Synchronization of Sub-picosecond Electron and Laser Pulses

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Sub-picosecond laser-electron synchronization is required to take full advantage of the experimental possibilities arising from the marriage of modern high intensity lasers and high brightness electron beams in the same laboratory. Two particular scenarios stand out in this regard, injection of ultra-short electron pulses in short wavelength laser-driven plasma accelerators [1], and Compton scattering of laser photons from short electron pulses[2, 3]. Both of these applications demand synchronization, which is sub-picosecond, with tens of femtosecond synchronization implied for next-generation experiments. Typically, an RF electron accelerator is synchronized to a short pulse laser system by detecting the repetition signal of a laser oscillator, adjusted to an exact sub-harmonic of the linac RF frequency, and multiplying or phase locking this signal to produce the master RF clock. Pulse-to-pulse jitter characteristic of self-modelocked laser oscillators represents a direct contribution to the ultimate timing jitter between a high intensity laser focus and electron beam at the interaction point, or a photocathode drive laser in an RF photoinjector. This timing jitter problem has been addressed most seriously in the context of the RF photoinjector, where the electron beam properties are sensitive functions of relative timing jitter. The timing jitter achieved in synchronized photocathode drive laser systems is near, or slightly below one picosecond. The ultimate time of arrival jitter of the beam at the photoinjector exit is typically a bit smaller than the photocathode drive-laser jitter due to velocity compression effects in the first RF cell of the gun. This tendency of the timing of the electron beam arrival at a given spatial point to "lock" to the RF clock is strongly reinforced by use of magnetic compression.

In a magnetic compressor [4], electron beam pulse compression is achieved by first imparting a front-to-back energy chirp on the electron pulse by running forward of the peak accelerating phase in the RF linac, and then propagating the beam through a magnetic chicane. In the chicane, shown schematically in Figure 1, lower energy particles are forced to negotiate a longer path length than higher energy particles. Since ultra-relativistic particles travel at essentially the speed of light, the path length difference rearranges the relative longitudinal position of the particles in the bunch by the same differential length. For small energy spreads a purely linear chirp in the (E, ϕ) phase space ($\phi = k_{rf}(z - ct)$) can be mapped through the chicane so that all the particles arrive at the

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same position z at the same time regardless of the initial time of arrival at the chicane entrance.
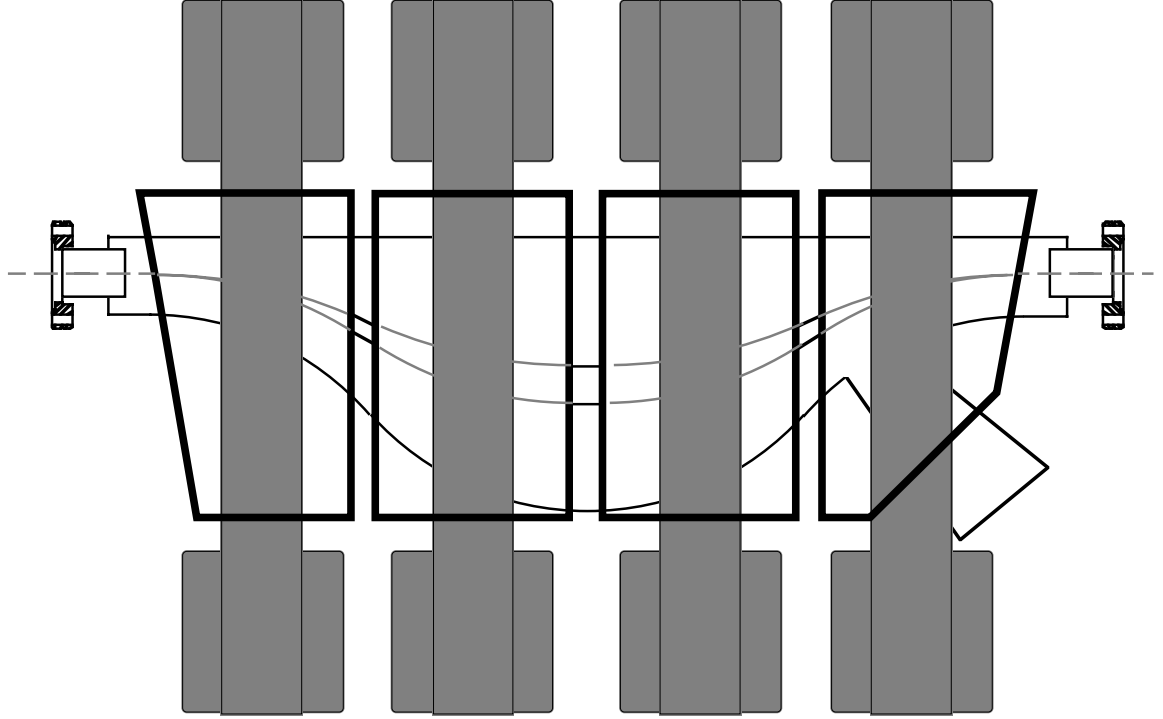

Figure 1. UCLA chicane system [5], showing path of two different energy electrons through magnetic compression system.

