

A LOW-COST FEW-PICOSECOND PRECISION TIMING AND SYNCHRONIZATION OVER ONE HUNDRED KILOMETERS

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Abstract

Large-scale accelerators, including colliders and accelerator-based light sources, require synchronization and time distribution over distances of several tens of kilometers. Precisions of femtoseconds have been demonstrated, but the systems used to reach such specifications are costly and difficult to integrate in a particle accelerator environment. Applications such as bunch-per-bunch position monitoring and Compton polarimetry require picosecond timing and precision and often meet tight integration requirements. This is particularly true for the latter, where a passively mode-lock laser must be integrated in the accelerator environment. We propose to implement a system exploiting a White Rabbit protocol-based frequency generation system, the IDROGEN. We demonstrate the proof-of-concept of synchronization of a pulsed laser with a few hundred MHz repetition rate with picosecond jitter precision through a hundred kilometer-long optical fiber. Drifts of a few picoseconds were observed, likely driven by environmental changes. Prospects for improvements will be exposed.

INTRODUCTION

Large-scale facilities, including accelerators of length of several tens kilometers, require proper synchronization and timing for beam diagnostics. Distribution of time standards with femtosecond-level stability have been demonstrated on large-scale facilities such as the European XFEL [1–8]. These all-optical or electro-optical synchronization systems are costly and difficult to implement. On the other hand, there exist some application whose requirements on timing distribution are less stringent (picosecond-level) : timing of large detectors [9–11], bunch-per-bunch beam monitoring [12], laser-based diagnostics (e.g. Compton polarimeters [13–16]). Here, we present the results of a proof-of-concept timing system based on the CERN White Rabbit protocol embedded in IDROGEN boards used to synchronize a pulsed laser to a RF reference clock virtually located up to one hundred kilometers away [17–19]. The test setup is described, and the results are presented, from which possible improvement prospects are drawn.

SETUP

The optical setup mainly consists in two subsystems: the White Rabbit clock distribution on one hand, and the laser lock loop on the other hand [19]. It is shown in Fig. 1, with a scheme on the left and a photograph on the right. The

critical elements are highlighted. A fan is used to mitigate the heating of the electronic boards.

The White Rabbit Clock Distribution

A first IDROGEN board, named “Master” (MIB) (μ TCA board based on an Altera Arria10 FPGA) is disciplined by a 10 MHz signal from a microwave signal generator, which serves as a RF reference (Rhode & Schwarz SMB100A equipped with an OXCO B1H). It is linked to a second IDROGEN board, named “Slave” (SIB) and in which the White Rabbit protocol is embedded, *via* an optical fiber whose length is made vary among 10 m, 5 km, 50 km and 100 km. The SIB provides a SkyWorks Evaluation Board (SI5362-EVB-A) (SIC) with a 250 MHz LVDS signal. The SIC output is synchronous to the SIB output and can be arbitrarily chosen with a Hz precision, and is here set to $4F_0$. The SMB reference RF output is set to $4F_0$. The heating of the MIB, SIB and SIC boards is mitigated *via* the use of a fan.

The Laser Lock Loop

The oscillator is a 1030 nm pulsed laser with a repetition rate $F_0 = 216.661\,555$ MHz from Menhir Photonics AG. The fine tuning of its repetition rate is allowed thanks to two piezoelectrical transducers (PZT), one fast PZT and one slow PZT. Its pulses are picked up by an ultrafast photodiode, whose output is thus a F_0 comb. The signal is then filtered by a band-pass filter around $4F_0$. Part of it is mixed with the RF $4F_0$ signal and monitored. The remaining signal is mixed with the $4F_0$ SIC output, filtered and amplified in order to generate an error signal for the laser lock feedback loop: the error signal controls the voltage at the terminals of the fast PZT so as to tune the laser repetition rate F_0 .

RESULTS AND DISCUSSION

Phase Noise Measurements

The power spectral density (PSD) of phase noise between two signals is measured at different spots in the setup and displayed in Fig. 1 and Fig. 2: (i) free-running laser ; (ii) SIC with respect to the SMB reference, which corresponds to the clock distribution phase noise ; (iii) laser locked on the SIC with respect to the SIC, which corresponds to the laser lock loop phase noise ; (iv) laser locked on the SIC with respect to the SMB reference.

