SYNCHRONIZATION OF X-RAY PULSES TO THE PUMP LASER IN AN ULTRAFAST X-RAY FACILITY*

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Abstract

Accurate timing of ultrafast x-ray probe pulses emitted from a synchrotron radiation source with respect to a pump laser exciting processes in the sample under study is critical for the investigation of structural dynamics in the femtosecond regime. We describe a scheme for synchronizing femtosecond x-ray pulses relative to a pump laser. X-rays pulses of <100 fs duration are generated from a proposed source based on a recirculating superconducting linac [1,2,3]. Short x-ray pulses are obtained by a process of electron pulse compression, followed by transverse temporal correlation of the electrons, and ultimately x-ray pulse compression. Timing of the arrival of the x-ray pulse with respect to the pump laser is found to be dominated by the operation of the deflecting cavities which provide the transverse temporal correlation of the electrons. The deflecting cavities are driven from a highly stable RF signal derived from a modelocked laser oscillator which is also the origin of the pump laser pulses.

1 PRODUCING FS X-RAY PULSES FROM PS ELECTRON BUNCHES

Our proposed source for production of ultra-short (< 100 fs FWHM) x-ray pulses utilises a scheme for manipulation of the relatively long (~ 2 ps) electron bunch in transverse phase-space, followed by compression of the emitted x-ray pulse in crystal optics [4]. Superconducting RF cavities operating in the first dipole mode (TM_{110}) provide a time dependent transverse (vertical) kick to the electron bunches before they enter a series of bend magnets and undulators in which the electrons emit synchrotron radiation. Ideally, the RF phase is adjusted such that the kick acts in opposite directions on the head and the tail of each bunch, with no perturbation to the centre of the bunch. Following the kick in the RF cavities, the electrons perform betatron oscillations, and the photon production bend magnets are x-ray sources with a vertical position-time correlation and the insertion devices are x-ray sources with an angular-time correlation. These correlations are exploited to compress the x-ray pulses.

Asymmetrically cut crystals are used as optical elements in the x-ray pulse compression scheme. By adjustment of the angle of crystal planes and beam incidence on the crystal, the optical path length may be varied linearly with transverse position on the asymmetrically cut crystal. The x-ray pulse may then be compressed by having a longer path length for the early part of the radiated pulse.

2 STABILITY OF THE X-RAY PULSE TO BUNCH ARRIVAL TIME AT THE DEFLECTING CAVITIES

Our scheme of manipulating the electrons followed by optical pulse compression carries the advantage of providing insensitivity of the x-ray pulse timing at a point (the sample) following the crystal optics, to the arrival time of the electron bunch in the deflecting cavities. An electron bunch arriving "synchronously" with the deflecting RF voltage will experience a transverse kick of equal amplitude to the head and the tail electrons. Electrons in a bunch arriving early or late with respect to the deflecting voltage phase will also receive a transverse kick dependent on their position within the bunch, but the bunch also receives a net offset kick and the centroid will oscillate afterward. Since the bunch duration is short compared to the RF period (3.9 GHz deflecting cavities), the transverse distribution of electrons within a bunch remains linear with the same slope. Figure 1 shows the perturbation to the electron bunch in the deflecting cavities, resulting in time-position-angle correlation.

In the x-ray crystal optics, the optical path length varies linearly with transverse position on the crystal, and early or late bunches produce radiation that will receive proportionately longer or shorter delays in the optical path, thus remaining synchronous with the deflecting cavity RF phase. Following the asymmetric crystal optics, the time of arrival of the x-ray pulses is the same regardless of the jitter in arrival time of electron bunches at the deflecting cavity. In this way, the temporal jitter of the electron beam is transformed into spatial jitter of the x-ray pulse. Figure 2 gives a pictorial view of the scheme.

