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A FIBER OPTIC SYNCHRONIZATION SYSTEM FOR LUX*

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Abstract

The LUX femtosecond light source concept would support pump-probe experiments that need to synchronize laser light pulses with electron-beam-generated X-ray pulses to less than 50 fs at the experimenter endstations. To synchronize multiple endstation lasers with the X-ray pulse, we are developing a fiber-distributed optical timing network. A high frequency clock signal is distributed via fiber to RF cavities (controlling X-ray probe pulse timing) and mode-locked lasers at endstations (controlling pump pulse timing). The superconducting cavities are actively locked to the optical clock phase. Most of the RF timing error is contained within a 10 kHz bandwidth, so these errors and any others affecting X-ray pulse timing (such as RF gun phase) can be detected and transmitted digitally to correct laser timing at the endstations. Time delay through the fibers will be stabilized by comparing a retro-reflected pulse from the experimenter endstation end with a reference pulse from the sending end, and actively controlling the fiber length.

SYSTEM DESIGN ISSUES

In a short pulse X-ray experimental facility, typical experiments need to synchronize an optical pump pulse from an ultrafast laser source to an X-ray probe pulse. In the LUX hard X-ray generation concept, a superconducting RF cavity imposes transverse deflection on the electron beam, which creates a correlation between the angular centroid and the position along the bunch. The resulting X-ray pulse from an undulator is reflected from a crystal oriented to bunch this sweep, resulting in a time compression of the X-ray pulse down to as little as 50 fsec [1]. At the experimental stations, there are lasers generating optical pulses, and these need a continuous clock signal (typically 80 MHz) synchronized with the X-rays. A facility like LUX would require distribution of timing signals over about 100 m of distance, making optical signals on fiber an attractive transmission medium. Recent demonstrations of frequency transmission over fiber optic links have shown that total timing jitter of a few tens of femtoseconds is achievable [2].

In the LUX concept, the X-ray pulse duration is as short as 50 fs. Synchronization between the X-ray and optical pulses should therefore be constant to within this pulse duration. Our goal is to provide for less than 50 fs rms synchronization between the endstation laser pulse and the X-ray pulse, which can then be checked by optical cross-correlation. There are several subsystems in the timing chain, each of which contributes to overall jitter. For now, we are assuming they are uncorrelated, and add incoherently. A quantitative breakdown of the contributions of all the subsystems allows for specification of subsystem performance.

A preliminary specification for the stability of a typical fiber link is 10 fs rms, based on an assessment of the overall timing system. Other experiments in distribution of high stability clock signals over fiber have achieved better than this level of performance when averaged over periods of many seconds [3]. Given the observed spectrum of timing errors, it appears that 10 fs over our periods of interest is achievable. Also, synchronization of commercial mode-locked lasers to high frequency clock signals has demonstrated timing jitter of around 30 fs within a 50 kHz bandwidth [4]. Most importantly, the timing error spectrum in these experiments shows that most of the jitter is at low frequencies, indicating that a suitable electronic system could detect and actively correct these errors, as indicated graphically in Figure 1.

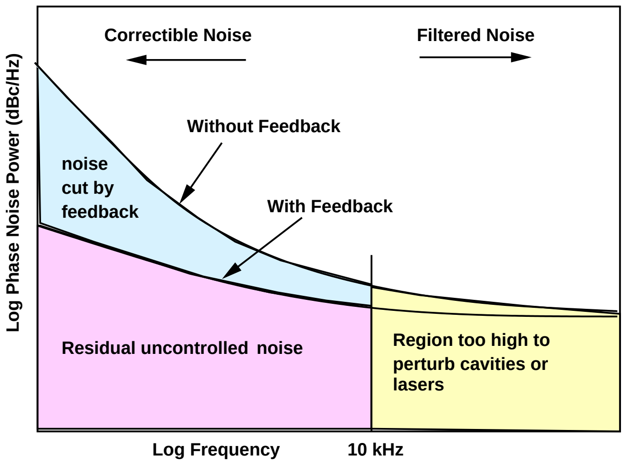

Figure 1: Partition of a typical noise frequency spectrum into regions where noise is either controlled or filtered.

It may not be necessary to correct timing jitter at higher frequencies than 10 kHz, because the devices which mainly determine timing (the superconducting transverse deflection cavities and the endstation lasers) are insensitive to high frequency perturbations. The superconducting cavities are actively phase locked to the incoming clock, but their Q and control circuit parameters reduce the control bandwidth to around 10 kHz. The lasers are also high Q devices and have very low phase noise at high frequencies. Mechanical limitations reduce the frequency response of the laser frequency control to a few kiloHertz. Typical timing errors in the accelerator come from mechanical sources

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such as microphonics and thermal drift, with bandwidths of a few hundred Hertz.

Another way to think of the situation is in terms of a "coherence time." If a device or chain of devices has an output which is coherent with the input over a certain time span, errors on the input with a duration shorter than this coherence time will not be propagated. Slow errors which are propagated can be reduced with controls which are sufficiently faster than the coherence time. In our case, the coherence time is 1/10 kHz or 100 microseconds.