The PSD of phase noise of the locked laser with respect to the SMB reference (red line in Fig. 2) is limited at lower frequencies (≤ 50 Hz) by that of the SIC with respect to the SMB reference signal (clock distribution phase noise,

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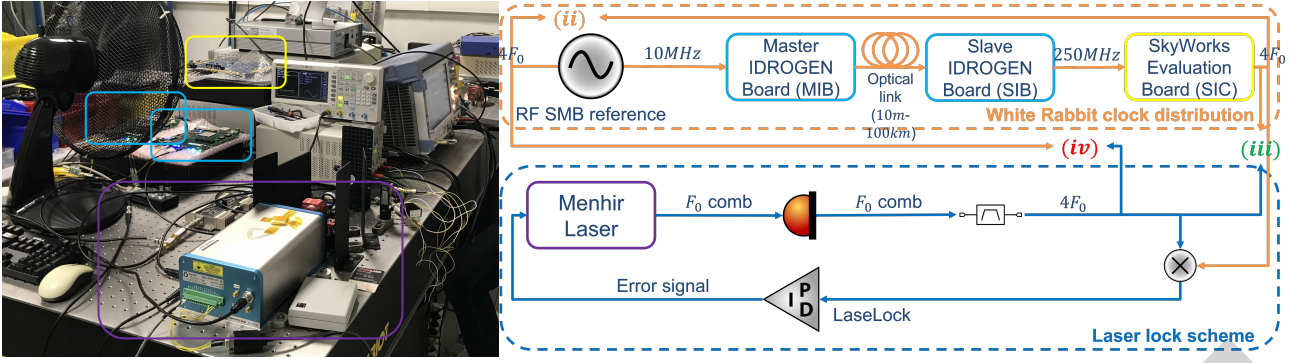


Figure 1: (left) Optical setup scheme. It is composed of two subsystems that are described in the text. (right) Photograph of a part of the optical setup. The critical elements are highlighted in the same color as in the optical setup scheme.

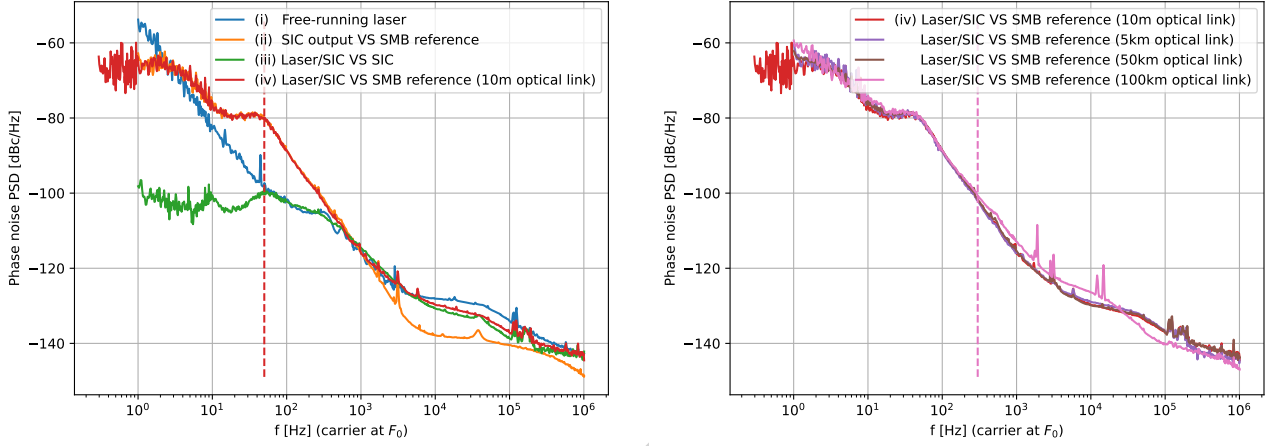


Figure 2: Power density of phase noise (left) at different locations in the setup (Fig. 1) and (right) between the laser locked on the SIC and the SMB reference for different optical link lengths.

orange line in Fig. 2), and at higher frequencies (≥ 50 Hz) by that of the locked laser with respect to the SIC (laser lock loop technical phase noise, green line in Fig. 2). It is measured for several different optical fiber lengths (10 m, 50 m, 50 km, 100 km) (Fig. 2), and, when increasing the optical link length to 100 km, the power spectral density of phase noise of the locked laser with respect to the SMB reference exhibits two differences compared to that measured with shorter optical links: the system seems less stable at lower frequencies (≤ 10 Hz), and for higher frequencies (≥ 300 Hz), the signal exhibits a slight degradation compared to shorter optical links (red, purple and brown lines on Fig. 2). The detailed interpretation of the increase at low frequencies require further detailed investigations. We observed that it is clearly related to temperature cycle of the air conditioned room where experiments were made. At high frequencies, the changes are related to a technical change in the choice of splitter, amplifiers and PID optimization. The latter however does not contribute to the total integrated jitter. The integrated phase noise over [1 Hz; 1 MHz] is computed to be 1.4 ps RMS, and this value does not change with the length of the optical link. It shows that the differences noted above are very small.

