival time monitor for SXFEL, as well some recent progress.

DESIGN OF THE BEAM ARRIVAL TIME MONITOR

Figure 1 shows the schematic diagram of the BAM for SXFEL. The BAM consists of three parts, the beam pick-up, the BAM frond-end and back-end. The beam pick-up is located in tunnel to extract the transient RF signal generated by the driving electron bunch. The BAM frond-end also placed in tunnel is used to transform the shifting of RF signal's first zero-crossing, which stands for the arrival time of the electron bunch, into intensity variation of a reference optical pulse. The BAM back-end placed outside the tunnel is used to detect the amplitude of the optical pulse and derive the electron bunch arrival time information.

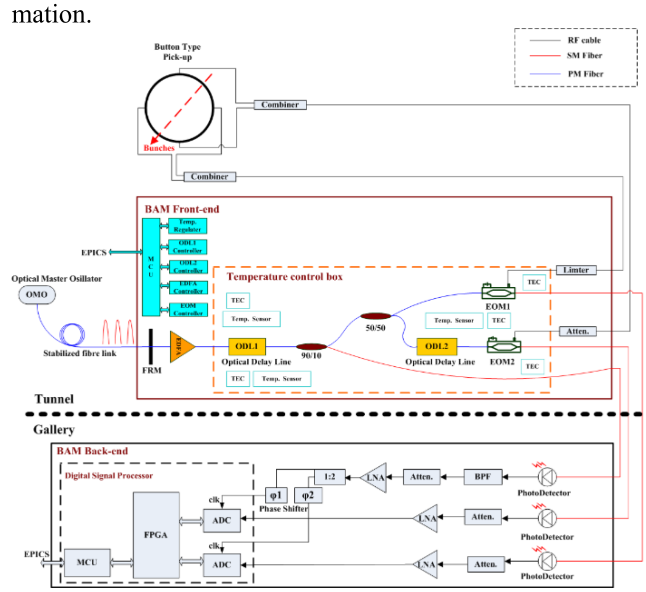

Figure 1: Schematic diagram of the BAM for SXFEL.

Operation Principle

As shown in Fig.1, the optical master oscillator (OMO) is a mode-locked fibre laser with 1550 nm wavelength and 238 MHz repetition rate. The ultra-stable femtosecond optical pulse emitted from OMO transmits over the stabilized fibre link to the remote BAM station and serves as the optical reference signal for BAM. The reference optical pulse enters the BAM front-end and a faraday rotator mirror (FRM) reflects part of it back to help stabilize the phase of the reference optical pulse. The rest optical pulse passes

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through the FRM is amplified by an erbium doped fibre amplifier (EDFA) to proper power level and then passes through one optical delay line (ODL). A 10:90 optical splitter placed behind the ODL divides the optical pulse into two parts, the smaller part will be used as a sampling clock of the BAM back-end, while the other part is again divided into two parts equally by a 50:50 optical splitter and then sent to two EOMs.

EOM is the core component of BAM since it can encode the arrival time of the electron bunch to the intensity variation of the reference optical pulse. Figure 2 shows the transmission characteristics curve of the EOM. By setting proper DC bias voltage for EOM, the output optical intensity will be proportional to the external driving voltage of EOM. Therefore, as shown in Fig.3, for reference optical pulse which transmits through the EOM, its intensity will be modulated by the beam pick-up signal applied on RF port of EOM. Since beam pick-up signal is a transient signal, only the exact optical pulse which coincides with the pick-up signal in EOM will be modulated by it. The first zero-crossing of the beam pick-up signal stands for the arrival time for the centre of the electron bunch. By adjusting the delay of the reference optical pulse, the optical pulse will coincide with that zero-crossing. Then the intensity of the modulated optical pulse will change with the temporal position of the zero-crossing and therefore change with the arrival time of the subsequent bunch. The intensity-to-time conversion factor can be acquired by scanning the delay of the reference optical pulse and detecting the corresponding intensity variation, which is accomplished in calibration procedure. By detecting the intensity of the modulated optical pulse, with the calculated intensity-to-time conversion factor, the bunch arrival time respects to the reference optical signal can be derived.

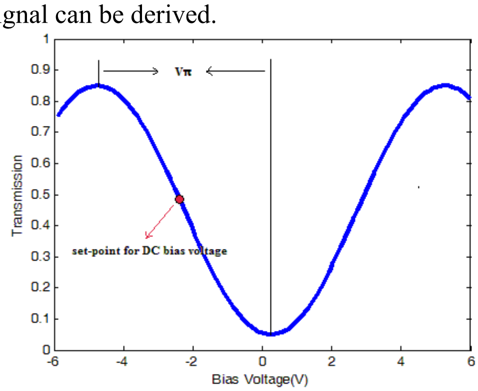

Figure 2: Transmission characteristics curve of the EOM.