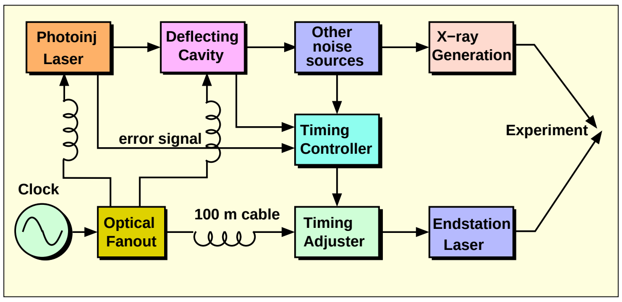

Figure 2: Overall Scheme. Each 100 meter cable length includes propagation time stabilization described below.

Referring to Figure 2, the accelerator/short pulse source can be broken down into a repetitively pulsed front end, a transversely deflecting RF cavity, the acceleration and transport parameters which also affect timing, and the X-ray generation and compression system. A clock synchronizes these systems and the endstation pulsed laser, by distributing optical signals on delay-stabilized fibers. None of the devices which determine X-ray pulse timing are timing error-free, and other, uncontrolled parameters will change the timing as well. All significant errors and parameter variations are measured, their magnitude converted to digital data for transmission, and their contribution to final timing error computed by a timing controller. This controller transmits a correction signal to each endstation laser, which is added to the clock signal to maintain synchronization.

This scheme depends on measurement of the phase difference between the clock reference and the output of each clocked device. Since the clock is the reference, low frequency noise on the clock which can be propagated through the system is common mode and is canceled. Since the propagation time of the clock signal through the facility is much shorter than the system coherence time, all parts of the synch system are equally affected and the slow clock noise is again common mode and is canceled.

A logical first step in development of the timing system is demonstration of the stabilized fiber clock distribution link, over the 100 m distance expected for the facility. Optical fibers are a convenient distribution medium, but suffer from large thermal variations in optical delay, as well as sensitivity to barometric pressure and mechanical perturbations. A one degree Celsius temperature change of a 100 m fiber results in an optical delay change of 3.6 ps, primarily due to thermal variation of the index of refraction. Any fiber distribution system must compensate for such effects by either passive (addition of a thermal strain-inducing member to the fiber, as in [4]) or active means. We chose to actively measure and control the fiber length to achieve greater precision.

There are different possible formats for clock signal distribution. One could distribute a CW laser signal amplitude-modulated by high-frequency RF, and demodulate to obtain an RF signal which provides phase information. Alternatively, one could distribute a pulse train from a mode-locked laser (or other pulse source), and demodulate to produce a comb of frequencies, where one or two harmonics of the fundamental rep-rate are used to derive phase information. Demonstrations comparing the two schemes show the mode-locked laser to have better absolute stability, but the detector-limited power of the detected RF signal is distributed among many harmonics, potentially reducing the signal-to-noise ratio of the one or two detected frequencies. Since our synchronization scheme does not require absolute stability of the clock, we are doing initial experiments with modulation of a CW signal.

Noise on the detected RF signal limits the smallest resolvable phase angle. The timing error due to this noise will be the total phase error divided by the radian frequency of the clock signal. In addition, noise power typically diminishes with increasing frequency. One can therefore reduce timing error by increasing the clock frequency to a maximum limited by available detectors and electronics. If the highest clock frequency is a harmonic of the frequency used in the RF cavities, just locking to the phase of the harmonic would result in ambiguity in determining phase for the lower frequency. One could resolve this by limiting the clock frequency to the highest RF frequency used in the system, or by sending two frequencies—fundamental and harmonic—as clock data. We intend to determine the most effective design by performing experiments on a test link.

As our first experiment, we chose to amplitude modulate a single frequency laser with a 1 GHz RF signal, and demonstrate detection and delay stabilization of a fiber.

EXPERIMENTAL PROGRAM

Initial Experiment

We will attempt to demonstrate, using inexpensive off-the-shelf 1550 nm fiber technology, the ability to transmit a 1 GHz clock over 100 meters of optical fiber with a corrected differential-mode jitter of tens of femtoseconds.

A 1.5 milliwatt distributed-feedback diode-pumped fiber laser supplies a continuous-wave 1550 nanometer signal that is amplitude-modulated by a fiber Mach-Zehnder interferometer, locally sampled with a fiber-based directional coupler and launched through a fiber circulator over 100 meters of optical fiber to a 50% reflecting mirror. Also at the far end of the fiber is a photodiode that will be used to verify the timing correction. APC connectors, where the fibers are joined with the polish at an 8 degree angle to the perpendicular used to minimize the effect of spurious back-reflections on the reflected signal.

