# Electron Bunch characterization with subpicosecond resolution using electro-optic technique

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**Introduction:**

In the past decade, the bunch lengths of electrons in accelerators have decreased dramatically and are in the range of a few millimeters (1,2). Measurement of the length as well as the longitudinal profile of these short bunches have been a topic of research in a number of institutions (3,4,5). One of the techniques uses the electric field induced by the passage of electrons in the vicinity of a birefringent crystal to change its optical characteristics. Well-established electro-optic techniques can then be used to measure the temporal characteristics of the electron bunch. The inherent fast response of the crystal facilitates the measurement to femtosecond time resolution. However, the resolution in experiments so far has been limited to 70 ps, by the bandwidth of the detection equipment (6). Use of a streak camera can improve this resolution to a few picoseconds. In this paper we present a novel, non-invasive, single-shot approach to improve the resolution to tens of femtoseconds so that sub mm bunch length can be measured.

**Theory:**

Let us consider an electron beam of charge density $\sigma(x, y)$, and bunch length l, focused to a sheet beam with transverse dimension of D. Let this relativistic charged particle beam traverse along x axis, the length of a birefringent crystal as shown in Figure 1,

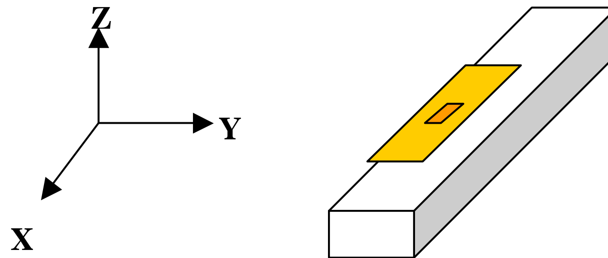


**Figure 1. Schematic of the sheet electron beam traversing the crystal and inducing transient electric field on the crystal**

The electric field experienced by the crystal at a distance r from the electron beam, due to the charge $\sigma(x, y)$ dx dy can be written as

$$dE_z = (\gamma/4\pi\varepsilon_0)\, \sigma(x, y)\, dy\, dx/\varepsilon r^2$$

$\varepsilon$ is the dielectric constant of the crystal in Z direction and $\gamma$ is the relativistic Lorentz factor. This field is present at this location for the time dt taken by this charge to traverse the distance dx. A polarized laser beam propagating along the y-axis inside this birefringent crystal would then experience this field over a distance dL.

$$dL = dx/n$$

where n is the refractive index of the crystal, along the direction of propagation at the laser frequency. The phase retardation experienced between the two orthogonal polarization components (z and x) of the laser beam $d\Gamma(t)$ is

$$d\Gamma(t) = \kappa\, (2\pi/\lambda)\, dL\, dE_z(t)$$

where $\kappa$ is the electro-optic coefficient and $\lambda$ is the wavelength of the laser beam. The total retardation is obtained by integrating over the entire charge, the time taken by the charge to cross the crystal, laser pulse duration, time taken by the laser to cross the crystal and the length of the crystal. The limits of integration would then depend on the smaller of these interrelated parameters. If the transmitted beam is detected after a wave plate and a crossed analyzer, then the transmitted intensity **I(t)** is given by

$$I(t) = I_0 [\eta + \sin^2(\Gamma_0 + \Gamma_b + \Gamma(t))]$$

where $\eta$ is the intensity extinction coefficient, $\Gamma_0$ is the residual retardation by the crystal in the absence of the electric field and $\Gamma_b$ is the retardation introduced by the wave plate. Typical values for $\Gamma_0$ and $\Gamma(t)$ are in the range of tens of milliradian. The value of $\Gamma_b$ is chosen to suit the detector capabilities and the experimental conditions.

