LASER ARRIVAL TIME MEASUREMENT AND CORRECTION FOR THE SwissFEL LASERS

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Abstract

SwissFEL will ultimately produce sub-fs X-ray pulses. Both the photo-injector laser and the pump lasers used for the experimental end stations therefore have tight requirements for relative arrival time to the machine and the X-rays. The gun laser oscillator delivers excellent absolute (including reference jitter) jitter performance at ~25 fs integrated from 10 Hz-10MHz. The Yb:CaF_2 regenerative amplifier, with an over 1 km total propagation path, calls for active control of the laser arrival time. This is achieved by balanced cross-correlation against the oscillator pulses and a translation stage before amplification. The experimental laser, based on Ti:sapphire laser technology will use a spectrally resolved cross-correlator to determine relative jitter between the optical reference and the laser, with fs resolution. To be able to perform fs resolution pump-probe measurements the laser has to be timed with the X-rays with <10 fs accuracy. These systems will be integrated into the machine timing and complemented by electron bunch and X-ray timing tools. Here we present the overall concept and the first results obtained on the existing laser systems.

INTRODUCTION

Excellent timing jitter can be achieved in modern mode-locked solid state lasers [1]. They are standardly used as master oscillator to act as the heart of large accelerator complexes, as timing signals can be distributed in stabilized fiber links over many km's [2]. However to reach required energy to drive photo-injectors, as well as for experiments in FEL's, further amplification is needed. To reach mJ levels of energy in each pulse at up to kHz repetition rates, regenerative and multi-pass amplifiers are used. These include many roundtrips and propagation both in material as well as in air and make the output pulse arrival dependent on environmental factors, such as temperature, humidity, pressure, vibrations and air-flow [3]. To reach required specification, active stabilization of the laser arrival time is necessary. In the following section we describe the laser systems to be used at SwissFEL as well as the required timing stability and present a general concept for laser timing stabilization.

Laser Systems at SwissFEL

Table 1 summarizes the laser parameters and timing requirements for both laser systems. The experimental laser system [4] is based on chirped-pulse amplification in Ti:Sa from Coherent. The system is seeded by Vitara Oscillator and pulses are amplified in Legend Elite Duo HE+ amplifier, with a custom made post amplifier stage and Revolution pump lasers. With this layout it provides a compressed output energy > 20 mJ, centred at 800 nm and at 100 Hz repetition rate.

Table 1: Laser Specifications and Timing Requirements

Parameter	Experiment Laser	Gun Laser	Units
Wavelength	800	260	nm
Meas. resolution	10 (1)	25	Fs
Overall rms jitter	150	40	Fs
Pulse length	0.03	4-10	ps
Rise and fall-time	10	700	fs
Pulse Energy	10	2	mJ
Reference wavelength	1560		nm
Pulse length	180		fs
Pulse energy	0.2		nJ

The gun laser is a hybrid fiber front-end Yb:CaF_2 CPA system, operating at 1041 nm [5]. The oscillator from OneFive[1] at 71.4 MHz delivers broadband pulses and seeds the regenerative amplifier (Amplitude Systeme[2]), which is operating at up to 100 Hz repetition rate. The pulses reach 2.5mJ energy before compression. The system has a UV output, a short probe diagnostic output and an IR beam for the laser heater, all with their individual compressors.

The reference laser is also delivered by OneFive, operating at 1560 nm, delivering 180 fs pulses in stabilized and dispersion compensated fiber links, with 0.2 nJ energy in each pulse. The repetition rate of the master oscillator is at 142.8 MHz, which is twice of the seed oscillators, used for the laser systems. It is expected that the added timing jitter of the links is below 10 fs rms, with a drift of less than 10 fs peak to peak over 24h [6].

Timing Overview

Figure 1 shows the general concept for obtaining timing overlap between the laser output and the master reference link. In both cases the pulse train from the link is compared on a fast ADC with the output pulses from the laser and coarse overlap is obtained via free-space delay stages.

