TECHNIQUES FOR SYNCHRONIZATION OF X-RAY PULSES TO THE PUMP LASER IN AN ULTRAFAST X-RAY FACILITY[*]

J. N. Corlett, L. Doolittle, R. Schoenlein, J. Staples, R. Wilcox, and A. Zholents, LBNL, Berkeley, California, USA

Abstract

Accurate timing of ultrafast x-ray probe pulses emitted from a synchrotron radiation source with respect to the signal initiating a process in the sample under study is critical for the investigation of structural dynamics in the femtosecond regime. We describe schemes for achieving accurate timing of femtosecond x-ray synchrotron radiation pulses relative to a pump laser, where x-rays pulses of <100 fs duration are generated from the proposed LUX source based on a recirculating superconducting linac. We present a description of the timing signal generation and distribution systems to minimize timing jitter of the x-rays relative to the experimental lasers.

PRODUCING FS X-RAY PULSES FROM PS ELECTRON BUNCHES

The techniques described here are developed for synchronization of ultrafast x-ray pulses produced in the LUX recirculating linac facility [1,2]. In this recirculating linac-based design, hard x-rays are produced after electron bunches receive a time-correlated vertical kick in a dipole-mode rf cavity. This imparts to the electron bunch a transverse momentum that is correlated in amplitude to longitudinal position within the bunch. The electrons then radiate x-rays in the downstream chain of undulators and dipole magnets, imprinting this correlation in the geometrical distribution of the x-ray pulse. The correlated x-ray pulse is then compressed by use of asymmetrically cut crystal optics to achieve the ultra-short x-ray pulse length. Stability of the x-ray pulse to bunch arrival time at the deflecting cavities is described in [1,3].

A laser-seeded cascaded harmonic-generation scheme produces EUV and soft x-ray pulses [4]. In this process the electron beam is passed through an undulator where a co-propagating seed laser modulates the charge distribution over a short length of the bunch. The imposed modulation results in enhanced radiation at specific wavelengths and a selected wavelength is amplified in a following undulator, tuned to a higher harmonic of the seed laser. The harmonic-generation scheme has been developed and demonstrated at the Brookhaven DUV FEL facility [5]. The process is directly seeded by a laser system, and the seed laser oscillator can also be used to drive the endstation pump laser, resulting in tight synchronization between laser pump and x-ray probe pulses.

MASTER OSCILLATOR

We propose a laser oscillator as master oscillator for the LUX facility, providing optical pulses at ~ 80 Mhz rate to the multiple experimental endstations, the cascaded harmonic generation seed laser, and the rf photocathode laser. In addition, the same master oscillator provides rf signals by use of photodiodes. The optical signals must be transported with fs-scale timing stability over distances of approximately 100 m.

Figure 1 shows the block-diagram of a master oscillator based on a passively modelocked femtosecond laser cavity providing optical pulses of less than 100 fs duration. In essence, this laser is a highly stable comb generator. By illuminating a photodiode with output pulses from this laser, one can generate RF harmonics extending from the fundamental oscillator frequency (cavity frequency = 81.25 MHz, round trip time = 12.3 ns), up to the bandwidth limit of the photodiode (which can extend well into the GHz range). Thus, this laser is a direct source for all the necessary RF signals for the linac and other rf systems. Because the laser is passively modelocked, the phase noise is substantially lower than that of conventional RF oscillators at frequencies above ~1 kHz. The dominant phase noise contribution for such lasers originates typically from mirror motion due to environmental acoustics as well as amplitude noise of the pump laser. With advances in stable diode-pump sources, pump laser effects can be largely eliminated. In addition, air turbulence effects are eliminated in hermetically sealed cavities, and in modelocked fiber lasers, both of which are available from commercial vendors. Low frequency acoustic effects and long-term cavity drift can be effectively suppressed by locking the fundamental cavity frequency to a conventional high-stability rf generator by constructing a phase-locked loop as illustrated in Figure 1, in which the laser cavity acts as a voltage-controlled oscillator by modulating the cavity length with a moving mirror attached to a piezoelectric transducer. Thus, a femtosecond laser phase-locked to a stable rf generator provides phase noise levels which match that of the rf generator at low frequencies (DC to ~1 kHz), and are substantially better at high frequencies. Table 1 summarizes the essential characteristics for two potential master oscillator laser systems.
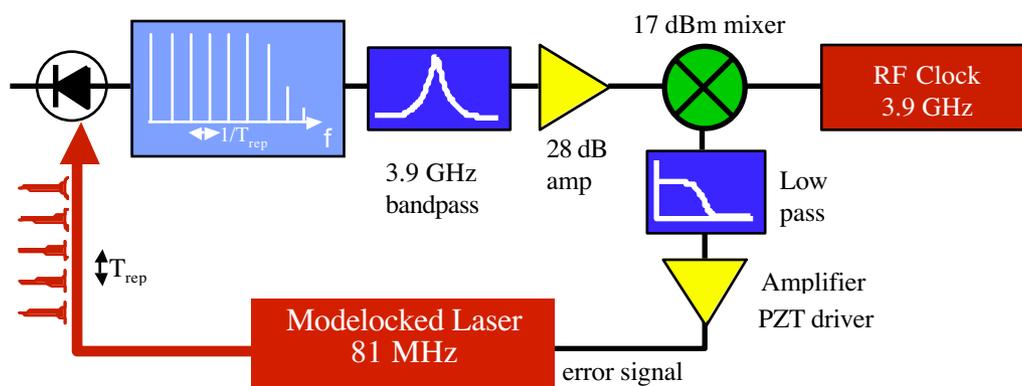