Phase Difference Measurements

The phase difference between the laser locked on the SIC and the SMB reference is also measured. It is measured by mixing the $4F_0$ signal of the laser after the photodiode with the F_0 signal of the SMB reference. The phase is sampled with 40 million samples over 1 s every 2 s, out of which an average and a RMS are extracted. These are shown on Fig. 3 (left, center). The RMS phase difference follows an exponentially convoluted Gaussian of mean μ , standard deviation σ and decay time τ [20]. The convolution models a drift in the RMS phase difference due to the fact that the IDROGEN and the SIC boards are not enclosed, thus sensitive to external factors. This could also explain the ≈ 1 h period variations of the average delay (Fig. 3 left top), which are likely due to the cycle of the room's air conditioning. The tail of the Gaussian is thicker in the case of the 100 km optical link, suggesting a wider spread of the samples, hence a less stable operation than at 50 km.

One finds a short term phase difference, defined as the mean of the RMS of the phase difference samples, of 1.6 ps for a 50 km optical link and 1.7 ps for a 100 km optical link. Both measurements are compatible with the integrated phase noise measurement (1.4 ps RMS). The long-term stability, however, is defined as the RMS of the average phase dif-

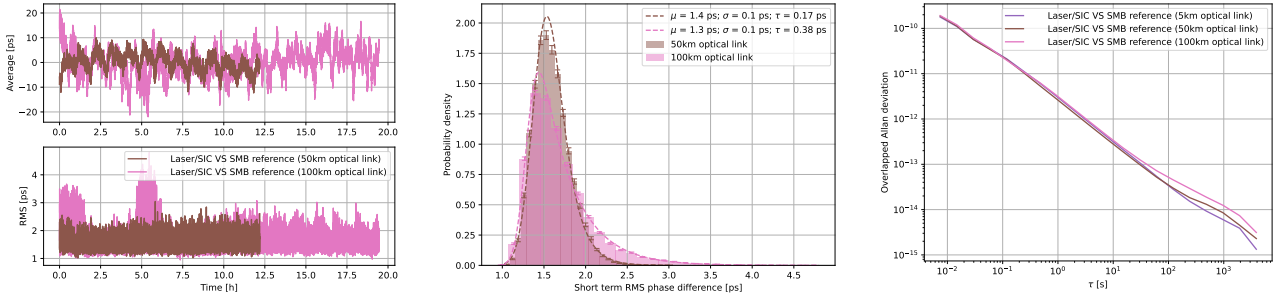


Figure 3: (left) Measurement of the mean (top) and RMS (bottom) phase difference between the locked laser and the SMB reference. (center) Histogram of the measured RMS phase difference showing an exponentially convoluted Gaussian. (right) Overlapped Allan variance for different optical link lengths.

ference samples, and is measured to be 3.5 ps for a 50 km optical link and 5.5 ps for a 100 km optical link. Those results are presented in Fig. 1. The difference between the short and long term measurements could be explained by a drift in the average phase difference due to external factors and modeled by an exponentially convoluted Gaussian distribution of the phase difference samples as stated earlier.

Table 1: Stability of the Phase Difference; The Short Term Value Corresponds to the Mean of the RMS Phase Difference and the Long Term Value Corresponds to the RMS of the Average Phase Difference; See Fig. 3 (left)

Optical link length	Short term [ps]	Long term [ps]
50 km	1.6	3.5
100 km	1.7	5.5

The resulting overlapped Allan variance (Fig. 3 (right)) follows a $\frac{1}{\tau}$ slope, denoting a system limited by quantum (Schottky) noise, and is measured to be 3.1 ps at 1 Hz.

CONCLUSION

Picosecond-level precision over a 1 s window was achieved in the generation of a 866.66 MHz frequency through the White Rabbit protocol embedded in a IDRO-GEN board. It was distributed through an optical link whose length was set up to 100 km, with little deterioration in the phase noise when increasing the optical link length. The integrated phase noise was measured to be 1.4 ps RMS in the [1 Hz; 1 MHz] range. It is compatible with short term phase difference stability measurements of 1.6 ps – 1.7 ps. Long term stability varies from 3.5 ps to 5.5 ps when replacing a 50 km optical link with a 100 km optical link, which is to be investigated.

Possible improvements include proper encapsulation of the IDROGEN boards and correction of thermal effects.

The scope of applications of this level of precision covers particle accelerator physics (photocathode laser systems for beam generation [21], Compton polarimeters [14], laser-beam interactions [22, 23], large-scale detectors [12, 24]), as well as astrophysics (cosmic rays detection) and medical physics [25].

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