ELECTRO OPTICAL BEAM DIAGNOSTICS SYSTEM AND ITS CONTROL AT PSI

P. Chevtsov[#], F. Mueller, P. Peier, V. Schlott, D. Treyer, PSI, Villigen, Switzerland
B. Steffen, DESY, Hamburg, Germany

Abstract

Electro Optical (EO) techniques are very promising non-invasive methods for measuring extremely short (in a sub-picosecond range) electron bunches. A prototype of an EO Bunch Length Monitoring System (BLMS) for the future SwissFEL facility [1] is created at the Paul Scherrer Institute (PSI). The core of this system is an advanced fiber laser unit with pulse generating, phase locking and synchronization electronics. The system is integrated into the EPICS based PSI controls, which significantly simplifies its operations. The paper presents the main components of the BLMS and its performance.

INTRODUCTION

Free Electron Lasers (FEL) are very powerful tunable light sources for a wide spectral range with excellent coherence. One such source, the SwissFEL, will be built at the Paul Scherrer Institute in Switzerland. To achieve optimal lasing conditions for the SwissFEL, the baseline design foresees to generate electron bunches with charges between 200 and 10 pC and lengths between 10 picoseconds (ps) and a few femtoseconds (fs). Accurate and non-destructive monitoring of such short bunches during the FEL operations is not easy to implement. One possible solution of this problem can be provided by Electro Optical (EO) methods [2].

EO electron bunch length measurements are based on the interaction between the electric field E_{THz} (which is in a THz range) generated by the electron bunch and the EO laser pulse in an electro optically active crystal (such as GaP or ZnTe). The electric field can be either the direct bunch Coulomb (near) field if the measurements are performed inside the beam pipe or coherently emitted synchrotron radiation outside of the beam pipe. The field induces a birefringence in the crystal that is proportional to the applied field. This changes the polarization state of the laser pulse, which can be detected by standard optical methods.

The simplest way to determine the E_{THz} shape is to sample it with much shorter laser pulses. If the laser pulses pass a crystal with some variable time delays Δt relative to the E_{THz} field, then they overlap with different parts of the E_{THz} field and experience different polarization rotations. By measuring the degree of the polarization rotation as a function of the time delay Δt, the E_{THz} can be mapped. It is clear that this method is not single shot and requires stable measurement conditions (such as electron bunch shape and EO laser intensity) over many pulses as well as a low relative arrival time jitter between EO laser pulses and E_{THz}.

Alternatively to the E_{THz} field sampling, the E_{THz} pulse can be overlapped with a longer EO laser pulse, which will transform the entire temporal structure of the electron distribution in a bunch on a single laser pulse. The EO laser pulse is stretched in a dispersive medium or by a grating compressor leading to a chirped pulse. A temporal profile of the E_{THz} field is linearly encoded into the laser pulse and can be determined by measuring its spectrum. This single shot technique is known as EO spectral decoding. It is not sensitive to the time jitter between EO laser and E_{THz} signals but requires a treatment of frequency mixing problems.

EO BUNCH LENGTH MONITORING SETUP

A prototype of a bunch length monitoring system (BLMS) for the SwissFEL was created at the PSI. It was successfully tested in the conditions of the Swiss Light Source (SLS), the only electron machine that was available at PSI before the SwissFEL Injector Test Facility was put in operations.

There are at least two places in the SLS ring, which can directly benefit from BLMS operations. The first one is the diagnostic section at the end of the injector where typical bunch lengths are from 2 to 20 ps. The second place is the SLS FEMTO facility [3]. The facility generates coherent fs X-rays based on the beam slicing technique, which utilizes the resonant energy exchange between a long (~35 ps) electron bunch and a fs laser pulse in a wiggler or an undulator. Beam slicing also results in a small (~100 fs) gap in the longitudinal distribution of the bunch that radiates coherently in a THz range. As the bunch continues to move around the ring, the gap quickly spreads and fills with electrons. Real time monitoring of this dynamics can be used to optimize the beam slicing quality.