Figure 1. Schematic diagram of an rf-stabilized modelocked laser oscillator

Table 1. Master oscillator laser parameters

Master oscillator laser	Ti:sapphire	Er fiber
Timing jitter	<50 fs	<50 fs
Phase noise	<120 dBc/Hz	<120 dBc/Hz
Pulse duration (fs)	<100	2000
Wavelength (μm)	0.78	1.55
Repetition rate (MHz)	81	81
Average power (W)	~ 1	~ 0.01

TIMING DISTRIBUTION

The optical distribution system must be extremely stable, particularly with respect to path length drift (e.g. a path length drift of only 10 μm corresponds to a time shift of 30 fs). One approach is to use free-propagating beams and mirrors. In this case, pointing stability will require an active position feedback system and hermetically sealed (low vacuum) optical transport lines. A second and currently preferred approach is to use a fiber delivery system. With either approach, active monitoring of the path length stability is assumed. This may be accomplished by back-reflecting a cw reference laser, with interferometric techniques to monitor and control the path length via a piezo-driven variable optical delay line.

One advantage of an optical fiber delivery system is that it completely eliminates any pointing stability problem. However, in a fiber delivery system the nonlinear optical effects and pulse-stretching effects (group-velocity dispersion) must be managed, by propagating sufficiently low pulse energies and by using photonic bandgap fiber in which the group velocity dispersion is balanced by the modal dispersion. Alternatively, by choosing a fiber laser operating at 1.55 μm as the master oscillator laser, one can take advantage of zero-dispersion fiber that is routinely used for telecommunications applications.

Figure 2 illustrates the general layout of the master oscillator and timing systems for a fiber system. The passively modelocked laser oscillator coupled to a high-stability rf generator is the original source for the rf signals required for the linac, as well as the original source of seed laser pulses for laser amplifiers at various locations in the facility. The photocathode drive consists of a second laser system (oscillator/amplifier combination) that is slaved to the master oscillator. Laser pulses from the master oscillator are distributed via an optical transport system to various beamlines. At the beamline endstations a separate modelocked femtosecond laser oscillator (synchronized to the master oscillator), followed by a power amplifier, provides the pump signal to the sample.

DELAY LINES AND PATH LENGTHS

The path lengths from the master oscillator laser to the various beamline endstations will in general not match the path length of the electron beam and x-rays. Thus, delay lines will be required. These delay lines should be as compact as possible and the length kept to a minimum (~1 m) in order to preserve stability. An important point is that the master oscillator laser acts as an extremely stable optical delay line. Beamline users can select any pulse, within a given time window (from the 81 MHz train of pulses) for triggering subsequent sample excitation.

SYNCHRONIZATION OF SYSTEMS

Synchronization of lasers to femtosecond timescales by rf locking at high harmonics in the GHz frequency range has been demonstrated by several groups [6,7,8]. We propose to use similar techniques to ensure synchronization between the master oscillator and all other laser oscillators in the facility. Experimental demonstration of locking lasers to fs stability using ps duration master oscillator pulses is to be demonstrated.

