COMPACT MTCA.4 BASED LASER SYNCHRONIZATION*

M. Felber[+], Ł. Butkowski, H.-T. Duhme, M. Fenner, Ch. Gerth, U. Mavrič, P. Peier,
H. Schlarb, B. Steffen, Deutsches Elektronen-Synchrotron DESY, D-22607 Hamburg, Germany
T. Kozak, P. Prędki, K. Przygoda, DMCS, Łódz University of Technology, Poland

Abstract

In this paper we present a compact and efficient approach for laser synchronization based on MTCA.4 platform. Laser pulses are converted to the RF signals using a photo-diode detector. An RF section performs filtering, amplification and down-conversion of a narrowband, CW signal. The resulting IF signal is sampled by a high resolution digitizer on the AMC (Advanced Mezzanine Card) side and transported via point-to-point links to an adjacent AMC board. The processing electronics on this board drives a digital-to-analog converter on the rear-side. The analog signal is then filtered and amplified by a high voltage power amplifier which drives the piezo stretcher in the laser. Some preliminary results of laser-to-RF locking with such a scheme are presented.

INTRODUCTION TO MTCA.4

MTCA.4 (Micro Telecommunications Computing Architecture - Enhancements for Rear I/O and Precision Timing) has become a viable standard for demanding applications in large-scale research facilities of the high-energy physics and photon science community. Originally derived from ATCA™ (Advanced Telecommunications Computing Architecture), the MTCA standard has gained popularity as a compact, versatile and cost-efficient alternative wherever low-noise analog and ultra-high speed digital signal processing is required. The mechanics and connectivity is defined by the standard PICMG MTCA.4 specification [1, 2].

The basic architecture follows the idea of a centralized powerful processing unit (CPU board) that is connected to various Advanced Mezzanine Cards (AMCs) over the backplane consisting of several PCIe lanes, gigabit ethernet links, dedicated trigger lines, SATA connections, clock lines, platform related management lines and 4 ports for point-to-point connections (eight differential pairs, full-duplex). On the back side of the crate there is the possibility to connect a Rear Transmission Module (RTM) to each AMC board. The platform is managed by the MTCA Carrier Hub (MCH) taking care of crate management (power, cooling), PCIe port switching and generation of timing signals.

The laser-based synchronization group at DESY [3, 4] decided to deploy this new standard for their fast feedback controls. Most of the needed boards are developed within the framework of the MTCA.4

Helmhotz Validation Fund which is used to bring the module developments to a mature state and establish MTCA.4 in industry applications [5]. Therefore the setup for laser synchronization consists mostly of commercially available boards which were designed by DESY or its collaborators to cover a wide range of applications, i.e. they are general purpose modules. Nevertheless during the design process it was taken care that the functionality also matches the needs for laser-based synchronization applications. A more detailed description of the used hardware is provided in the section about system components.

BASIC CONCEPT FOR LASER SYNCHRONIZATION

In accelerator facilities, especially free-electron lasers (FEL), the use of mode locked lasers is very common e.g. as photo-cathode laser, for electro-optical diagnostics, seeding, and pump-probe experiments. The repetition rate of the laser pulse train is usually a sub-harmonic of the main RF reference. At DESY, for example, the main RF at the FELs FLASH and European XFEL is at 1.3 GHz while the lasers usually run at 54.2 MHz (24th sub-harmonic), 81.25 MHz (16th sub-harmonic), 108.3 MHz (12th sub-harmonic), or 216.7 MHz (6th sub-harmonic).

Both the frequency stability and phase noise close to the carrier of mode locked lasers is usually very bad compared to conventional RF oscillators. The lasers are synchronized to the accelerator reference with the help of a piezo element within the laser cavity to tune the repetition rate and phase. This is usually realized by a piezo stack moving a mirror. In fiber lasers this can also be done by a piezo stretcher in fiber.

