TIMING JITTER MEASUREMENTS OF THE SWISSFEL TEST INJECTOR

C. Vicario, M. Csatari Divall, M. G. Kaiser, M. Luethi, S. Hunziker, B. Beutner, T. Schietinger, M. Pedrozzi, Paul Scherrer Institute, Villigen PSI, Switzerland
C. P.Hauri, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland and Paul Scherrer Institute, Villigen PSI, Switzerland

Abstract

To reach nominal bunch compression and FEL performance of SwissFEL with stable beam conditions for the users, less than 40fs relative rms jitter is required from the injector. Phase noise measurement of the gun laser oscillator shows an exceptional 30 fs integrated rms jitter. We present these measurements and analyze the contribution to the timing jitter and drift from the rest of the laser chain. These studies were performed at the SwissFEL Injector Test Facility, using the rising edge of the Schottky-scan curve and on the laser system using fast digital signal analyzer and photodiode, revealing a residual jitter of 150 fs at the cathode from the pulsed laser amplifier and beam transport, measured at 10Hz. Spectrally resolved cross-correlation technique will also be reviewed here as a future solution of measuring timing jitter at 100 Hz directly against the pulsed optical timing link with an expected resolution in the order of 50 fs. This device will provide the signal for feedback systems compensating for long term timing drift of the laser for the gun as well as for the pulsed lasers at the experimental stations.

INTRODUCTION

For SwissFEL to provide the high brightness ultra short hard X-ray pulses, the 4-10 ps FWHM electron bunches at the injector source have to be compressed by a factor ranging from 140 to 300 depending on the operating mode [1,2]. For stable output of the FEL, accurate timing of the initial electron injection is necessary.

Table 1 summarizes the main stability requirements for the laser system. Tolerance studies show, that at the electron gun photocathode less than 40fs relative rms phase jitter can be tolerated between laser arrival and RF [3]. A substantial contribution to the phase jitter comes from the drive laser of the photoinjector source.

While oscillators can be synchronized to RF reference signals with very high accuracy (sub-100 fs), maintaining this level through several stages of pulsed amplifier systems and long beam transport paths - often required at accelerator facilities - is challenging.

The aim of this study was to quantify the timing jitter of the two existing drive laser sources at SITF [4-5] and to identify main timing jitter and drift sources. The long term timing drift of the laser system was observed with a fast photodiode and a high bandwidth sampling oscilloscope.

Measurements were also performed at the SwissFEL Injector Test Facility where the electrons are generated by photoemission from a copper cathode inside an RF gun. Timing and correlation studies were based on charge detection operating the gun at the fast rising edge of the Schottky-scan (Figure 3), using consecutive Beam Position Monitors (BPM) downstream of the gun.

Table 1: Laser Requirements

Parameters at the cathode	Required	Unit
Wavelength	~260	nm
Energy/pulse (Cu)	60	μJ
RMS laser spot size	100-270	μm
Energy stability rms	<0.5	%
Pointing stability/beam size	<1	%
Shot to shot timing jitter versus RF reference	40	fs
Pulse length (flat top)	4-10	ps
Rise- and fall-time	700	fs

THE LASER SYSTEMS

The electron source can be driven by two laser systems (Table 2).

Table 2: The Two Drive Lasers' Parameters at the Cathode

Laser/ characteristic	Pulsar (Amplitude Systemes)	Jaguar (TBWP)
Material	Ti:sapphire	Nd:YLF
Mode-locking	Kerr-lens	SESAM
Wavelength	800nm THG 266nm	1047 nm FHG 262nm
Synchronization	FemtoLock	PSI dev.
Amplifiers	CPA, 1 regen, 3 multipass	1 regen
Overall propagation	84 m	30 m
Final pulse shape	Flat top Stacking 4-10 ps	Gaussian fixed 10ps
Amplitude stability	1.2% rms	<1% rms

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The high power, chirped pulse, ultra-broadband Ti:sapphire system is used for low emittance beam production and compression studies, using the third harmonic frequency for photo-emission [4-5]. This system provides good flexibility for temporal and spatial shaping at the cost of increased complexity and overall path length. The directly diode pumped Nd:YLF oscillator and regenerative amplifier system (Jaguar, Time-Bandwidth Product) converted to its fourth harmonic wavelength, is used as a diagnostic tests system for the injector.

JITTER AND DRIFT MEASUREMENTS

Vibration are expected to be the most important timing jitter sources affecting stretcher and compressor optics as well as the regenerative amplifier cavities. Environmental changes affect the refractive index and hence change the overall path length, causing long term time drifts of the laser system. Table 3 shows the estimated drift for the two lasers over a typical day in the environmentally controlled clean room.

Table 3: Estimation of Residual Laser Jitter From the Measurements

Effect over the total propagation path	Environmental changes over a typical day	Pulsar	Jaguar
Humidity	5.5 %	140 fs	50 fs
Pressure	10 mbar	-740 fs	–266 fs
Temperature	0.83 °C	220 fs	80 fs

Passive stabilization was applied wherever possible to reduce other effects. The system is covered to avoid airflow, the optical tables are vibration damped and the cooling for the amplifier crystals is stabilized to <0.1°C accuracy.