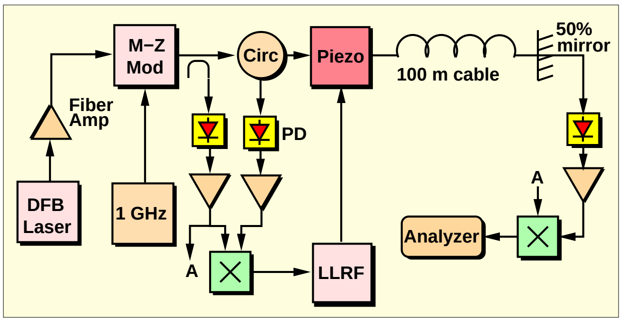

Figure 3: Experimental Setup for Fiber Stabilization

A sample of the launched signal from the directional coupler, along with the return signal from the mirror coupled out through the circulator are detected by photodiodes. The changes in propagation time through the 100 meter fiber are measured by detecting the phase difference between the forward and reflected 1 GHz signals by mixing down to baseband. The resultant phase error signal is processed in a simple low-level RF controller and applied to a piezoelectric phase modulator (mechanical line stretcher) to correct dynamic changes in propagation delay through the 100 meter fiber.

To verify the correction, the signal from the far end of the 100 meter fiber is also mixed with a reference signal from the same photodiode which provides the forward reference signal, and analyzed. This signal represents the remaining error signal from the correction of the propagation time through the 100 meter fiber. The split ratio used in the retroreflector and directional couplers is selected so that the optical power to each photodiode is equalized. The approximately 1 psec clock jitter, a common-mode signal, is not present in this signal. In an actual fiber timing distribution network, each fiber will be corrected individually, and the differential timing error at the end of each fiber is calculated to be in the tens of femtosecond range.

Hardware Issues

The various hardware components have already been characterized experimentally. The validation of the reduction of time jitter through the 100 m fiber awaits the completion of the low-level electronics.

Phase noise spectra have been taken of the 1 GHz Wenzel driver chain consisting of a 100 MHz low-noise crystal oscillator, a times 5 frequency multiplier followed by a frequency doubler providing a measured signal level of +16.5 dBm. The time jitter is calculated from the single-sideband phase noise around the 1 GHz carrier by

$$\sigma_\tau = \frac{1}{\omega}\sqrt{2\int \mathcal{L}(f)df} \qquad (1)$$

where $\mathcal{L}(f)$ is the phase noise power measured at a distance f from the 1 GHz carrier. The noise floor of the HP 8563E spectrum analyzer with a -40 dBm 300 MHz clean input signal gives a jitter σ_τ of .37 psec, integrated from 1 Hz to 100 Hz, and the 100 MHz Wenzel 501-04516 100 MHz oscillator, multiplied up to 1 GHz results in a phase noise of 1.0 psec, integrated from 1 Hz. This is the waveform that is applied to the JDS Uniphase X5 Mach-Zehnder modulator, biased for maximum modulation depth.

The correction of the two-way propagation time along the 100-meter fiber takes place in an Optiphase PZ1-STD piezoelectric fiber optic phase modulator, comprising 40 meters of fiber wound around the piezoelectric element. The frequency response of this device includes a sharp peak at 18.04 kHz with a mechanical Q of 138. This was measured by placing the phase corrector in a Mach-Zehnder interferometer configuration with directional couplers splitting and recombining the fiber laser and measuring the open-loop transfer function of fringe modulation with a low-frequency network analyzer. This frequency and phase response function is needed in designing the closed-loop controller driving the phase corrector from the phase detector output signal.

A simple controller has been designed with two major poles: at 10 Hz and 1 kHz to allow the feedback loop to be closed with 30 dB low-frequency gain. We may further modify the loop response once measurements are underway.

Without further optical amplification, the Thorlabs S3FC1550 1.5 milliwatt DFB laser provides optical signal levels to the photodiodes of -8 dBm, resulting in a 1 GHz demodulated signal level of -52 dBm to the following amplifier, a Mini-Circuits ZRL-1150LN with a 1 db noise figure (75K noise temperature). The amplifier noise adds about 9 femtoseconds to the jitter budget. A fiber amplifier may be added after the fiber laser, increasing the signal level at the photodiodes, further reducing the relative jitter caused by noise in the photodiodes and amplifiers.

REFERENCES

[1] J.N.Corlett, et al, “LUX A Recirculating Linac Based Facility for Ultrafast X-ray Science”, this conference.

[2] David Jones, “Optical Transmission of Frequency Standards using Mode-Locked Lasers”, in *Proceedings of the Conference on Lasers and Electro-optics 2004*, San Francisco, paper CTuH3.

[3] Jun Ye et al, “Delivery of high-stability optical and microwave frequency standards over an optical fiber network”, J. Opt. Soc. Am. B, **20**, p1459 (2003).

[4] Long-Sheng Ma, Robert K. Shelton, Henry C Kapteyn, Margaret M. Murnane, and Jun Ye, “Sub-10-femtosecond active synchronization of two passively mode-locked Ti:sapphire oscillators”, Physical Review A, **64**, 021802 (2001).

[5] T. Naito, K. Ebihara, M. Suetake, E. Ezura, “RF Reference Distribution using Fibre-optic Links for KEKB Accelerator”, in *Proceedings of the 2001 Particle Accelerator Conference*, Chicago p. 791.