STATUS OF THE FIBER LINK STABILIZATION UNITS AT FLASH

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Abstract

State-of-the-art X-ray photon science with modern free-electron lasers (FEL) like FLASH (free-electron laser in Hamburg) and the upcoming European X-ray Free-Electron Laser Facility (XFEL) requires timing with femtosecond accuracy. For this purpose a sophisticated pulsed optical synchronization system distributes precise timing via length-stabilized fiber links throughout the entire FEL. Stations to be synchronized comprise bunch arrival time monitors (BAM's), RF stations and optical cross-correlators (OXC) for external lasers. The different requirements of all those stations have to be met by one optical link stabilization unit (LSU) design, compensating drifts and jitter in the distribution system down to a fs-level. Five years of LSU operation at FLASH have led to numerous enhancements resulting in an elaborate system. This paper presents these enhancements, their impact on synchronization performance and the latest state of the LSUs.

INTRODUCTION

The laser based synchronization system depends on a stabilized optical pulse-train with femtosecond precision. This pulse-train is generated by a master laser oscillator (MLO) - a mode-locked laser - which is phase-locked against a master oscillator (MO) being the master timing for the complete accelerator [1]. A free-space distribution (FSD) splits the optical pulse-train into several channels each serving one link-stabilization-unit (LSU). Within the LSU the optical pulses are again split into reference and link pulses. The latter travel through a link fiber to a station where a part of the light is reflected back to the LSU for detection and compensation of timing changes.

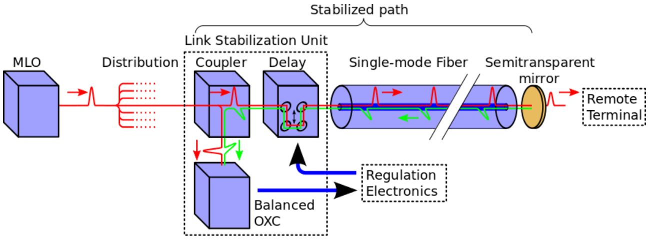

Figure 1: Simplified link-stabilization unit scheme.

This reflected light is mixed with the reference light inside a balanced optical cross-correlator (OXC) based on a PPKTP crystal providing a signal proportional to a timing deviation [2, 3]. The compensation actuators comprise a piezo fiber-stretcher for fast and a motorized delay stage for slow drifts. In Figure 1 this scheme is depicted.

LINK STABILIZATION UNIT

The above described scheme is a further improved version, presented in Figure 2, of the last engineered implementation reported in [4]. As the limited MLO optical power has to serve multiple channels and diagnostics, each LSU features an erbium-doped fiber-amplifier (EDFA) at its input. To generate a defined linear polarization at the first beam-cube, which works as a splitter, a set of $\lambda/4$ and $\lambda/2$ waveplates is used. An optical isolater is included here to protect the MLO from any kind of backreflections. The $\lambda/2$ plate is used to set the splitting ratio at the first beam-cube for the reference path and the link path. In the link path the pulse-train passes the first actuator for large timing changes, the motorized delay stage. The subsequent part is coupled into a single-mode fiber. Here a 2×2 coupler follows for diagnostic purposes. Then an EDFA follows compensating losses in the link and providing sufficient optical power for the stations. A spool of dispersion compensating fiber (DCF) is required to stay chirp-free at the station and the OXC. The last component in the LSU is the second actuator for fast timing changes and jitter, the piezo fiber-stretcher.

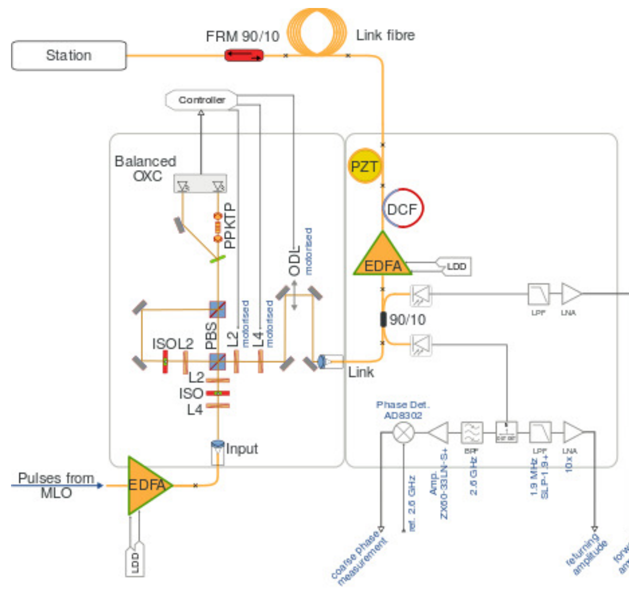

Figure 2: New LSU setup, version 3.2.