If the energy spectrum of the beam is entirely due to the RF accelerating forces, then the spectral dependence on phase is simply $E(\phi) \cong E_{max} \cos(\phi)$, and there is a curvature of the energy chirp, causing a non-zero longitudinal emittance to appear. For such a case, in which we ignore the space charge and wake forces on the particle distribution, the beam is optimally compressed when the slope of the $E(\phi)$ distribution is linear, so that only the quadratic and higher dependence is left. In the absence of these higher order dependencies, and ignoring the weak nonlinearity of the chicane mapping, it would be possible to compress the beam to infinitesimally short length. It was pointed out in Ref. [4] that injection timing jitters are suppressed using the linac chirp/chicane system, as in lowest order in the timing error, all nearby injection times result in the identical time of passage through the chicane exit.

For beams with non-negligible charge, this picture changes somewhat, as is illustrated in Figure 2. The effects of collective space-charge and wake-field forces can change the slope of chirp in addition to introducing new nonlinear longitudinal and radial dependencies of the longitudinal forces. These forces thus increase the longitudinal emittance of the beam in addition to moving the optimum linac phase for compression forward relative to the small charge case. Thus if one optimizes compression, by removing the linear correlation in the longitudinal phase space, one is actually

overcompensating the timing error associated with the beam centroid, which is unaffected by space-charge. In this case the linear component of the timing jitter is not cancelled, but merely suppressed. This is shown in Figure 3, which presents PARMELA simulations of the equivalent spatial jitter for a 40 pC beam in the UCLA Neptune photoinjector and compressor [5]. For optimum compression in this case, the initial timing jitter is suppressed by a factor of 10. If one wishes to suppress the timing jitter optimally, the chicane will undercompress beams with non-negligible collective forces. This trade-off will have to be considered when designing a given experiment.
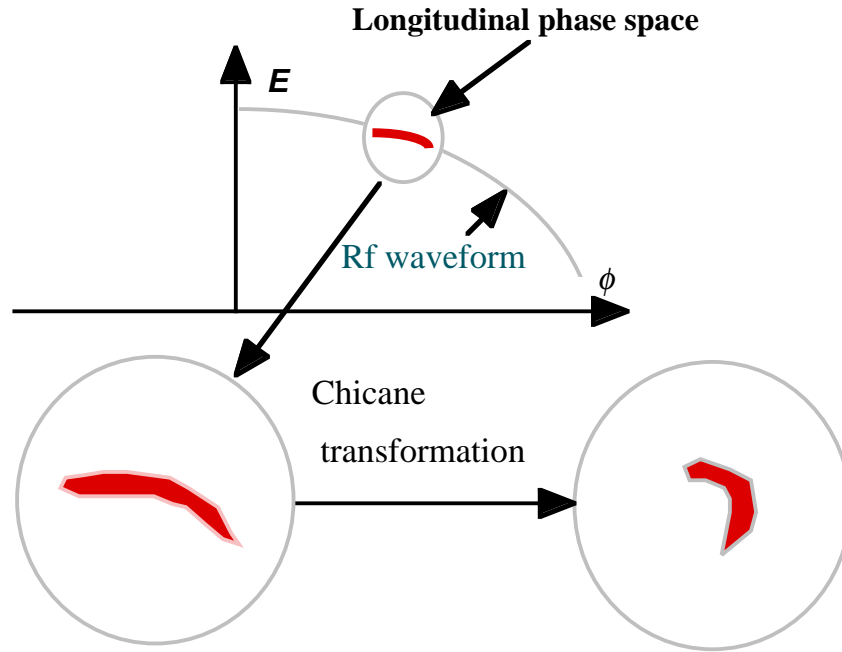
Figure 2. The transformation of a beam with non-negligible charge and phase extent from RF acceleration, collective forces and magnetic chicane. Note that collective forces cause the energy space at the rear of the to beam to sag off of the RF waveform.