Figure 2 represents the dependence of the transmitted intensity as a function of the total retardation. In general, $\Gamma_0 + \Gamma_b$ is chosen to be $\pi/4$ so that the operating region has the strongest and linear dependence on the field. However, the time independent component arriving at the detector is nearly half of the input intensity, which needs to be suppressed to measure the time dependent component. This requirement necessitates a very low noise laser as well as the capability to AC couple the signal. Choosing the operating regime in low $\Gamma_0 + \Gamma_b$ reduces the magnitude of the time independent

component. However, the dependence of the signal on the field is sublinear, resulting in smaller signal.

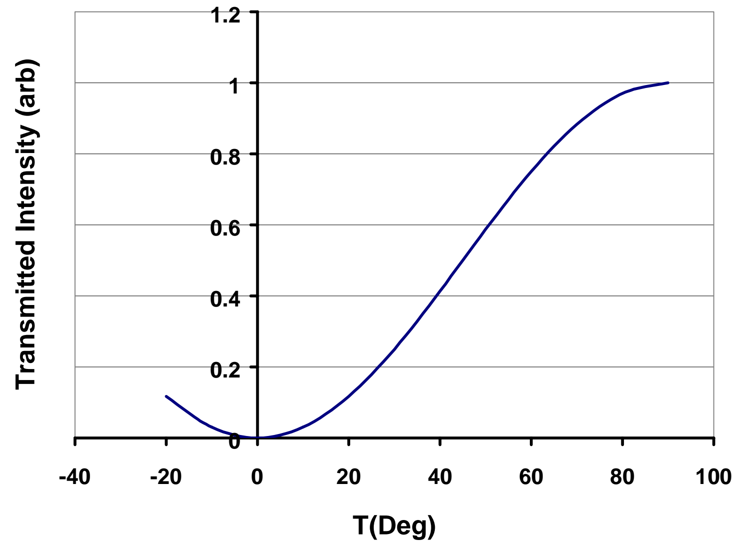


**Figure 2. Dependence of the transmitted signal as a function of the total retardation.**

**Measurement of sub picosecond electron bunch length:**

This scheme has been used successfully to measure the bunch length of 45 MeV electron beam (5,6). The limit on the resolution had been the bandwidth of the detection system. A number of schemes to measure subpicosecond electron bunch have been proposed so far. These include characterizing the frequency modulation on a laser spectrum caused by the electron bunch, performing autocorrelation measurements and using FROG technique to determine both the frequency and time distribution of the laser beam transmitted through a birefringent crystal. In the following section another scheme that converts temporal information to spatial information to measure subpicosecond electron bunch is described. Bunch length measurement with resolution down to the response time of the crystal is possible using this technique since linear arrays with small pixel dimensions is readily available. Furthermore, where pixel dimension proves to be the limitation, effective use of optical imaging technique can be used effectively to overcome this limitation..

A short laser pulse polarized in the YZ plane, 45° to the z-axis, focused using a cylindrical lens to form a line focus, propagates along the y-axis. A thin birefringent crystal with extraordinary optic axis along z and ordinary axis along x is positioned at the waist of the laser beam. The electron bunch propagates simultaneously along the x-axis, at a distance r from the laser beam. The transmitted intensity is passed through a crossed analyzer and detected by a linear detector array. As shown in the Figure 3, only those sections of the laser beam that are below the electron bunch will experience a phase retardation proportional to the linear charge density of the electron beam and viewed by the linear array. The acceptable jitter between the electron beam and the laser beam is determined by the x dimension of the crystal, length and sensitivity of the detector array, length of the line focus of the laser and laser energy available. For a typical diode array of

1024 elements, 1 cm crystal length and ~ 100 pJ of laser energy in a 1 cm line focus, jitter up to 30 ps can be tolerated as well as measured using this arrangement.