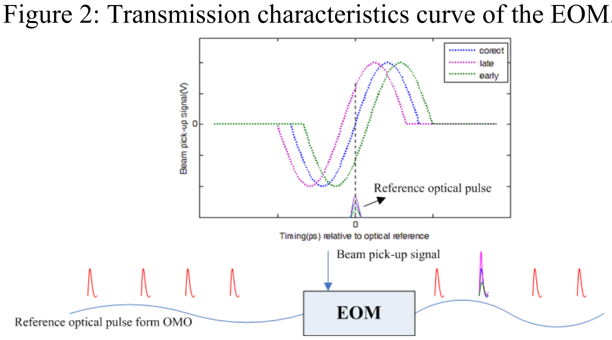

Figure 3: Illustration of the principle for detecting electron bunch arrival time by electro-optica modulation.

As shown in Fig.1, the button type beam pick-up has two pairs of electrodes and they are located in horizontal and vertical directions, respectively. To reduce the orbit-dependency effect, and acquire steeper slope around the zero-crossing as well, signals coupled from oppositely placed electrode-pair are combined in a RF combiner. The combined signal for horizontal electrodes is sent through a voltage limiter and transported to EOM1 to obtain femtosecond level arrival time resolution. While combined signal for vertical electrodes is sent through a power attenuator and transported to EOM2 to assure large dynamic range of several hundred picoseconds. The ODL1 is used for adjusting the delay of the reference optical pulse until the optical pulse coincides with the first zero-crossing of the driving signal in EOM1. To make sure the reference optical pulse also coincides with the first zero-crossing of the driving signal in EOM2, another ODL2 is inserted to eliminate the phase difference between them due to different optical and electrical path length. The modulated optical pulses from EOM1 and EOM2, as well as the aforementioned optical pulse used for clock extracting, are transmitted through three optical fibres to the BAM back-end placed outside the tunnel. BAM back-end employs three high speed photodiodes to convert the optical signals to electrical signals. The converted signal used for clock successively passes a band pass filter (BPF), an attenuator, a low noise amplifier (LNA) to extract the 476 MHz clock signal with proper power level for high speed ADCs. While the other two electrical signals converted from output optical pulse of EOMs are sent to two high speed ADCs for digitization. To match with the ADC saturation voltage, LNA and attenuation are used to adjust the amplitude of ADC input signal. Since the frequency of ADC sampling clock is twice of the repetition rate of the electrical pulse signal, the peak and baseline of the pulse signal can be sampled simultaneously. Meanwhile, two phase shifters are used to adjust the delay of ADC sampling clock, which assures ADC can correctly sample the peak of the pulse signals. The two digitized signals are then processed in FPGA to detect their pulse peak and therefore derive the electron bunch arrival time.

BAM Front-End

BAM front-end which is made up of different optical components, is a crucial module of BAM since it is where the electro-optical modulation takes place. As the electro-optical crystal material like $LiNbO_3$ in EOM has birefringent effect, the performance of EOM is sensitive to the polarization state of the incident light. To assure stable polarization state, all the optical components used in BAM front-end are planned to adopt polarization maintaining (PM) fibre components. This is practicable because the optical fibre used in stabilized fibre link for SXFEL is also PM fibre, meanwhile, commercial PM fibre components such as EDFA, ODL and EOM needed by BAM front-end are easy to find. Since fibre components are sensitive to environmental fluctuation due to temperature and humidity changes, a temperature control module and proper thermal

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isolating shield will be employed to assure stable climatization for BAM front-end.

BAM Back-End

BAM back-end will detect the intensity of the modulated optical pulse so as to extract the bunch arrival time. Conventional high speed photodiode can convert the modulated optical pulse signal into electrical pulse signal for pulse amplitude detecting. The amplitude detection precision dominated by the performance of electronics will affect the resolution of BAM. Thus the most important part of the BAM back-end is the high-speed signal processor which digitizes the electrical pulse signal, detects its pulse amplitude and derives the corresponding bunch arrival time by proper algorithm. The main design parameters for BAM high speed signal processor is listed in table2. Figure 4 shows the photograph of the current BPM signal processor on SXFEL [4], by upgrading the present features and employing high speed ADCs instead of the current ADCs, the new version processor will be applied on BAM.