Jitter of the Oscillators

Both laser systems are electrically phase locked with

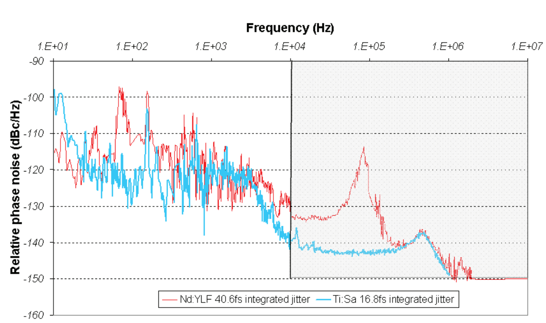

Figure 1: Jitter of the laser oscillators measured with AnaPico Signal analyzer (APPH6000-IS400). The shaded area on the right side marks the region outside the loop bandwidth.

the accelerator RF via the RF reference signal of the SITF synchronization system.

Commercial Femtolock (Femtolaser) phase locked loop (PLL) acts on the Ti:Sa oscillator cavity and provides <20 fs integrated residual jitter (IRJ), when the loop is optimized. For the synchronization of the Nd:YLF oscillator we uses in house PLL electronics (S.H., M.G.K.), which brings the IRJ to ~40 fs, mainly limited by the relaxation oscillations of the Nd:YLF , marked in the shaded area, which falls outside the correction bandwidth of the loop (Fig.1.).

Direct optical locking is under test at PSI [6]. With its extended loop bandwidth a further reduction of the oscillator jitter is expected.

Jitter and Drift at the End of the Laser Chain

Drift measurements were performed on a shot to shot basis at 10 Hz, using a fast oscilloscope (LeCroy WaveMaster 816Zi; 40 GS/s; 16 GHz bandwidth) and a UPD-50-UD 50 ps rise-time UV photodiode, comparing the rising edges of the signal to the RF reference in time-domain. The measurements show a few ps drift over a day and ~110 fs rms jitter on a short timescale. Fig.2. shows the measurements performed over a day on the Jaguar laser. Similar results were obtained from the Ti:sapphire system.

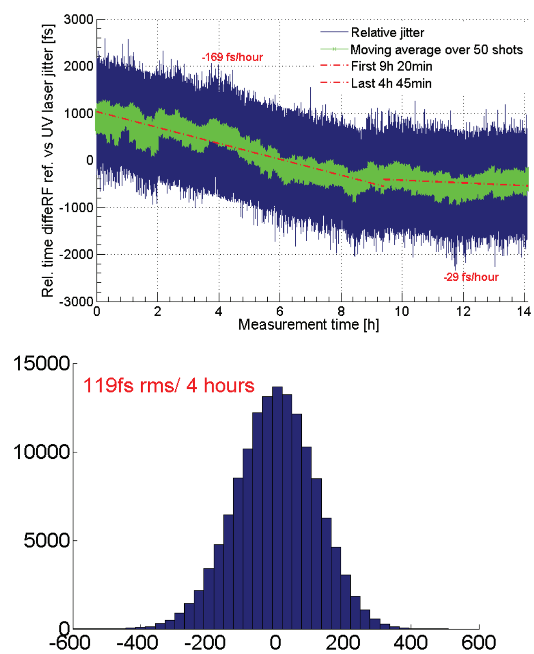

Figure 2: Long term drift measurement performed with fast PD and a 16GHz sampling oscilloscope.

Jitter and Drift at the Gun Cathode

Measurements of the RF to laser phase jitter were also performed observing directly the electron beam. To maximize the resolution of the measurement the relative phase of the laser and the RF was adjusted to the point, where small phase changes translate to large charge

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variations, in this particular case 6.2 pC/deg at 3 GHz (Fig.3). Calibration of the Schottky-slope was performed before each long term measurement and RF phase as well as laser and RF amplitude contribution was measured synchronously.

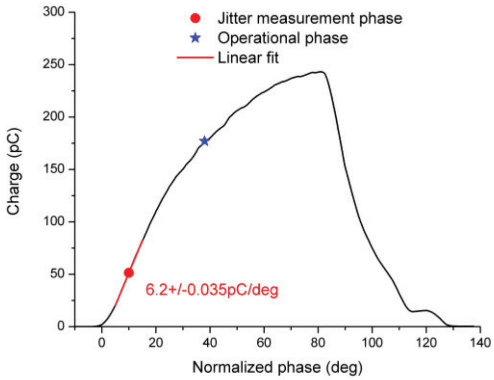

Figure 3: Schottky-scan with the operational phase (blue star) and the jitter measurement phase (red dot) marked.

Correlation measurements between two consecutive BPM's show a potentially very high resolution <10 fs. (Fig.4.)

