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Techniques for Electro-Optic Bunch Length Measurement at the Femtosecond Level[†]

P. Bolton, D. Dowell, P. Krejcik[*], J. Rifkin

Stanford Linear Accelerator Center
2575 Sand Hill Rd, Menlo Park CA 94025

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[*] corresponding author, pkr@slac.stanford.edu

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Abstract. Electro optic methods to modulate ultra-short laser pulses using the electric field of a relativistic electron bunch have been demonstrated by several groups to obtain information about the electron bunch length charge distribution. We discuss the merits of different approaches of transforming the temporal coordinate of the electron bunch into either the spatial or frequency domains. The requirements for achieving femtosecond resolution with this technique are discussed. These techniques are being applied to the Linac Coherent Light Source (LCLS) and the Sub-Picosecond Photon Source (SPPS) currently under construction at SLAC.

INTRODUCTION

New generations of accelerator-based x-ray laser sources will utilize extremely short electron bunches. The bunches are considerably shorter than can be measured with existing streak camera technology and will require new, innovative techniques to diagnose and tune them. The Linac Coherent Light Source (LCLS) [1] to be built at SLAC utilizes electron bunches as short as 80 femtoseconds rms to generate self-amplified stimulated emission (SASE) X-ray radiation in a FEL. The new Sub-Picosecond Photon Source (SPPS)[2] at SLAC offers a near term opportunity to test and compare these different diagnostic techniques with bunches as short as 30 fs rms, far shorter than anything so far produced in a high energy electron accelerator.

Conventional laser technology has succeeded in producing and characterizing visible light pulses with the time structure that is well matched to these electron beam requirements. The bridge between the two systems exists in the form of electro optic (EO) crystals whose birefringence properties are modulated by the electric field of the electron bunch to be measured. The transmission of polarized light through an EO crystal is in turn modulated and the problem of measuring an electron bunch length is thereby transformed into one of measuring the duration of a light pulse.

This paper discusses first the choices of configurations between laser and electron beam geometry. For a given geometry the sensitivity and bandwidth requirements are then presented. The light pulse detection techniques discussed show the evolution from interferometric techniques to nonlinear autocorrelation methods and the advantages they offer. Finally, the limits to resolution are discussed and the latest developments towards pushing this limit.

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ELECTRO OPTIC PROBE GEOMETRY

Two basic configurations are possible. One is where the probe laser pulse is transverse to the electron beam and the second where the two beams are parallel and co-propagating. Each of these geometries has implications for: laser power in the crystal; whether the pulse sampling should be performed in the spatial or frequency domain; and on the ultimate resolution that could be achieved. An illustration of the transverse geometry is shown in figure 1, similar to that proposed in reference [3].

In the transverse scheme a cylindrical lens brings the polarized laser beam to a ribbon focus at the EO crystal where it overlaps the electric field of the electron bunch. The length of the ribbon focus determines the duration of the timing gate in which the electron bunch must be coincident. A cross polarizer normally extinguishes the light reaching the CCD detector. However, the light will be modulated in proportion to the change in birefringence induced by the electric field of the bunch. The image recorded on the detector is therefore a convolution of the electron bunch charge distribution and the temporal profile of the laser pulse. In order to achieve good resolution a laser pulse length much shorter than the electron bunch length must be used. For example, a Ti:sapphire laser with 20 fs would resolve sub-picosecond electron bunches.

A 100 fs electron bunch is 30 μm in length so some magnifying optics must be used in front of the detector to overcome the pixel resolution limit of approximately 9 μm in a CCD camera. Furthermore, the retardation in the crystal is wavelength dependant and since a short pulse laser has by nature a very large bandwidth, care must be given to calibrating the system. Wavelength calibration is difficult in the transverse geometry where the extent of the bunch is to be measured in the spatial domain.

This problem is partially overcome in the second transverse geometry scheme shown in figure 1. The laser pulse is chirped and the modulation of the electron bunch now acts to gate a portion of the stretched laser pulse. A spectrometer detects the modulation in the frequency domain thereby avoiding limitations due to pixel resolution and beam size. The wavelength calibration of the optical elements is readily done with the electron beam off and using quarter-wave plates.