Because both those places are important for the SLS, it was decided to create the first BLMS as a mobile beam diagnostics station, which could easily be moved around the SLS ring.

We note that most of BLMS parameters presented in this paper are specific for the SLS but can easily be adjusted to fit the SwissFEL case.

Main BLMS Components

The core of the BLMS system is an advanced Ytterbium fiber laser unit [4] together with pulse generating, mode locking and synchronization electronics.

The laser unit was designed and built in the frames of the collaboration between the PSI and the University of

[#]pavel.chevtsov@psi.ch

Bern. It consists of a 50 MHz oscillator and a 1 MHz amplifier. The oscillator cavity is split in free space and fiber sections. A piezo fiber stretcher can correct the resonator length on a µm scale in order to synchronize the repetition rate to the master clock. Cavity length adjustments on a larger scale are done by free space mirrors movable by remotely controlled stepper-motors. The required EO laser operational stability is achieved with the use of laser diode controllers (ITC5xx Series, Thorlabs) and a set of heating elements connected to temperature controlling devices (CT16A, Minco). The laser diode controllers have a GPIB interface to remote computers. Temperature controllers can talk to the external world via serial (RS-232) ports.

The BLMS electronics was developed and built at the PSI. It is based on the FPGA technology and has a modular design. All active elements form two compact 19″ electronics modules: the laser synchronization (LS) unit and the universal pulse divider and generator (UPDG) unit. Both units implement RS-232 interfaces to remote computers, which allows one to relatively easily integrate them into any control system.

BLMS Controls Software and Hardware

BLMS operations at the PSI are automated with the use of controls software based on EPICS [5]. The software consists of two main parts: the laser and the LS/UDPG control modules. Both parts utilize the EPICS Stream Device support [6] package to handle RS-232 and GPIB devices.

The controls software runs on three EPICS Input Output Controllers (IOCs).

The first one is a VME based single board computer MVME-5100 running VxWorks. This IOC handles

- a PSI timing event receiver (EVR, Micro-Research) board that is used to trigger electronics equipment based on any event available from the PSI timing event distribution system;
- BLMS stepper-motors on the basis of a MAXv-8000 (Pro-Dex) VME card and standard PSI motor drivers;
- serial BLMS control devices via RS-232 ports provided by TIP-866 IPAC modules (TEWS Elektronik).

Another IOC is a LINUX microIOC (Cosylab) handling GPIB control components via an Agilent E5810A LAN GPIB multiport controller. It also runs control applications automating major BLMS operations.

Finally, the EO data acquisition and control server is implemented as a softIOC embedded on a fast digital oscilloscope running WindowsXP.

All BLMS components, except the laser unit, are placed in a mobile 19″ electronics rack. The rack is also equipped by its own EO PC. This PC primarily acts as a boot computer for the VxWorks IOC. As a result, the IOC is booted on any PSI sub-network automatically, by turning on its power, without changing its boot parameters. The EO PC also acts as a port server to access the IOC VxWorks shell and as an additional computing power for EO related EPICS development activities.

The following paragraph explains how the BLMS electronics and controls software work by way of an example of their operations for the SLS beam slicing diagnostics.

BLMS at Work

As it was shown above, EO measurements rely on a temporal overlap between a laser pulse and the electric field generated by the electron bunch in an electro optically active crystal. This requires a very good synchronization to a reference signal (RF) and a low jitter of the laser signal. On the other hand, the absolute timing is also important and needs to be taken care of. If the overlap is found once, the absolute timing should be the same after any required laser resynchronization.

In this context, a problem arises if two signals of different repetition rates have to be locked, such as, for example, the EO laser at 50 MHz and the RF at 500 MHz. As it is more precise to compare these signals at higher frequencies (the same phase mismatch at 500 MHz leads to a ten times lower temporal offset than at 50 MHz), the comparison is done at 500 MHz, which means that the 10-th harmonic of the laser repetition rate is locked to the RF. As a result, the laser can be synchronized to the reference in ten different ways in terms of the absolute timing. The following shows how this problem is solved for BLMS. It also describes how the whole synchronization system works.