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[1] http://www.onefive.com/

[2] http://www.amplitude-systemes.com/amplifiers-s-pulse.html

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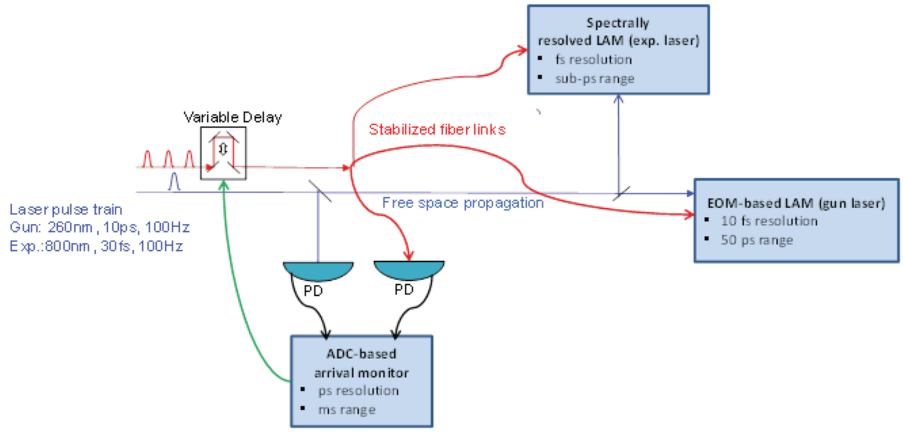

Figure 1: General concept for laser arrival time measurement (LAM) and control.

Eventually this can become part of the stabilized link, where a phase-shift can be set while maintaining the same stability from the reference. For the experimental laser a spectrally resolved cross-correlator will be used, which has shown to achieve fs resolution [7]. For the gun laser it is important to compensate for the drift up to the entrance of the gun and therefore timing measurements must take place in the UV. Here, a technology well established for Beam Arrival Monitors (BAM) will be used [8], based on ultra-broadband electro-optical modulators driven by fast photo-diode signals generated by the UV pulse. From this system 10 fs resolution is expected.

GUN LASER TIMING

Figure 2 shows the general layout of the laser system with the laser arrival related hardware. Near the oscillator there is a LAM development area aiming to stabilize the output of the regenerative amplifier, as well as space for optical locking of the oscillator against the optical reference, which is planned for 2017. The pulse is compressed after the chirped pulse regenerative amplifier and converted to UV. After pulse shaping both in space at time, detailed in [5] the laser is propagated to the tunnel output port. Here, part of the beam is taken for development of the UV LAM and for temporal characterization of the UV pulses. The beam is then sent into the tunnel, where the final LAM will be installed to generate timing error signals against the optical reference, using part of the beam entering the gun. The error signal will be fed back to the translation stage before the regenerative amplifier to compensate for slow drifts.

Oscillator

The oscillator delivers three outputs. The main, 2nJ free-space output seeds the amplifier. The output of the pulse-picker is also available with quasi 71.4 MHz to be used for LAM development. The additional fiber outputs at ~0.18nJ are used for synchronization and to generate clock-signals. The laser is locked to the master RF distribution system (42^{nd} harmonic of the laser), showing an excellent 23.8 fs integrated absolute jitter 10Hz-1MHz, which is well within the specification for the gun operation. More details on the oscillator performance can be found in [9].

Amplifier

The cw diode pumped regenerative amplifier provides the required IR energy in a single stage with high beam quality. However the amplifier build-up time mounts to several microseconds, corresponding to over 1 km total propagation path. To ensure good passive stabilization all the components are packaged in a single, thermally stabilized box. This ensures also high mechanical stability of the system preventing sensitivity to environmental changes and vibration.

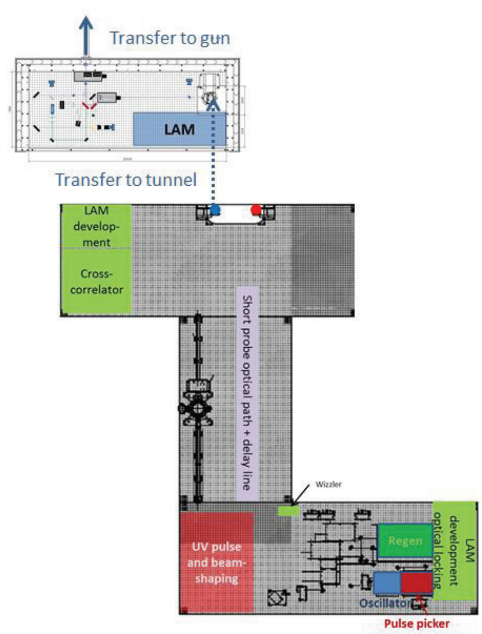

Figure 2: Layout of the gun laser system, with the position of the laser arrival monitors

Timing jitter characterization was performed by the company (Amplitude Systeme) on a similar laser system, running at 10 kHz. With active stabilization, using

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Smaract delay stages[3], a 5 fs additive jitter was achieved (0.1 Hz-10 kHz) over an hour [10].