From the LSU a link fiber guides the light conveniently to its station. Here, a Farady rotating mirror (FRM) reflects a part of the light in the very same fiber back to the first

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splitting beam-cube, where it also ensures an orthogonal polarization.This orthogonal polarization travels straight through the first splitting beam-cube and an isolator to avoid parasitic reflections back into the link. A subsequent$\lambda/2$ plate sets the correct polarization for the spatial pulse overlap in the second combining beam-cube. The combined pulses from reference and link path are focused then into an PPKTP crystal for timing deviation detection.

LATEST IMPROVEMENTS

Integrated Electronics

The link electronics inside a LSU contains various components:

- ▷ Forward and backward power detection: Photodiode, low-pass filter and amplifier
- ▷ RF phase detector: Shared photodiode, diplexer, band-pass filter, RF amplifier and phase-detector

The previous electronics set-up for diagnostics consisted of individual discrete components, each separately housed and individually mounted into the LSU. To save space and reducing cabling complexity a single integrated electronics board has been developed as shown in Figure 3 in comparison to the previous set-up.

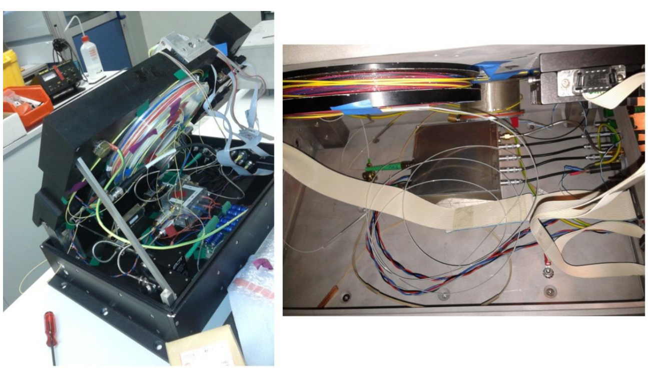

Figure 3: Comparison of the LSU with old link-electronic (left) and with the new integrated one placed in the bottom of the housing (right).

Balanced Detector

The balanced detector transforms the differential optical response from the PPKTP crystal to an electrical signal. Its quality for optical timing synchronization strongly depends on noise, electrical drift and offset error. To obtain high accuracy for the detection of the optical signals, delivered by the PPKTP crystal in the balanced OXC. Commercially available products have been evaluated, but do not provide achievable performance to meet our standarts.

Consequently, an own development has been launched to obtain optimum results from the balanced OXC. White noise as well as the noise-gain of transimpedance amplifiers

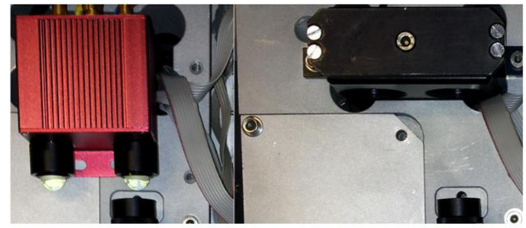

Figure 4: The new balanced detector (left) and a commercial (right) detector viewed from the top. The commercial one requires a cut-out in the baseplate due to its large height.

have been reduced. A detailed description of this development will be published elsewhere. The transimpedance gain can be set manually or remotely. The design has been kept mechanically and optically compatible to the existing LSUs, while reducing physical size. Both designs are shown in Figure 4.

Opto-Mechanical Free Space Parts

The previous version of the free-space layout allowed parasitic reflections to be coupled back into the link. The major source for parasitic pulses is the highly-reflective rear side of the PPKTP-crystal in the OXC. A pronounced example is shown in Figure 5. Other sources can arise from imperfect anti-reflection coatings on any surface and fiber imperfections.

Once pulses get coupled back into the fiber part they get amplified by the EDFA, get straight through the link with all its components and potentially distort timing at the station. The laser-to-laser applications using OXCs is influenced by the parasitic pulses when they are close in time with respect to the original pulse train. However, applications using electro-optical modulators are influenced strongly by any distortions on the optical pulse train, since the photoreceiver integrates over the opportunistc pulses.

To resolve this issue a second isolator is deployed in the path of the returning beam between both beam-cubes. Only this two beam-cube configuration is able to accommodate the second isolator, which is indispensable for reliable operation. Independent to this, all of the optics needs careful inspection of the pulse train.