3 TIMING SYSTEM

The laser oscillators used in generation of electrons at the photocathode and in excitation of the experimental samples are considered fundamental to the machine timing system. Control of the bunch arrival time at the deflecting cavity is enhanced by deriving all RF signals from the phase locked laser oscillators. The timing scheme block diagram is shown in Figure 3. RF signals are derived by multiplication of the laser oscillator signal - the 1.3 GHz gun and linacs are roughly 16 times the 80 MHz laser oscillator frequency, and the 3.9 GHz deflecting cavity is approximately 49 times the laser oscillator frequency.

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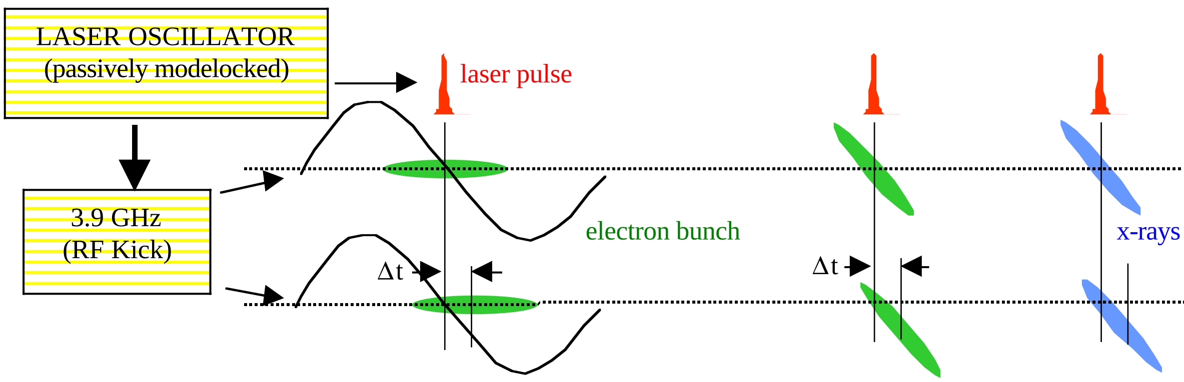

Figure 1. Time-position-angle correlation of deflected bunches

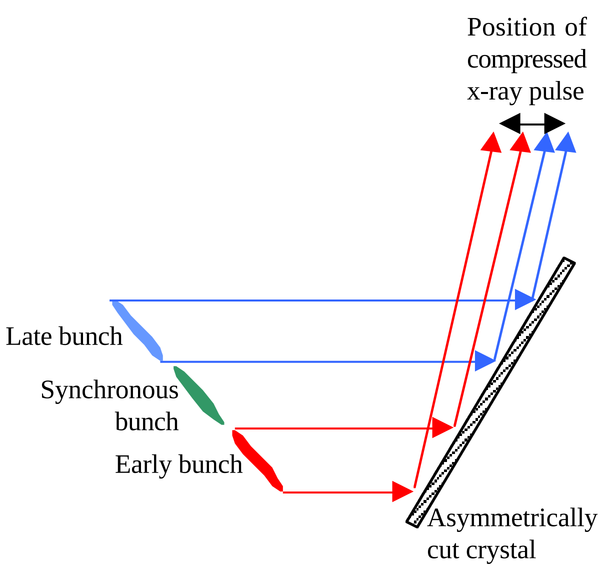

Figure 2. X-ray pulses arrive at the sample with equal time delay for all electron bunches

Feedback on all RF systems (RF gun, injector linac, main linac) is expected to allow control of the bunch arrival at the deflecting cavities to better than 1 ps. The cavities in the linacs are individually powered and controlled with phase and amplitude feedback systems to provide optimal stability.

An alternate but less attractive scheme could involve taking a part of the pump laser pulse to illuminate a fast photodiode, producing harmonics of the laser repetition frequency (approximately 10 kHz), and selecting a signal around 3.9 GHz to drive the deflecting cavities. The experimental laser itself is expected to be less stable than the oscillator and will inject additional timing jitter and amplitude variations. Amplitude variations are of particular concern as they have potential for generating amplitude-phase conversion in the deflecting cavities. Drift of the pump laser amplifier would move the phase of the deflecting cavity with respect to the rest of the machine.