The next signals are relevant for the EO diagnostics:

- RF – 500 MHz;
- EO fiber laser oscillator – 50 MHz;
- SLS revolution clock – 1 MHz;
- FEMTO slicing trigger – 2 KHz;
- SLS linac trigger – 3 Hz.

The revolution clock is synchronous to the revolution of a particular bunch in the SLS storage ring and the FEMTO slicing trigger is used for measurements of the sliced bunches.

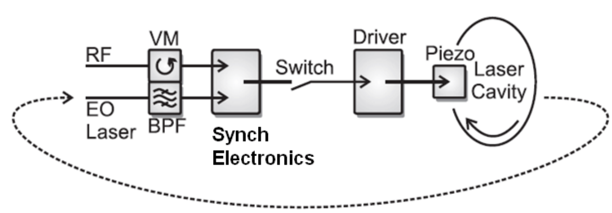

Figure 1: EO phase locked loop (PLL) scheme. The 10-th harmonic of the EO laser repetition rate generated by the bandpass filter (BPF) is locked to the RF, which can be shifted in time by the vector modulator (VM).

The 10-th harmonic of the EO laser repetition rate (see Fig. 1 above) is generated by a bandpass filter (BPF) and is compared to the RF, which can be shifted in time by a vector modulator (VM). The VM shifts the phase with a resolution of 2^{12} steps per revolution (360°). At the RF repetition rate of 500 MHz this leads to a minimal step width of about 488 fs. Two signals are compared by the synchronization electronics, generating a correction signal. The switch between the electronics and the driver is remotely controlled in order to interrupt the PLL in case of any required interlock conditions or simply to switch the synchronization on or off. A piezoelectric device finally corrects the cavity length. The repetition rate of the laser serves as a feedback signal and is closing the loop.

In the second step, a reproducible starting point has to be found. This is done by the coincidence detector (see Fig. 2), which compares the repetition rates of the EO laser and revolution clock. As long as the signals are not synchronous the coincidence detector control software shifts the EO laser pulse in time by rotating the phase of the RF until the overlap is found. The accuracy of this method is in the order of ±5 ps, which allows one to find such an overlap very quickly.

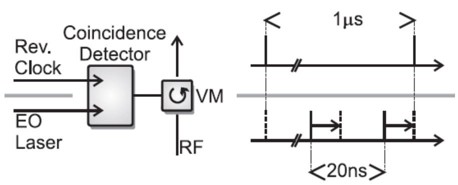

Figure 2: The second step of the EO synchronization. The coincidence detector shifts the EO laser pulse in time until coincidence to the revolution clock is achieved.

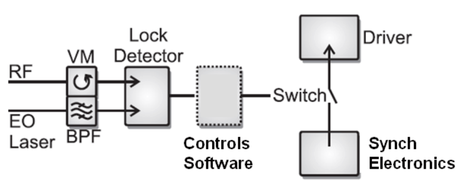

Figure 3: The lock detector control software interrupts the PLL if the offset frequency between the RF and the repetition rate of the EO laser becomes larger than 1 Hz.

In case of any malfunctions of the synchronization system, interlock signals have to be generated in order to interrupt the PLL and protect the piezoelectric fiber stretcher. It is done by the lock detector controls software (Fig. 3). As soon as the frequency difference between the RF and the 10-th harmonic of the EO laser repetition rate exceeds 1 Hz the output of the lock detector switches from logic high to low disconnecting the PLL link between the synchronization electronics and the piezo driver.

Between the oscillator and the amplifier the repetition rate is reduced to 1 MHz by an Acousto Optic Modulator (AOM). Because this pulse picker needs to be synchronous with the laser, it is triggered by the repetition rate of the EO laser. The BPF generates a sinusoidal signal at 200 MHz, which is connected to the clock of a resettable counter. The counter is reset by the 3 Hz SLS linac trigger.