To summarize, magnetic pulse-compression techniques apply a longitudinal "restoring force" which improves synchronization between electron bunches and the RF drive, partially or completely correcting errors in the exit time from the injector. While this feature is beneficial in terms of linac related phase matching issues and jitter in the photocathode laser system, laser jitter with respect to the RF clock is in fact worsened in terms of the final interaction of laser and electron pulses. That is, if one attempts to synchronize the electron bunch to an external laser, deriving external laser timing from, say, the photocathode drive laser oscillator, the relative timing of electron and the external laser will be mismatched, because the electron beam is pulled toward a given phase of the RF clock. Thus, if one wishes to take advantage of the locking of the electron beam to the (assumed stable) RF clock, then an equivalent mechanism must be found for locking the external laser to the RF clock as well.

Figure 3. The equivalent spatial jitter at chicane exit in the UCLA Neptune photoinjector, with optimal compression of a 40 pC electron bunch. Note that an initial timing jitter of 1 psec (300 microns at the speed of light) is reduced to 0.1 psec (30 microns).
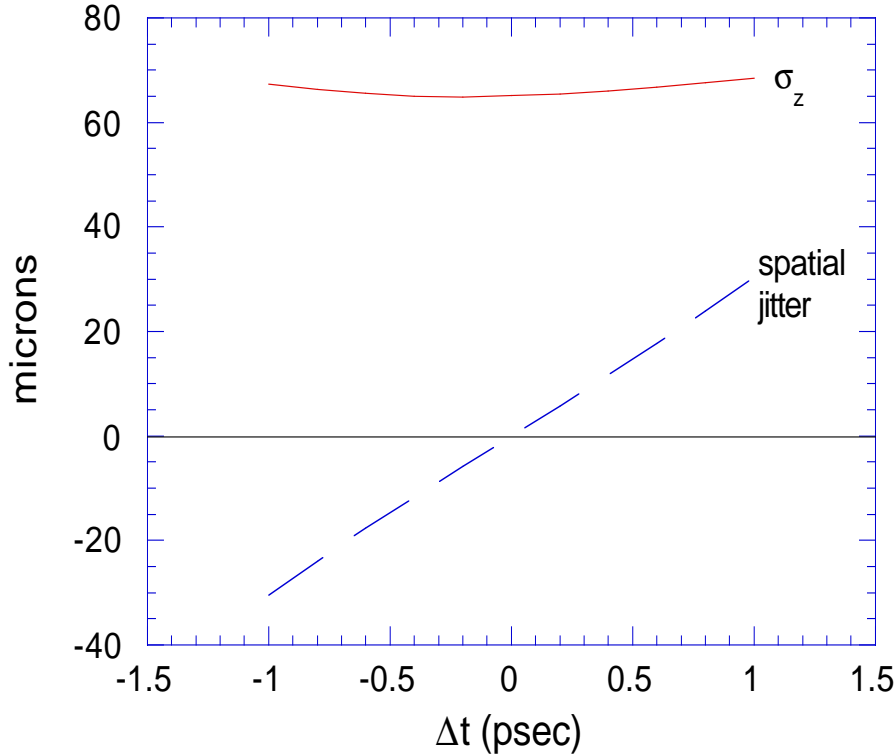
There are distinct causes associated with laser-electron timing in a complex high power laser and RF linac system. For propagation over long path lengths, mechanical vibration and thermal changes in the optical transport system will contribute to long time scale phase changes between the laser and electron pulses. These contributions are correctable in the kHz range using electro-mechanical feedback systems. Pulse-to-pulse jitter produced by laser oscillator pump variations as well as other sources of timing error correspond to picosecond range errors between the arrival time of a laser pulse with respect to the phase of the RF derived from the laser repetition signal. Picosecond jitter corresponds to frequencies well outside of the bandwidth delivered to a high Q RF accelerator cavity, so that the RF system can not respond to deviations in the timing of a single laser pulse. An optical analog to the restoring force provided by a magnetic chicaine would therefore represent an ideal solution to the single pulse synchronization between the laser and RF systems.