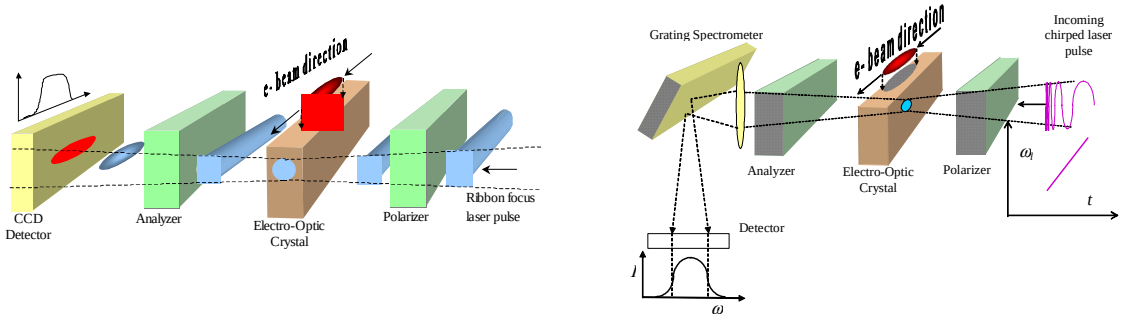

FIGURE 1. Transverse, line-focus probe geometry can produce a spatial image of the bunch[3] (left), or gating of a chirped laser pulse (right).

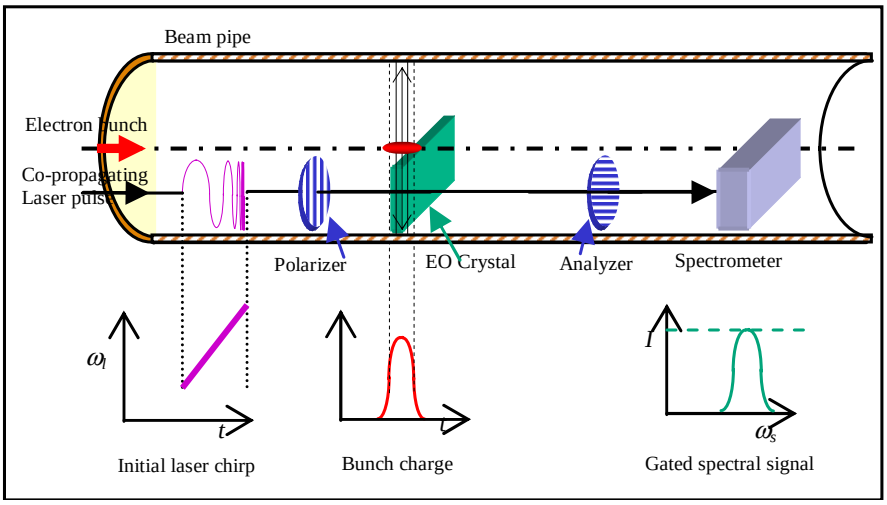

FIGURE 2. In the longitudinal geometry the electric field from a bunch modulates the polarization in an electro optic crystal and gates the transmission of a co-propagating, chirped laser pulse.

In order to achieve good resolution the laser must be focused to a spot at the EO crystal much smaller than the bunch length. Spot sizes of a few microns would be adequate for a 30 micron (100 fs) bunch but the technique now suffers from excessive power density in the EO crystal.

Transverse probe geometries were used successfully in early experiments[4] with picosecond beams, but for femtosecond resolution the longitudinal probe geometry shown in figure 2 has distinct advantages. In the longitudinal geometry the laser pulse co-propagates with the electron bunch. The chirped laser pulse is stretched to around 10 ps to ensure timing overlap with the electron bunch. The chirp provides a correlation between the time domain and the frequency spread of the pulse which can be measured with great precision[5] with a spectrometer. The laser pulse need not be focused to small dimensions in the EO crystal so there is no limitation due to laser power density in the crystal. To understand the limiting resolution of this technique we first look at some of the properties of the EO interaction.