4 DEFLECTING CAVITY CONTROL

With the deflecting cavity thus locked to the laser oscillator, stability of the x-ray pulse will depend on the phase stability of the deflecting cavity voltage.

The superconducting cavity has an external bandwidth requirement of approximately 100Hz to allow feedback control of phase and amplitude required due to cavity resonant frequency perturbations arising from microphonically induced changes in cavity geometry. We propose to detect the phase and amplitude of the

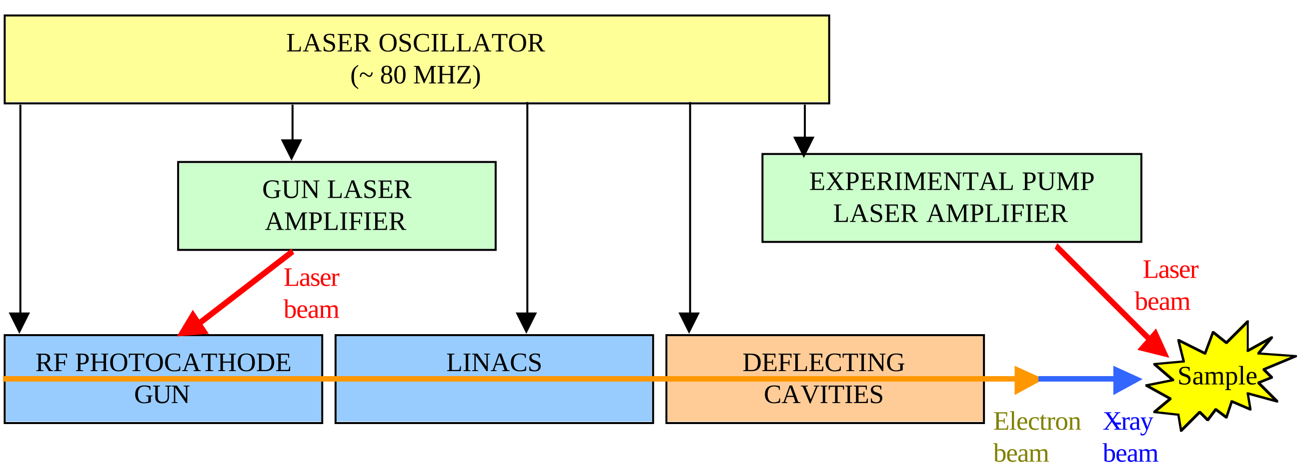

Figure 3. Timing system block diagram

cavity resonance by an IQ method - mixing the detected cavity signal with the drive signal and the drive signal with a 90° phase shift, see figure 4.By measuring these signals in quadrature, and processing the two channels, we may obtain the amplitude and phase of the cavity signal. Since the system bandwidth is limited to 100 Hz by the superconducting cavity, we sample only variations over this timescale, and feedback on cavity amplitude and phase to control stability.

A 10 fs timing error is equivalent to 0.014° in phase at 3.9 GHz, and we require sensitivity at this level. Resolution of 1 fs requires phase control to $2.44\text{x}10^{-5}$ rad, or one part in 41,000. A 16-bit DAC would offer the required resolution. The system bandwidth of approximately 100 Hz allows ample time for signal processing.

We estimate the thermal noise in the system by assuming a room temperature (T) amplifier with 3 dB noise figure (NF) and 30 dB gain (G), bandwidth (Δf) 100 Hz,

$$P_{thermal} = k\ T\ \Delta f\ NF\ G$$

to be $8\text{x}10^{-16}$ W or $2\text{x}10^{-7}$ volts in 50 Ω (k is the Boltzmann constant). A 7 dB NF mixer would contribute significantly less noise. A resolution of 1 fs requires that the signal equivalent to a 1 fs phase change be greater than the noise level:

$$\Delta V_{fs\ resolution} \approx \sin\,(2.44\times10^{-5})\ V_{signal} > 2\times10^{-7}\ V$$

or the cavity signal amplitude must be greater than approximately 10 mV. Such a signal level may readily be obtained from a cavity probe.