In addition to synchronization of the laser systems, the electrical rf signals in the accelerator will be derived from the optical master oscillator by high frequency photodiodes, commercially available up to 60 GHz bandwidth. Use of low-noise rf signal amplifiers reduces the electrical noise to the inherent Schottky noise in the diode. Rf feedback systems as depicted in Figure 3 control the phase and amplitude of the rf waveforms in the accelerator cavities, to control modulation arising predominantly from microphonics in the superconducting cavities.
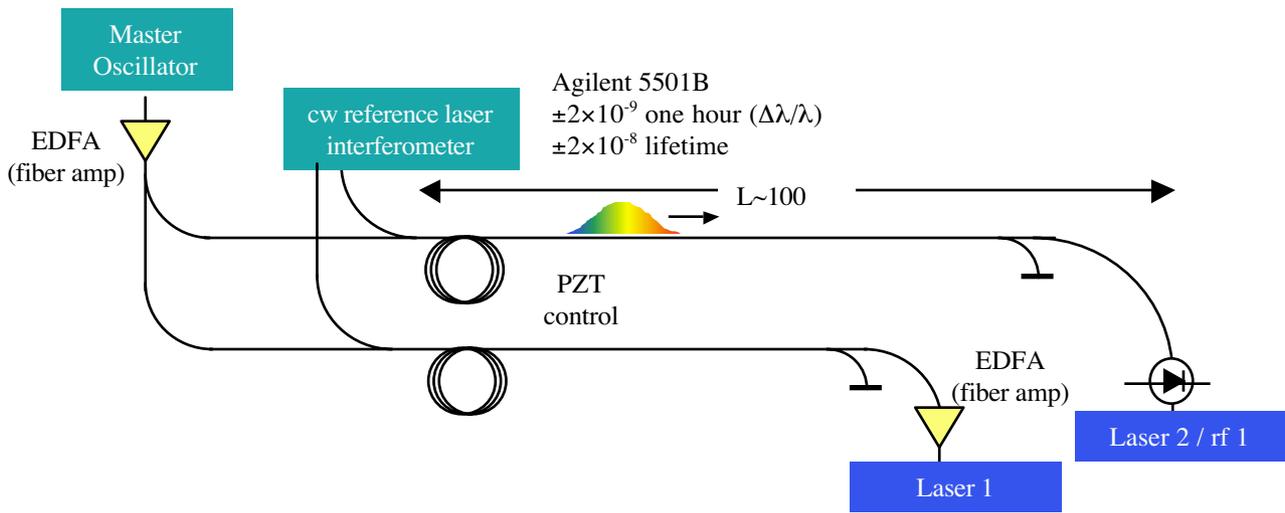
Figure 2. Schematic of fiber distribution network with path length control $\Delta l = \pm 2\ \mu$m, $\Delta t = \pm 7$ fs.

DEFLECTING CAVITIES AND PHASE NOISE

The phase of the deflecting cavity voltage with respect to the experimental pump laser is most critical in hard x-ray synchronization in LUX [1,3]. Phase noise from a passively modelocked femtosecond laser is typically superior to rf sources at frequencies above ~ 1 kHz, and the deflecting cavity loaded bandwidth may be adjusted to allow the cavity phase to follow the low-frequency variations inherent in the laser master oscillator, with minimal residual timing jitter resulting from the laser phase noise. To control the cavity phase and amplitude a system similar to that shown in Figure 3 will be employed. The drive power to control the superconducting cavities, even with loaded bandwidth of 1 kHz, remains in the order of 100 W. Controlling the cavity phase to 0.01° would result in a timing stability of 7 fs. The expected timing jitter for the hard x-ray pulses, including effects of movements in the beamline downstream of the deflecting cavities, is then a few tens of femtoseconds
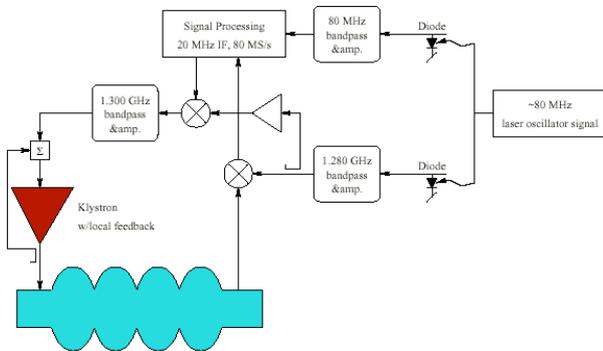

Figure 3. Rf systems control schematic.

ELECTRON BEAM TIMING JITTER

Contributors to the timing jitter in the electron beam include photoinjector laser and rf errors, time of flight changes in the transport lines due to energy variation from coherent synchrotron radiation emission, and magnet ripple. The lattice design has been carefully developed to control and minimize path length variations as a function of bunch charge, for example [9]. These effects are currently being evaluated to produce a timing jitter budget - our initial estimate is that the jitter in the electron beam with respect to the master oscillator will be approximately ±0.5 ps. This is well within the requirements for overlap of the cascaded harmonic generation seed pulse, and the requirement that the electron beam arrive in the linear region of the rf waveform in the deflecting cavities.

REFERENCES

[1] J. N. Corlett et al, "Feasibility study for a recirculating linac-based facility for femtosecond dynamics", LBNL formal report LBNL-51766, December 2002.

[2] J. N. Corlett, et al, "A Recirculating Linac Based Facility for Ultrafast X-ray Science", this conference.

[3] J. N. Corlett, et al, "Synchronization of x-ray pulses to the pump laser in an ultrafast x-ray facility", Proc. EPAC'02, Paris, France, June 2002.

[4] W. Fawley et al, "Simulation studies of an XUV/soft x-ray harmonic-cascade FEL for the proposed LBNL recirculating linac", this conference.

[5] L.-H. Yu et al, "High-Gain Harmonic-Generation Free-Electron Laser", Science **289** 932-934 (2000).

[6] R. Shelton et al., *Opt. Let.*, **27**, 312 (2002).

[7] D.J. Jones et al., *Rev. Sci. Instruments*, **73**, 2843 (2002).

[8] A. Bartels, S.A. Diddams, T.M. Ramond and L. Hollberg, *Opt. Lett.,* 28, 663 (2003).

[9] A. Zholents et al, "Longitudinal phase-space control in the Berkeley Femtosecond X-ray light source", this conference.