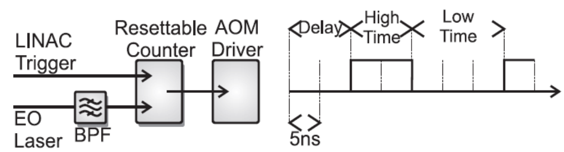

Figure 4: The trigger for the AOM is generated by a resettable counter. The delay, width and spacing can be adjusted in steps of 5 ns.

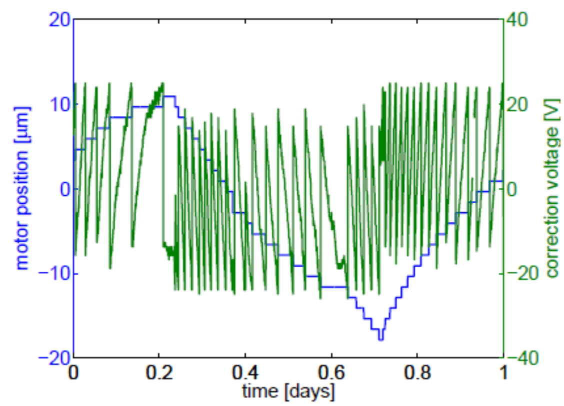

Figure 5: Typical automated corrections of the EO laser oscillator cavity length over one day. The green line is the piezo stretcher voltage, the blue line is the mirror position change.

The output is controlled in terms of a one-time delay, a high and a low time. As the device is counting with 200 MHz, these parameters can be adjusted in 5 nanosecond (ns) steps.

Besides handling the interlocks, the controls software ensures that if the piezo voltage exceeds a certain threshold then the required correction is done by one of free space mirrors. The Fig. 5 shows a typical behaviour of the piezoelectric stretcher (green line) and the mirror stepper motor (blue line), which is routinely provided by the controls software. We note that it is exactly what is expected of it.

The EO setup for the SLS beam slicing diagnostics [7] can be used for both techniques mentioned above: sampling and spectral decoding.

In case of sampling, the measurements of the signal amplitude as a function of the time delay are done by the oscilloscope software. The experiment is controlled by an EPICS high level application, which drives the VM, handles time delays, processes and stores the data.

Spectral decoding measurements are based on the use of a spectrometer. The spectrometer data are digitized and processed by embedded software, which makes these data immediately available for the control system.

CONCLUSION

The EO BLMS at the PSI has been in operations for more than one year. The system is fully integrated into the EPICS controls, which significantly simplifies all its functions. Bunch length measurement results obtained at the SLS show that the performance of the BLMS is absolutely adequate to its main task for the SwissFEL. Some additional work is required though, mostly for dealing with signal jitters in EO sampling procedures.

REFERENCES

[1] B. Patterson, R. Abela, H. Braun, et al. “Coherent Science at the SwissFEL X-ray Laser”, New J. Phys. 12, 035012 (2010)

[2] E. Friedman and J. L. Miller, “Photonics Rules of Thumb: Optics, Electro-Optics, Fiber Optics, and Lasers”, McGraw-Hill, 2004, 418 p.

[3] V. Schlott, et al. “THz Diagnostic for the Femtosecond Bunch Slicing Project at the Swiss Light Source”, EPAC-2006, Edinburg, Scotland, 2006.

[4] F. Mueller et al. “A Compact Electro Optical Bunch Length Monitoring System – First Results at PSI”, FEL-2010, Malmoe, Sweden, 2010.

[5] R. Lange, J. Anderson, et al. “EPICS: Recent Developments and Future Perspectives”, ICALEPCS-2003, Gyeongju, Korea, 2003.

[6] D. Zimoch, et al. “Standardization of the DELTA Control System”, ICALEPCS-1999, Trieste, Italy, 1999.

[7] F. Mueller, et al. “Electro Optical Sampling of Coherent Synchrotron Radiation for Picosecond Electron Bunches with Few pC Charge”, BIW-2010, Santa Fe, NM, USA, 2010, p. 538-542.