5 LONG-TERM DRIFT

Long-term drift of the electron beam with respect to the experimental laser may be determined by using synchrotron light emitted by bunches in the dipole magnets. The visible spectrum may be reflected off an echelle grating to compress the optical pulse to order 100 fs, see Figure 5. This pulse may then be used as a timing signal to determine changes in timing of the electron bunch with respect to the experimental laser, and allow feedback control of the linac and gun RF systems and deflecting cavity phase set point.

6 LIMITS TO TIMING STABILITY

10 fs corresponds to a distance of 2.7 μm in coaxial cable with ß=v/c=0.9. For copper, with a coefficient of thermal expansion of $17\text{x}10^{-6}$ K^{-1}, this corresponds to a temperature change of 0.16 K m^{-1}. For a 10 m cable, the temperature must be maintained to 0.016°C. All cables must be thermally isolated to ensure reliable operations. A key component will be the phase stability in all branches of the IQ detection scheme, where thermal stabilization of components will be required. Optical systems may be considered, however additional noise will be injected in up- and down-conversion.

Vibration of the cavity and coupling probes may introduce phase errors, as would cable movement.

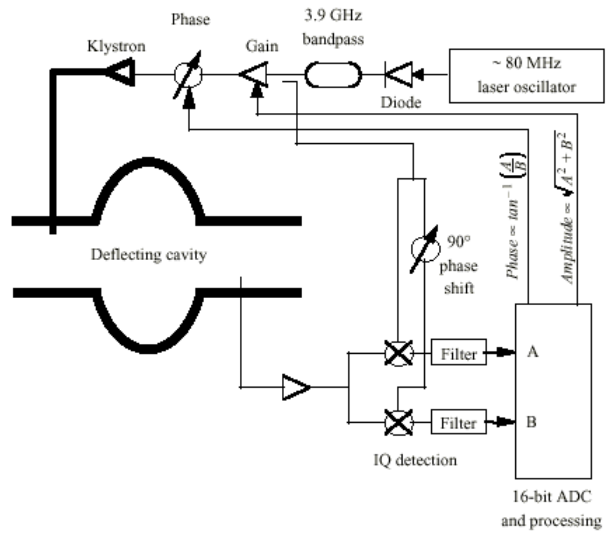

Figure 4. Deflecting cavity feedback systems

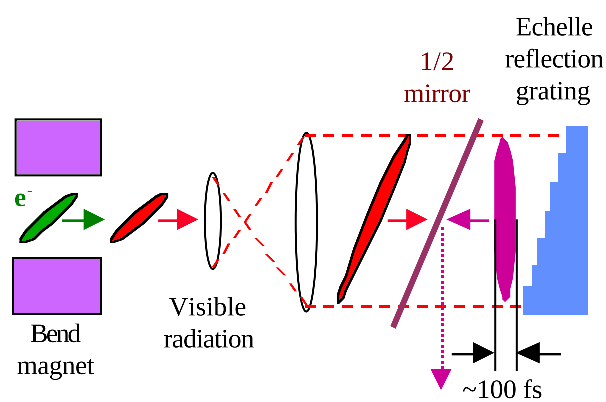

Figure 5. Generation of optical timing pulse

Drift and timing jitter of the pump laser amplifier will also result in timing jitter between optical probe pulse and x-ray pulse.

We will continue to explore the limits of synchronization of x-ray pulses from our recirculating linac-based light source. Technical challenges remain to be addressed, however we believe that our design lends itself to controlled timing of x-ray pulses.

7 REFERENCES

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