ELECTRO OPTIC BASICS

The electric field of the bunch alters the optical retardation of the birefringent crystal. The polarization, *P*, of the probe laser in the crystal changes with the electric field, *E*, in proportion to the susceptibility according to

$$P = \varepsilon_0 \left[\chi_1 E + \chi_2 E^2 + \chi_3 E^3 + \ldots \right] \qquad (1)$$

The susceptibility, χ, has the same symmetry as the crystal so that all crystals except those with inversion symmetry exhibit some EO properties. The first term in the expansion in equation (1) is the linear, isotropic term. It is the second-order term that is exploited here, namely the linear EO effect, or Pockels effect, in which the polarization changes under the influence of the external, applied electric field of the bunch. A third-order term also exists which drives the second-order EO effect, referred to as the Kerr effect. Birefringence is the anisotropy of the crystal's refractive

indices and results in differing propagation velocities along the different crystal axes. In isotropic media the index of refraction, n, is related to the susceptibility by

$$\chi_1 = n_1^2 - 1 \tag{2}$$

It is convenient to define the change in index through the EO crystal, following the methodology of Yariv[6], by defining an index ellipsoid with principal axes

$$\frac{x^2}{n_x^2} + \frac{y^2}{n_y^2} + \frac{z^2}{n_z^2} = 1 \tag{3}$$

The change in index with applied field is then given by the coefficients r_{ij} for a specific crystal

$$\Delta\left(\frac{1}{n^2}\right)_i = \sum_{j=1}^{3} r_{ij} E_j \tag{4}$$

The electric field of an ultra-relativistic bunch of N_e electrons at a distance r, from the crystal is [7]

$$E_r = 9\times10^9 \frac{2N_e e}{r} \frac{e^{-\frac{s^2}{2\sigma_z^2}}}{\sqrt{2\pi}\sigma_z} \quad \textit{in m.k.s units}$$
$$\textit{and} \quad E_{r_{\max}} = 9\times10^9 \frac{2N_e e}{r} \frac{1}{\sqrt{2\pi}\sigma_z} \tag{5}$$

measured at the center of a Gaussian bunch of length σ_z.

The opening angle, $1/\gamma$, of the electric field lines dictates that the crystal should be within a couple of millimeters of the bunch for low energy bunch length measurements at the electron gun. At GeV energies the crystal can be a centimeter away without loss of resolution or sensitivity.

The retardation, Γ, of the light transmitted by a crystal with trigonal symmetry such as $LiTaO_3$ or $LiNbO_3$ is

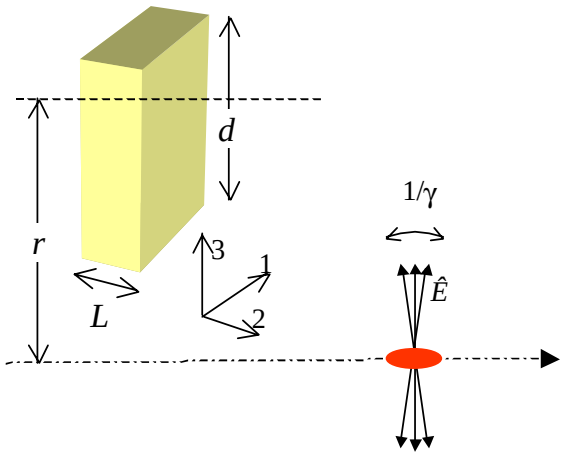

FIGURE 3. A relativistic bunch at a distance r from the crystal and laser pulse.

$$\Gamma = \frac{\pi L}{\lambda_0} E\left(n_e^3 r_{33} - n_o^3 r_{13}\right) \tag{6}$$

and is determined by the electric field strength, E, and the thickness of the crystal along the light path, L,

The electric field corresponding to a retardation of $\lambda/2$ (when the polarized light changes from zero to 100% transmission) is therefore

$$\begin{aligned} E_\pi &= \frac{\lambda_0}{L} \frac{1}{\left(n_e^3 r_{33} - n_o^3 r_{13}\right)} \\ &= 9\times 10^9 \frac{2N_e e}{r\sqrt{2\pi}\sigma_z} \end{aligned} \tag{7}$$

from which the required thickness of the crystal can be determined.