One of the key components for a synchronization setup is the phase detector which shows the frequency offset in the unlocked (i.e. not synchronized) state and the phase difference in the locked state. Over the past years several methods for phase detection between RF and laser pulse train were developed, investigated, and deployed in different facilities. These include analog RF-to-baseband mixing [6, 7], Sagnac-Loop interferometer [8, 9], MZI-based schemes [10, 11], and the down-conversion scheme which is presented in this paper. The main advantages of the latter are that there are no baseband signals on the detection side and there is no need for a vector-modulator as phase shifter for timing scans. Furthermore it is easily integrated into the MTCA.4 form factor using partly the same hardware components and firmware resources as the low-level RF system. Nevertheless this scheme depends on the direct conversion process which has certain disadvantages concerning noise and drift [6]. Depending on many parameters of the individual setup the

performance is typically limited to about 20-30 fs$_{rms}$ short- and long-term [12].

SYSTEM COMPONENTS

In this section we describe the setup in the current development state by the example of a 54.2 MHz Yb-fiber laser which will be used for electro-optical diagnostics in the European XFEL. A sketch of the system is shown in Figure 1. Main components are the MTCA.4 hardware, an RF front-end, and the Yb-laser.

MTCA.4 Components

Besides the basic MTCA.4 crate infrastructure composed of crate, MCH, CPU, power supply, AMC backplane and cooling, the laser-locking application comprises two AMCs and two RTMs in MTCA.4 standard occupying only two slots in the crate. Up to now the laser pulses are translated to RF and processed accordingly in an external RF front-end 19" chassis. The integration of this unit into a dedicated laser synchronization RTM with enhanced functionality is under development. The output of the RF setup is fed to the down-converter board DRTM-DWC10 which is placed as RTM in the MTCA.4 crate.
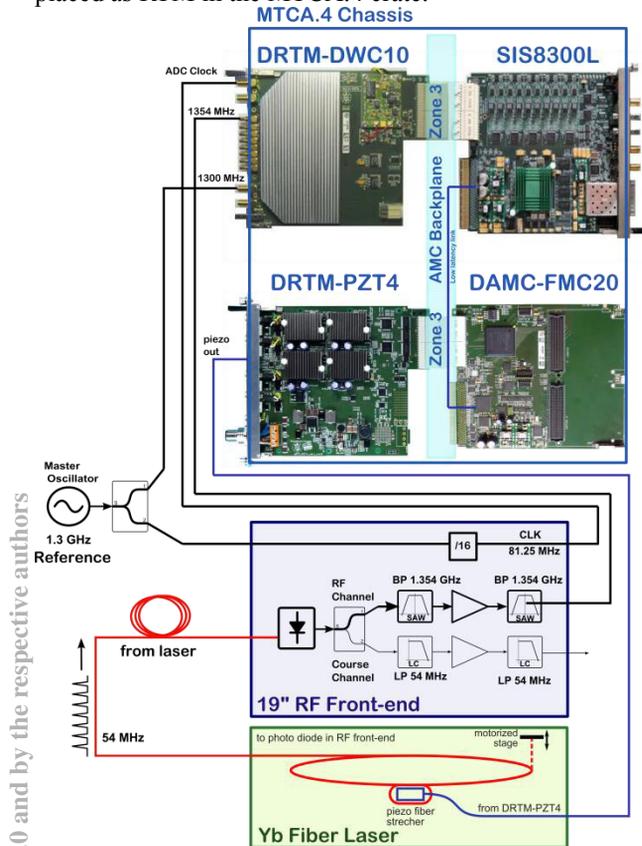

Figure 1: Synchronization setup consisting of a MTCA.4 chassis with AMC and RTM boards, the RF front-end and the laser (in this case an Yb-fiber laser)