We propose a new technique which produces a self correcting laser pulse delay, based on a drive signal at the fundamental or an harmonic of the linac RF [6]. In short, propagation of laser light polarized along the extraordinary axis of a birefringent electro-optic (EO) crystal immersed in an electric field varying at the linac RF frequency can delay the laser pulse by an amount proportional to arrival phase or time. The fundamental physical process is analogous to a Pockels cell (EO modulator). In a standard Pockels cell, linearly polarized laser light is transmitted at 45 degrees with

respect to the extraordinary and ordinary axes of an EO crystal. The linear polarization vector is divided into two vectors aligned along the e-axis and o-axis. An applied voltage changes the index of refraction by different amounts along the two axes. The vector components are delayed by different amounts, so that the net polarization vector of the laser light exiting the crystal is rotated by an amount proportional to the crystal length, applied voltage, and material EO coefficient. If the linearly polarized light is aligned directly along the e-axis, the net effect is to modulate the phase of the light proportional to the same factors that affect the Pockels cell. If the applied voltage comes from an RF signal in a resonant cavity, rather than from a pulsed DC source, the laser pulse will witness an index of refraction proportional to the arrival time of the laser pulse with respect to the RF phase. For a laser pulse with length much less than the period of the RF modulating signal, this modulation approaches a constant index. In analogy to the chicaine bunch compressor, this system provides a restoring force that can correct timing errors between the laser pulse, and master RF phase.

Using the Pockels cell analogy, a half wave Pockels cell typically has a length on the order of a centimeter, and has an applied field on the order of a few kilovolts. At 800 nm, a half wave rotation corresponds to a timing delay of one half of an optical cycle, or approximately 1.3 fs. Applying RF fields on the order of a kilovolt in a resonator cavity seems to be a reasonable requirement. Though the single pass delay time is short in this initial evaluation, compared to the desired correction of a few tenths of a picosecond, multiple passes through such a structure could allow significant timing corrections. A modulated EO crystal used in this new configuration could be integrated into an optical cavity tuned in length to have round trip time corresponding to an RF subharmonic. The basic schematic of the proposed system is shown in figure 4. In this case, the EO crystal is shown integrated into a laser amplifier cavity. The optical cavity length between each end of the crystal and end mirror, as well as the overall optical path length must correspond in this case to a sub-harmonic of the master RF frequency, so that the laser pulse witnesses the proper RF phase at each pass through the crystal. The standing wave in the RF resonator can be considered as two counter-propagating travelling waves. The laser pulse travelling in the crystal must be synchronous with the forward component on the initial pass, and the reverse component during the remainder of the round trip.

There are some immediately recognizable difficulties associated with the proposed technique, as applied to the intended application. While an UV laser pulse for photocathode applications is typically picoseconds in length, an interaction laser pulse for Thomson scattering can be much less than 50 Fs. Many passes through dispersive bulk material is not an appealing prospect for producing laser pulses with duration less than 50 fs, though short incident pulse length assures that nonlinear phase modulation of the optical pulse will be negligible. Also, the microwave loss tangent of the crystal could limit design alternatives at high frequencies. Stability of the cavity length in addition to the previously required oscillator length stability represents an additional difficulty, though in this case there are commercially available cavity length feedback systems which can overcome thermal or vibrational variations. Driving with continuous (CW) RF power could stabilize the RF resonator temperature. Since the RF relative dielectric constant of EO crystal material is high, the crystal will absorb most of the incident microwave power. This is beneficial in the sense that the required drive power is small, though the heating of the crystal will be significant. Also, if one considers the use of

harmonics of the master RF to drive the EO crystal, there is an optimization between the fact that lower frequencies require higher drive power to achieve the same correction slope, while the RF loss tangent is worse at high frequencies ($\tan(\delta) \propto \omega_0$).

A stand-alone cavity, not integrated into an amplifier has the advantage of introducing a significant net delay from its many round trips in addition to the small timing adjustment. Since the photocathode laser pulse is derived from the same laser system as the high intensity final-focus interaction laser pulse, additional time delay for the high power laser arm is beneficial. Ideally, one would prefer to derive the photocathode laser and interaction pulses from the same oscillator laser pulse. In this case, if there is no delay introduced in the high power laser amplifier chain with respect to the laser pulse used for photoemission, a significant timing mismatch is present. The linac length must be traversed twice, once to deliver the laser pulse to the cathode, and once for the electrons to accelerate back to the interaction point. For a linac with length of several tens of meters or more, this is a significant delay consideration. On the other hand, losses through a multi-pass timing correction system could represent a significant disadvantage for a stand-alone, multi-pass time correction system.
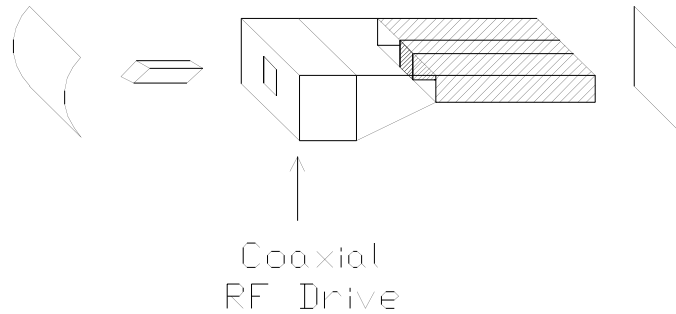