AUTOCORRELATION AND DETECTION

The light pulse transmitted by the EO crystal is characterized by its amplitude A, carrier frequency ω_0, carrier phase φ_0 and chirp $\varphi(t)$,

$$E(t) = A(t)\cos\left(\omega_0 t + \varphi(t) + \varphi_0\right) \tag{8}$$

Its temporal profile, $C(t)$, can be measured by interferometric means, shown in figure 4a, which is an autocorrelation technique

$$C(t) = \int_{\infty}^{\infty} \bar{E}(\tau) E(t+\tau) d\tau = \bar{E}(-t) \otimes E(t) \tag{9}$$

However, by the Wiener-Khinchin theorem this is equal to the Fourier transform of the magnitude squared, $\mathcal{F}\left[\left|E_\nu\right|^2\right]$, and consequently does not preserve phase or asymmetry information about the bunch.

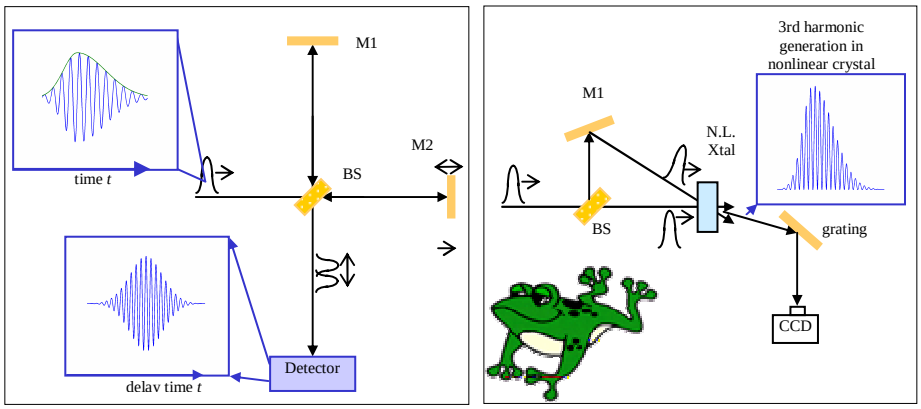

FIGURE 4. Autocorrelation (left) with an interferometer, and a nonlinear autocorrelator (right) for Frequency Resolved Optical Gating.

Alternatively, if the light rays cross at an angle inside a nonlinear crystal, as illustrated in figure 4b, higher harmonics are generated and the unbalanced, third-order correlation terms preserve pulse asymmetry information. Combining the nonlinear autocorrelator with a grating spectrometer results in a powerful diagnostic to Frequency Resolve the Optically Gated (FROG) pulses.

LIMITS TO RESOLUTION

The EO detection method is resolution limited by the phase slippage that occurs from the slight difference in propagation velocity for the sub-millimeter radiation from the bunch and the 800 nm laser radiation in the crystal arising from the difference in refractive index, Δn,

$$\Delta t = \frac{L}{c}\Delta n \tag{10}$$

This effect is minimized by choosing a crystal with small Δn and small thickness, L. For example, in $LiTaO_3$ Δn= 0.1 so that a 100 μm thick crystal has a slippage of 30 fs.

As an alternative we are investigating a new technique based on measuring the wavelength shift that occurs at the entry and exit of the crystal where there is a time-dependant change in refractive index

$$\frac{\Delta\lambda}{\lambda} = \frac{L}{c}\frac{dn}{dt} = \frac{L}{c}\frac{1}{2}\left(n_e^3 r_{33} - n_o^3 r_{13}\right) \tag{11}$$

This effect has been observed in laser-plasma interactions[8] and is proposed as a means to surpass the resolution limits set by phase slippage. For the crystal parameters above, equation (11) predicts a 3% wavelength shift at the edges of the crystal.

In conclusion, it is expected that improvements in EO detection techniques will go hand-in-hand with progress in the generation of ultra-short electron bunches over the next few years.

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