Amplifier box Before the delivery of the laser system, extensive tests were carried out on the amplifier box to estimate timing drifts due to environmental changes as well as vibration. For this an interferometer (Renishaw XL-80[4]) was used. The optics were placed were the cavity mirror positions were planned, with the interferometer outside the box (Fig. 3.). The total path-length for the HeNe beam was 169 cm, corresponding to 11.27 ns delay in double path. The final system laser system has 2 µs build-up time with an allowable 40fs total drift shot to shot. Our aim was therefore to show that the drifts and shot-to shot variations stay below 68nm/roundtrip. Temperature sensors were installed to monitor the environment and the box.

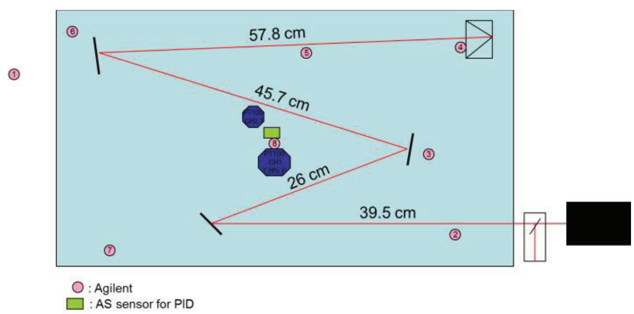

Figure 3: Experimental setup to measure performance of the laser box, using interferometry

The measurement shown on Fig. 4 was performed at 10 Hz with the temperature recorded every 2 seconds. The temperature changes of the box matches well the outside temperature and the optical path-length drift show clear correlation to these changes.

Drift, corresponding to the total build-up time of the amplifier, would be 16 ps/°C. The laboratory temperature is stabilized to 0.1°C, which would give a drift ~1.6 ps. It is clear, that active stabilization is necessary. Tests will be done in the future to stabilize the box temperature independently to 0.01°C. For this, resistors are installed and equally distributed underneath the amplifier box and are connected to a PID loop driving a heating unit.

Further measurements were performed to analyse the sensitivity of the box to vibrations and to determine characteristic frequencies. These measurements are shown on Fig. 5. The box and the table were tapped by a rubber hammer a few times to see how vibration propagates into the box. The measurement results were compared to the vibrations picked up by the table to identify characteristic frequencies of the box. Peaks were found at 360 Hz and 490Hz. This is important, as the laser will run at 100 Hz and therefore these vibrational modes will appear as shot to shot noise no possible to compensate for. High quality optical table and proper fixing of the box will ensure the damping of these modes. Short term measurements have shown 40 fs/min equivalent drift, which is easy to compensate for. Shot to shot jitter at 50 kHz sampling rate gave 0.19 fs equivalent jitter, which is excellent and shows that with active stabilization the system can deliver the specified jitter and drift.

Extensive measurements and correction are planned in the final position of the amplifier, using a balanced optical cross-correlator and comparing the output pulses of the amplifier with the seed oscillator.