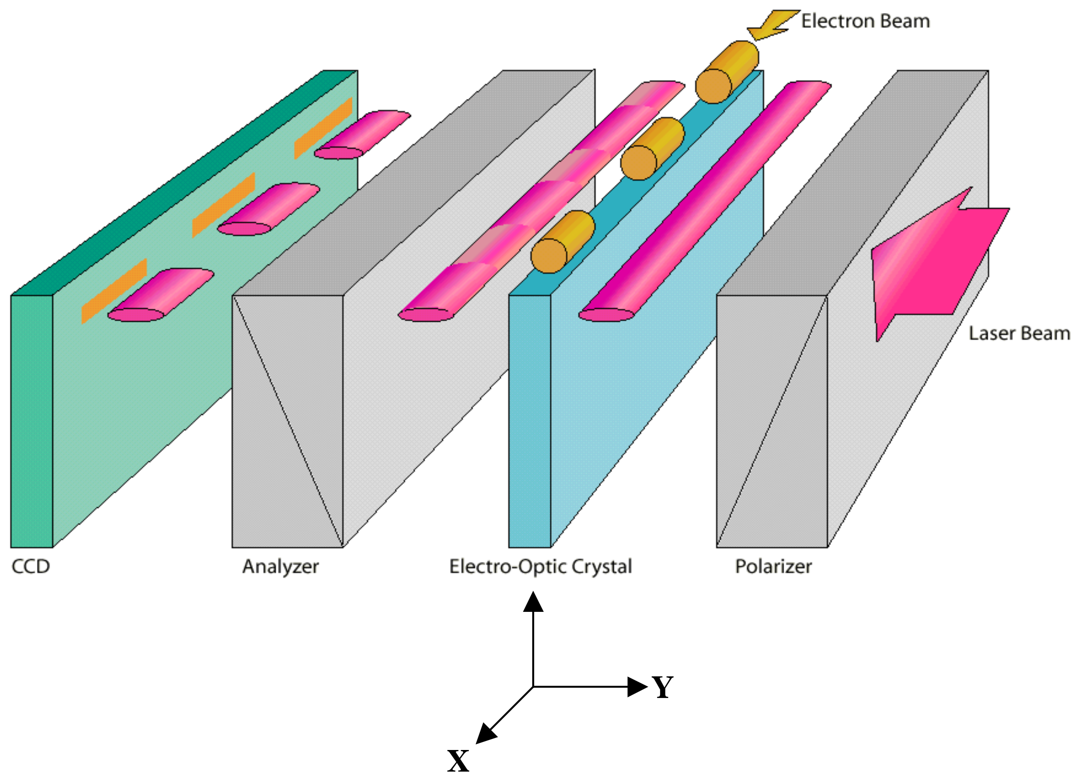


**Figure 3. Schematic of the experimental arrangement to measure subpicosecond electron bunch**

The pulse duration and the thickness (y dimension) of the crystal determine the resolution and fidelity of the temporal profile. The distance traveled by the electron bunch during the laser pulse constitutes the uncertainty in the bunch length measurement. A relativistic electron travels 30 μm during a laser pulse duration of 50 fs, causing a corresponding widening in the image on the detector array. The laser pulse duration should then be a small fraction of the electron pulse duration to be measured. Short laser pulses down to tens of femtoseconds are readily achievable. However, the optical beam transport must be designed carefully to reduce pulse stretching.

The phase rotation of a single photon travelling along the crystal is caused by the integrated charge density along the diagonal of the sheet of charge shown in Figure 2, seen by the photon while in the crystal. Thus, only an infinitely thin crystal would preserve the temporal profile of the electron bunch. The choice of the thickness of the crystal is, hence, a function of the magnitude of the obtainable electric field (determined by charge density achievable and distance between the electron beam and the laser), the strength of electro-optic coefficients, the sensitivity of the detection system, and the structural integrity of the system.

In Conclusion a number of promising techniques are available to measure the length of subpicosecond electron bunches. These techniques need to be tested for limitations before a judicial choice can be made. This work was supported by the department of Energy under Contract No. DE-AC02-98CH10886.

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