Coaxial
RF Drive

Figure 4: Microwave timing modulator integrated into laser amplifier cavity

An initial experiment that could be used to test this new concept would use the same EO crystal and RF cavity arrangement and CW laser light with incident polarization rotated to 45 degrees between the extraordinary and ordinary axes, in the more standard polarization rotation arrangement. If placed between two crossed polarizers, the modulation depth of the CW laser light would indicate the single pass delay introduced by the modulated EO crystal. This same concept can be used to diagnose synchronization between the laser pulses and RF by simply monitoring the transmission through crossed polarizers of the short laser pulse. An initial experiment will test these concepts by applying a moderate power microwave signal at 2856 MHz to a Lithium Niobate ($L_iN_bO_3$) crystal and passing a CW beam through the crystal and two crossed polarizers. Modulation depth can then be examined as a proof of the principle.

The RF electric field modulation could be accomplished using a TM cavity, driving a longitudinal field in a z-cut EO crystal such as KDP, or a TE resonator driving a transverse field in Lithium Niobate. A ridged waveguide is desirable for this application since the electric field is concentrated in the central, cutoff region of the waveguide. Because of the decreased vertical dimension, the field profile will also be more linear in the transverse direction, avoiding a transverse lensing effect. Vertical thermal lensing is still a potential problem, though at our higher operating frequency of 2856 MHz, the

dimensions of the RF cavity will be smaller, allowing more uniform distribution of heat in the crystal. Forced gas or low dielectric constant liquid cooling of the crystal in the cavity could be considered. Techniques of correcting thermal lensing utilized by optical slab amplifier designers may also be applicable in some modified form [7].

A similar arrangement has been developed for the purposes of time lensing [8] and pulse length adjustment [9] by using the crystal for quadratic temporal phase modulation rather than bulk phase shift. For these applications, the optical pulse length fills a significant portion of the RF "bucket" in the synchronous travelling wave inside of the crystal, inducing a parabolic phase modulation over the pulse. For our short pulse application, the optical pulse will witness a narrow, linear region of the RF drive. We in fact want to avoid phase modulation to the largest possible extent in order to preserve the short pulse characteristics and central frequency. The referenced time lens experiment used a 40 mm Lithium Niobate crystal, in a ridged waveguide cavity, driven with approximately 30 Watts of 1.76 GHz RF power in a TE_{101} mode. The achieved modulation corresponded to approximately one radian per root Watt at an optical wavelength of 632.8 nm. In terms of our application, this result would correspond to approximately 0.34 fs per pass. The time lens experiment also achieved 14 passes (7 round trips) in an optical cavity configuration. Since we require jitter correction on the order of tenths of picoseconds, we will need a longer electro-optic crystal, corresponding to a higher order longitudinal RF cavity mode (TE_{104} for instance), higher microwave power level, and more passes through the crystal. There are also new materials that have demonstrated EO coefficients, which are orders of magnitude higher than Lithium Niobate [10], which warrant examination for our application. Our higher operating frequency has the advantage that the EO coefficient increases linearly proportional to frequency, assuming a constant drive power level ($\Delta\tau \propto E_0\omega_0$). On the other hand, our Ti: Sapphire laser system operates at an optical wavelength of 820 nm, and the EO coefficient decreases linearly with optical wavelength. Lithium Niobate has an RF loss tangent of 0.05 and an RF relative dielectric constant of ε_r of 28 at 2 GHz. For 1.06 micron light (YAG), the index of refraction along the extraordinary axis with no applied electric field is 2.15. The EO coefficient (R_{33}) is 30.8 picometers per Volt at 632 nm. The phase velocity of the RF guiding structure must be matched to the group velocity for our optical wavelength.

The design of this microwave timing modulator system is now being investigated in more detail. In addition to research into appropriate optical cavity geometries and EO materials, we are using three-dimensional electromagnetic simulations to aid in the design of the microwave cavity itself. Demonstration experiments at LLNL should follow shortly. In addition, we plan to study the issues associated with handling of higher power picosecond laser sources in this device, such as are found in laser-scattering and laser wake-field accelerator experiments[11].

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