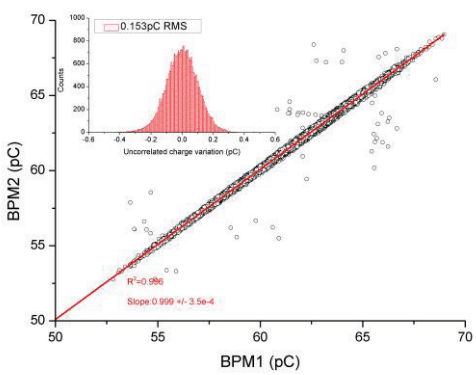

Figure 4: Charge variations with synchronized acquisition of two consecutive BPM's downstream the gun.

Measurements performed without RF feedback running confirm the validity of this technique, where jitter measured through charge variations (Fig.5.black) could be correlated well with the independent RF mixer based jitter measurement (Fig.5. blue).

The residual jitter from the laser is estimated to be ~150fs for both laser systems at the gun, measured at 10 Hz repetition rate. The variations are also visible at this level on a shot to shot basis, which indicates noise sources above the Nyquist-frequency.

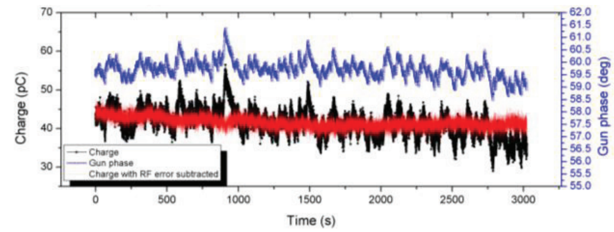

Figure 5: Jitter measurements performed with RF feedback off to validate the technique against the independent RF phase measurement.

Table 3: Estimation of Residual Laser Jitter From the Measurements

RF feedback status	OFF	ON	ON
Synchronization Laser	**PSI Jaguar**	**PSI Jaguar**	**Femtolock Pulsar**
Charge jitter	8.4 %	3.3 %	2.37 %
Laser energy jitter	1 %	1 %	1.16 %
RF amplitude jitter	0.34 %	0.32 %	0.21%
RF phase jitter	335 fs	65 fs	57.3 fs
Residual laser jitter	159 fs	126 fs	158 fs

OUTLOOK

A dedicated Laser Arrival Monitor is under development both for the injector laser system and for the experimental lasers of the future SwissFEL. The former will measure and compensate for drifts of the Time Of Arrival (TOA) between the stabilized pulsed fiber link of the SwissFEL synchronization system operating at 1550nm and the UV pulses as close to the cathode as possible. The latter it will measure and correct the drift of the main pump laser's TOA at 800nm just after compression. Conventional balanced cross-correlation technique is shown to have sub 10-fs resolution and enough sensitivity to measure relative timing [6], however its range is limited to the length of each pulse. A novel stretched pulse cross-correlation [7] is being investigated (Fig. 6), whereby stretching one of the pulses - to be compared- before the mixing process the information of the relative timing will be contained in the spectrum of the sum-or difference frequency signal. For the UV version ~50fs, while for the 800nm resolution below 10fs resolution is expected.

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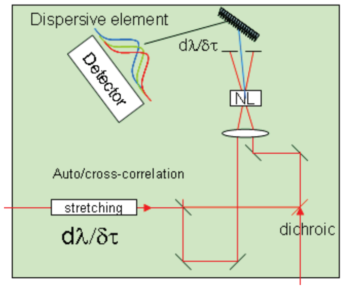

Figure 6: Schematic of the stretched pulse, spectrally resolved cross-correlator.

Other, optical ring-down cavity based techniques, using the electronics and the IQ measurements, such as for resonant cavity BPM's are also under investigation, as they offer reduced complexity (Fig. 7).

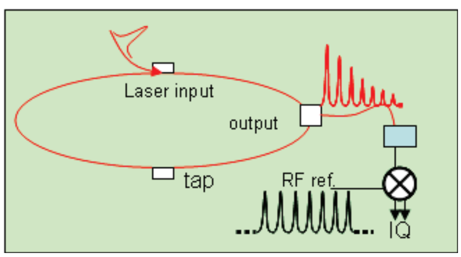

Figure 7: Schematic of the ring-down cavity enhanced IQ measurement.

CONCLUSION

The tight requirements of less than 40 fs arrival time of the injector laser at the cathode as well as of the future experimental pump laser pulses call for high level of passive and active stabilization of the laser.

The currently used state-of-art Ti:sapphire laser system at SwissFEL Test Injector reaches this performance at the oscillator (<30fs integrated residual jitter), which could be further improved by direct optical locking. However the multistage chirped pulse amplification system and long beam-transport degrade the shot to shot timing jitter in the region of 100-150fs. This was confirmed by measurement directly performed on the laser system or indirectly measuring the electron beam charge fluctuation in SITF. Similar values are reached with the backup Nd:YLF laser system. The long term drift during a typical day is in the few picoseconds range and is mainly driven by environmental changes.

In the future the development of few picosecond-range, high resolution laser arrival monitors will allow systematic studies of the jitter and the drift at different stages of the laser system, as well as providing an error signal for compensation of long term variations. Shot to shot jitter at above 50 Hz, where vibration and electro-magnetic noise play a big role will have to be solved by passive stabilization.

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