The signals are down-converted and the intermediate frequency (IF) is transmitted via the Zone 3 connector to the AMC side of the crate where it is sampled by a 10-channel digitizer SIS8300L (www.struck.de). The processing includes I/Q detection of the sampled signals, amplitude and phase transformation, feedback controller, and feed-forward table. In order to achieve suppression of Eigen-modes of the piezo, a digital notch filter has been included. The output of the controller is routed to the DAC outputs on the digitizer (for monitoring purposes) and transmitted over low-latency links on the AMC backplane to the neighboring AMC board DAMC-FMC20. The DAMC-FMC20 is a low-cost FPGA Mezzanine Card (FMC) carrier board which consists of two FPGAs. One FPGA is used for backplane interconnects (PCIe, multi-gigabit transceivers etc.), and the second FPGA is used for interconnecting with the rear-transition module (RTM) over the Zone 3 connector. The RTM module is a MTCA.4 compliant piezo driver called DRTM-PZT4 [13]. The board is equipped with four power amplifiers supplied from internal DC/DC converters (output range: 0-100 V, or ±100 V). The software programmable span DACs (500 kSPS) have been applied to fulfil all demanded control signal ranges. Each power amplifier gain has been fixed to 10 V/V. The RTM module can drive up to four parallel piezos with capacitances of up to 10 µF. The output of the piezo driver is directly connected to the piezo of the laser.

RF Front-end

The default frequencies for the down-converter are RF: 1.3 GHz and LO: 1.354 GHz such that the IF is at 54 MHz. This scheme would require a LO generation from the 1.3 GHz reference line in the accelerator. In order to avoid this additional RF setup, which is - besides the obvious disadvantages like complexity, size, and price - also a source of noise and drift, the RF and LO frequencies are exchanged in this scheme. The front-end 19" chassis converts the photodiode signal generated from the laser pulses into an RF signal at 1.354 GHz which is the 25th harmonic of the laser repetition rate. Then the 1.3 GHz reference is used as the LO input. The clock signal of 81 MHz (or 54 MHz for the 81 MHz lasers) for the SIS8300L ADCs is generated from the 1.3 GHz reference with a low-noise divider to avoid clock timing jitter.

Due to under-sampling the digital values are interpreted as a 27 MHz signal without loss of information. The other possible laser frequencies mentioned before may have a different fundamental repetition rate but the digital values still result in the same 27 MHz after under-sampling, which eases the firmware development.

For the detection of the absolute timing of the laser pulses with respect to the over-all machine timing the phase of the repetition rate has to be set correctly and monitored which is called bucket detection. In order to do this detection, the fundamental frequency of the laser is extracted in the RF front-end as well. It can be fed to the ADC directly without down-conversion; the phase detection algorithm is the same for the fundamental and the down-converted signal. Again the same counts for the other possible repetition rates.
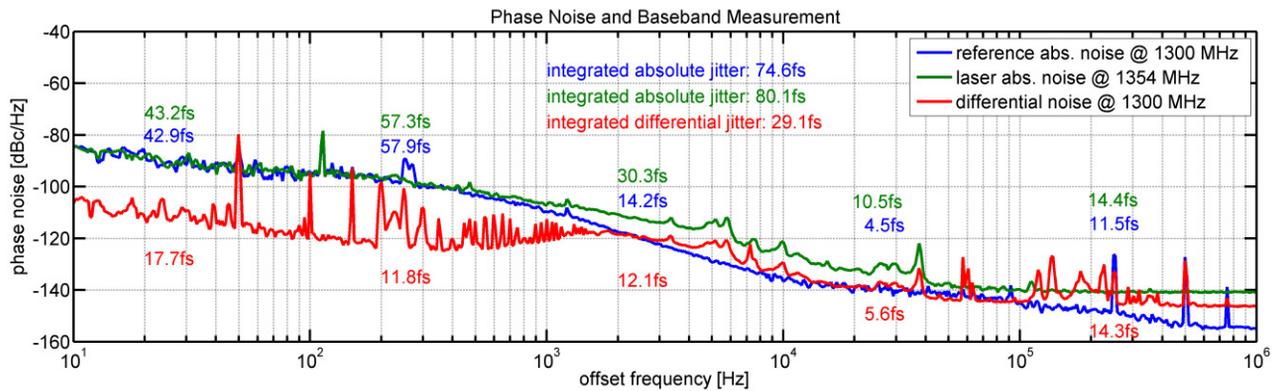
Figure 2: The phase noise spectrum of the 25th harmonic (1354 MHz) of the laser fundamental (54.2 MHz) (green curve) and phase noise spectrum of the local oscillator (reference @ 1300 MHz) (blue curve). The baseband noise of the 24th harmonic (1300 MHz) of the laser mixed with local oscillator (red curve). The jitter per decade is indicated with colored numbers. The 50 Hz lines in baseband noise considerably contribute to the jitter per decade.