Table 2: Main Parameters of High Speed Signal Processor

parameter	value
RF channels	4
ADC bits	12
Max ADC rate	500Msps
Signal processor	FPGA
Clock	Ext./Int.
Trigger	Ext./Self/Period
software	Arm-Linux/EPICS

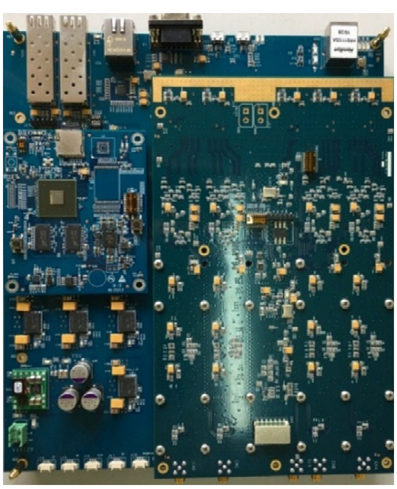

Figure 4: Photography of the current BPM signal processor on SXFEL.

RECENT PROGRESS

We have just finished the project design of the beam arrival time monitor based on EOM. Now components used in BAM are under purchasing procedure and supposed to be arrived at the end of this year. Therefore, main BAM experiments will be carried out in next year. Here we will briefly introduce the preliminary results about the BAM.

Button Type Beam Pick-Up

The beam pick-up used for BAM will adopt the button type pick-up. Figure 5(left) shows the preliminary designed pickup's structure and the simulation result of one pickup in time domain is shown in Figure 5(right). The simulation result shows that the voltage slope around the first zero-crossing is 300 mV/ps. By combining two pickup signals together, the maximum voltage slope applied on EOM1 is 600 mV/ps, which is sufficient for achieving femtosecond level bunch arrival time resolution. More efforts will be made to further optimize the performance parameters of the beam pick-up. For example, steeper voltage slope may be obtained by decreasing the distance between the electrode and electron bunch, while it's possible to increase the bandwidth of the pickup by decreasing the radius of the electrodes.

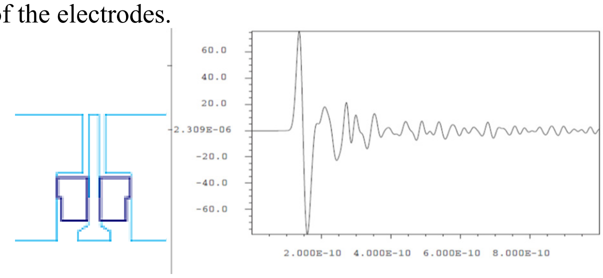

Figure 5: The preliminary designed pickup's structure (left) and the simulation result of one pickup in time domain (right).

Clock Extracting

The signal to noise ratio (SNR) of ADC is critical to amplitude detection precision of BAM back-end. To avoid the SNR deteriorating due to large sampling clock jitter, ADC sampling clock is extracted from the reference optical pulse, which will achieve minimum relative timing jitter between ADC sampling clock and ADC input signal. We built a clock extraction setup (see Figure 6) to observe the timing jitter of extracted clock for ADC. Figure 5b shows the timing jitter of the clock measured by signal source analyzer (E5052B, Keysight), the absolute timing jitter of the extracted 238 MHz clock signal is 263 fs integrated from 10 Hz to 10 MHz (see Figure 7). It can be expected that the relative timing jitter between the ADC sampling clock and ADC input signal will be much lower than that value, and ADC sampling clock won't be the limiting factor for BAM resolution.

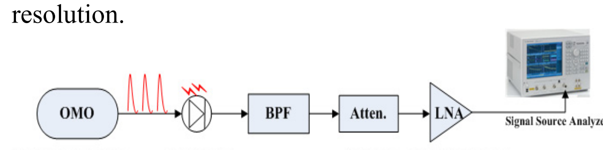

Figure 6: The clock extraction setup.

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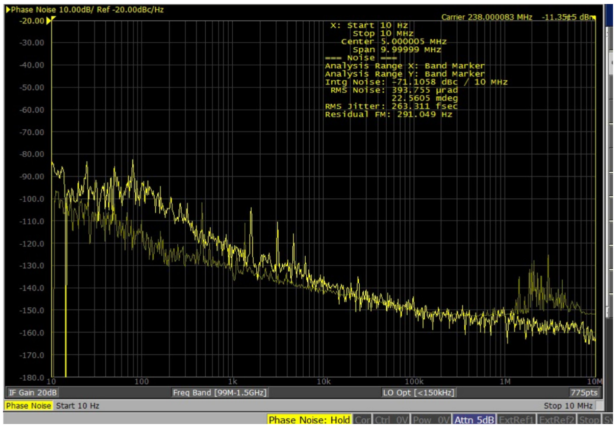

Figure 7: Absolute timing jitter of the extracted 238 MHz clock.

SUMMARY

We report the design of beam arrival time monitor based on EOM for SXFEL, as well as the recent progress. At present, we have finished the design of BAM. Components used in BAM are under purchasing procedure and are supposed to be ready in this year. The first BAM prototype will be developed for SXFEL and we hope to obtain preliminary test results by the end of 2019.

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