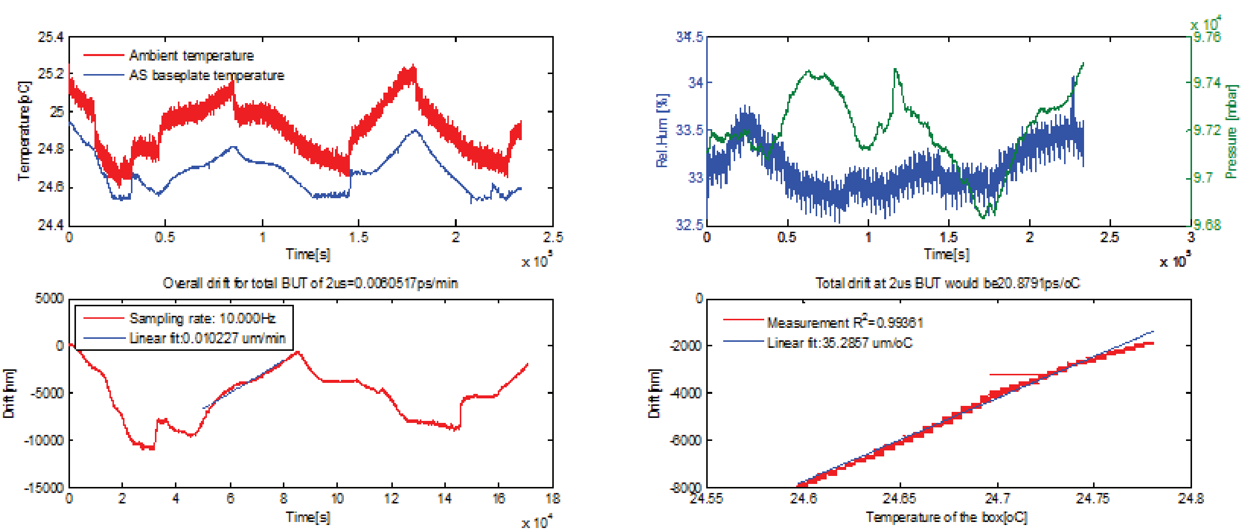

Figure 4: Interferometric drift measurements performed on the amplifier box showing correlation between ambient and box temperature (top left), as well as drift of the optical path with the temperature change (bottom left) and correlation plot (bottom right). Other environmental changes were also recorded during the measurement (top left).

[3] http://www.smaract.com/products/linear-positioners/slc-series
[4] http://resources.renishaw.com/en/details/manual-laserxl-english--61500

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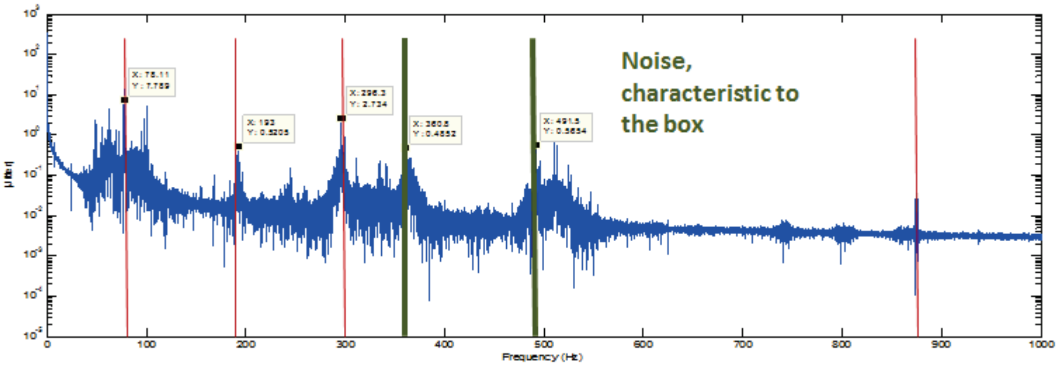

Figure 5: Vibrational noise of the laser box.

EXPERIMENTAL LASER TIMING

The laser oscillator in the final configuration will be optically locked to the master reference of the machine, delivered in the stabilized fiber links. Expected performance is similar to that one of the gun laser. The amplification and transport to the experimental station will give a total path length in the order of 100 m. As the laser room is on the top floor, while the experiment is below, the air-conditioning systems are decoupled and the propagation path will change significantly with the environment. It has been shown for the former Ti:Saph based gun laser system, that drifts in the order of few 100 fs is expected from such beamlines [7].

Figure 6 shows the experimental station ESA [11], where the laser is delivered. The compression and the conversion to other wavelengths from the fundamental of the Ti:Sa system (~795 nm) takes place here. Optical link is delivered for the LAM, which performs the correction after compression and before conversion, using spectrally resolved cross correlation. This setup has a demonstrated resolution of <0.3 fs and is described in detail in [7]. With this technique, the output from a comparable Ti:Sa amplifier system was stabilized to 2.36 fs rms.

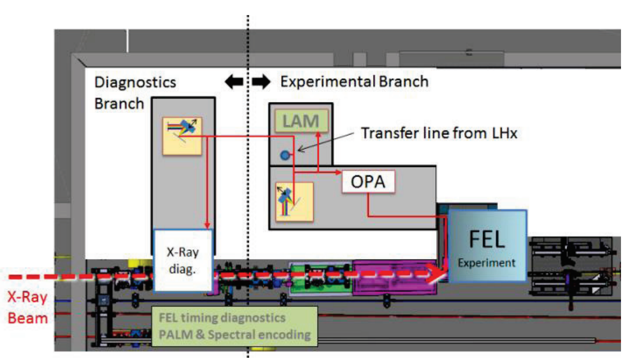

Figure 6: Layout of the timing diagnostics in ESA.

CONCLUSION

High precision timing diagnostics and correction system is well on its way for both gun and experimental lasers at SwissFEL. Further tests are planned for the final location of the lasers, using the developed tools. 10 fs measurement resolution and 40fs shot to shot jitter is expected for the gun laser, while sub-fs resolution has been demonstrated and correction to the few fs level is expected for the experimental laser.

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