Ytterbium Fiber Laser

The Ytterbium fiber laser is housed in a 19" chassis with 6 HU [14]. It delivers 1 nJ pulses at a wavelength of 1030 nm with a repetition rate of 54 MHz. The laser consists of a ring oscillator with a fiber and a free space part. The amplification and pumping is done in fiber The free space part is necessary for dispersion compensation and the mode locking mechanism. A piezo fiber stretcher changes the resonator length and therewith the laser pulse repetition rate.

MEASUREMENT RESULTS

The performance of the laser synchronization is given by the phase noise of the locked laser at the locking frequency (1354 MHz) and the resulting integrated jitter. Figure 2 shows the in-loop phase-noise of the laser RF (green curve) and the local oscillator (LO, blue curve). It is clearly visible that the locking to the LO has strong influence to the laser up to 1.5 kHz offset frequency, i.e. the phase noise curve of the laser RF follows the phase noise curve of the LO. Amplified noise and resonances in the locking loop prevent from setting higher locking bandwidth.

The baseband noise depicted in Figure 2 (red curve) shows the differential timing jitter between the laser and the RF reference measured independently (out-of-loop) with a 1300 MHz double-balanced mixer at baseband.

Several peaks can be identified in the red curve in Figure 2. The most prominent is located at 37 kHz and corresponds to the piezo crystal resonance. The plateau at higher offset frequencies (>50 kHz) is caused by the limited performance (noise) of the photo receiver. The spurious peaks at multiples of 50 Hz result from ground loops in the measurement setup.

The total integrated rms jitter of the laser in the interval between 10 Hz and 1 MHz was determined to be 80 fs with the rms jitter of the LO being 75 fs. The differential

jitter (rms) of laser and LO (baseband) was 29 fs. The analysis of the jitter per decade (Fig. 2: colored numbers) reveals room for improvement of the locking setup in the range of 1−10 kHz.

CONCLUSION

Synchronization of a 54 MHz Yb-laser to an RF reference has been demonstrated on a compact system based on commercially available MTCA.4 components and prototypes. The test setup still serves for further development of hardware, firmware, and software. The next steps are to include the bucket detection and coarse tuning. The scheme is already deployed at selected locations for different laser types and frequencies and will be the standard system for synchronizing lasers at the European XFEL and other facilities.

REFERENCES

[1] http://www.picmg.org
[2] http://mtca.desy.de
[3] S. Schulz et al., WEPC32, IBIC (2013).
[4] C. Sydlo et al., MOPC32, IBIC (2013).
[5] H. Schlarb et al., THPWA003, IPAC (2013).
[6] B. Lorbeer et al., MOPAN017, PAC (2007).
[7] M. Felber et al., THOA3, FEL (2010).
[8] J. Kim et al., Optics Express, Vol. 15, Issue 14, pp. 8951-8959 (2007).
[9] M. Felber et al., TH6REP088, PAC (2009).
[10] E. Janas et al., WEPRI115, IPAC 2014, these proceedings.
[11] M. Titberidze et al., IBIC 2014, to be published
[12] M. Felber et al., WEPPD048, IPAC (2012).
[13] K. Przygoda et al., THPRO105, IPAC 2014, these proceedings.
[14] F. Mueller et al., TUPD31, DIPAC (2009).