Fiber Components

The unstabilized fiber behind the actively stabilized link end is subject to temperature, relative humidity and vibration induced timing drifts. In order to reduce the drifts and additional jitter sources, it is desirable to avoid additional components, especially an unstabilized EDFA. Therefore, the link pulses should deliver sufficient optical power. But here the problem arises that the non-linearities in standard single-mode fibers scale with the peak power of the pulse. The mode-locked laser of the synchronization system delivers pulses with less than 200 fs FWHM. If the dispersion is

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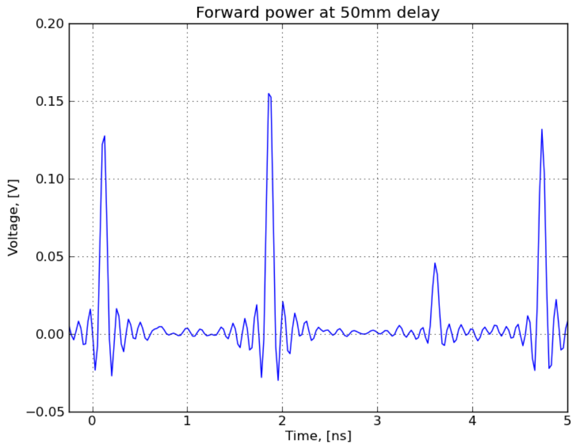

Figure 5: Regular laser pulses of the FLASH synchronization system have a repetition rate of 216.7 MHz or a period of 4.6 ns. This graph shows a drastic example of parasitic pulses.

compensated pulses become short again and are amplified with the EDFA to more than 30 mW average optical power. Here, the pulse peak power already reaches 400 W at about 140 pJ of pulse energy. In effect, the optical spectrum of the pulses around 1550 nm deteriorates and the efficiency of the second-harmonic generation inside the PPKTP decreases.

There are two solutions to this problem: first, one has to empirically find a trade-off between spectral purity within the link and output power behind the link end. The second and more promising option is to put the intra-link EDFA to a location where the link pulses are temporally broadened and consequently carry less peak power. It is noticeable, that even the fiber-stretcher contributes to spectral distortions. All possible permutations with the fiber components have been tested and this has led to a new sequence of components which is presented in table 1.

Table 1: Comparison of the Order of Fiber Parts in a LSU

Order No.	Until Version 3.0	New Version
1	Link-collimator	Link-collimator
2	2 × 2 Coupler	2 × 2 Coupler
3	Fiber-stretcher	EDFA
4	DCF-spool	DCF-spool
5	Fiber link	Fiber-stretcher
6	EDFA	Fiber link
7	FRM	FRM

With this new configuration it is easier to optimize the power budget within and behind the link, while maintaining an acceptable OXC signal shape and slope steepness.

The LSU scheme contains yet another EDFA, which is located in front of it. The large number of LSUs, in case of FLASH 16, which are supplied by one Master laser oscillator necessitates this EDFA. In the actual synchronization system, a portion of 5 mW from the free-space MLO power is reserved for each LSU, resulting in 3.2 to 4.8 mW which is coupled into the gain fiber and amplified to about 70 mW. This gain fiber[1] used for this amplifier is different from the intra-link EDFA and provides a larger gain as well as a negative dispersion around -10 fs/(nm m), thus has a sligthly dispersion compensating effect. Anyhow, the optical spectrum gets distorted through non-linearities (self phase modulation - SPM) which gives potentially bad start conditions for the OXC scheme.

In addition, the uncompensated EDFA adds timing drift and jitter due to environmental factors like vibration, relative humidity and temperature. Thus, if one can dispense with the fiber amplifier in front of the LSU, the spectral and temporal behavior of the optical pulses can be improved. This has been investigated in a test set-up, where the MLO pulses had been coupled into the LSU optics in free-space. The average power with about 10 mW is much less here compared to what is normally provided by an EDFA. But in this case, best results have been achieved with optimium OXC signal together with clean spectral shapes.

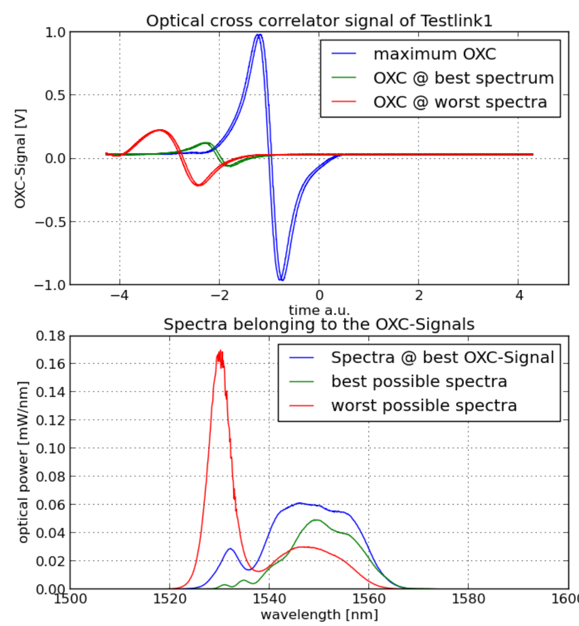

Figure 6: Trade off from optical cross-correlator signal shape to spectral purity

OUTLOOK

Future LSUs, for example at XFEL, will get a free-space in-coupling to get rid of uncorrelated fiber drifts and to get best shaped pulses in terms of spectrum and length. The problem of lower power is currently under investigation.

[1] Er110-4/125 - 4µm core, LIEKKI

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