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PROPOSAL FOR A NON-INTERCEPTIVE SPATIO-TEMPORAL CORRELATION MONITOR *

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Abstract

Designs toward TeV-range electron-positron linear colliders include a non-zero crossing angle colliding scheme at the interaction point to mitigate instabilities and possible background. Maximizing the luminosity when operating with non-zero crossing angles requires the use of "crab" cavities to impart a well-defined spatio-temporal correlation. In this paper we propose a novel non-interceptive diagnostic capable of measuring and monitoring the spatio-temporal correlation, i.e. the transverse position of sub-picosecond time slices, within bunch. An analysis of the proposed scheme, its spatio-temporal resolution and its limitations are quantified. Finally, the design of a proof-of-principle experiment in preparation for the Fermilab's A0 photoinjector is presented.

INTRODUCTION

It is sometimes crucial to measure, in a quasi non-interceptive fashion, correlations between the temporal and one of the transverse coordinates. For instance most of the designs for next-generation high-energy linear electron-position colliders are based on intersecting the electron and positron bunch with a non zero-crossing angle. To maximize luminosity using such a configuration requires the beam to be "chirped" in the horizontal-longitudinal space. This is done by passing the electron beam through deflecting cavities at the zero-crossing phase so that the head and tail get deflected in opposite directions. Simulations have shown that luminosity is very sensitive to chirp which is controlled by the phase and amplitude of the deflecting cavities [1].

Similarly in a linear collider transverse wake fields can produce a nonlinear correlation between time and the transverse coordinate, so the diagnostics proposed here would be an ideal tool for helping mitigating transverse wake field. In applications such as the free-electron laser (FEL), being able to measure the transverse parameters of temporal slices within a picosecond bunch would provide a new tool for maximizing the FEL performance.

In this paper we briefly describe a concept for measuring spatio-temporal correlation along a charged particle bunch. The ultimate goal is to provide a proof of principle experiment for a high temporal resolution electro-optic (EO) 1-axis beam position monitor. The approach is uses a pair of EO crystals to encode the temporal and transverse spatial profile of a passing bunch onto laser pulses on either side of the beam.

A technique based on simultaneous spectral and spatial EO encoding [2] is suggested. The information extracted can in principle be used to track a beam's centroid of charge over sub-picosecond time slices. Ideally such an arrangement would allow the decoding of the full three-dimensional configuration space from shot to shot.

The arrangement suggested further offers an experimental configuration that reduces wake field contributions to the signal that contribute strongly [3, 4].

SPECTRAL AND SPATIAL ENCODING IN AN ELECTRO-OPTIC CRYSTAL

The approach chosen for the experiment is based on a combination of spectral and spatial encoding in an electro-optic crystal [2] as illustrated in Fig. 1 as a five-step process.

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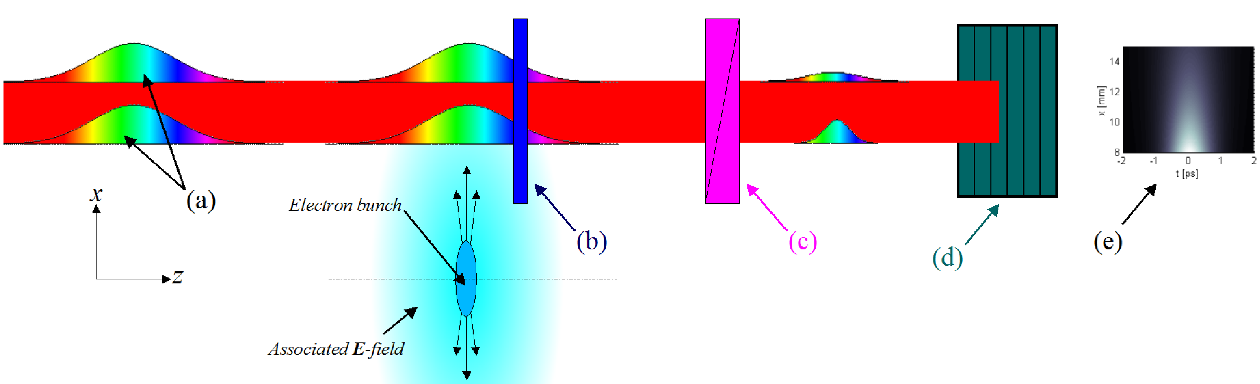

Figure 1: Illustration of simultaneous spectral and spatial encoding. (a) Chirped laser pulse (profiles along minimum and maximum x extent of laser pulse shown), (b) Electro-optic crystal, (c) Polarizer, (d) Cylindrical diffraction grating focusing out of page, (e) Resulting ideal image of bunch-field squared in x-z plane.

First a chirped, collimated laser pulse is generated from an ultra-short pulse. As drawn in Fig. 1, this is linearly polarized in *x*. This then passes through an electro-optic crystal in the vicinity of the subject electron bunch to be profiled. The THz field of the passing electron bunch induces a birefringence in the crystal which, for the configuration shown, will cause a rotation in the polarization of the laser pulse proportional to the local field of the bunch. A polarizer (permitting *y* polarization as drawn), then filters out the remaining *x* polarization. For final imaging a cylindrical diffraction grating is used to focus and disperse the laser pulse out in the *x*-*z* plane.

In the ideal case the image produced by this system then has encoded on each horizontal slice the squared, time-resolved field of the electron bunch as seen at different distances from the beam axis. While we lose sign information about the field for the polarization and crystal orientations under consideration, this setup maximizes the sensitivity of the measurement. Other configurations may be used should sign resolving be required [2].

EXPERIMENTAL SETUP

By mirroring the setup detailed above about the longitudinal axis we can in principle extract the near field of the bunch on both sides of the beam. With this added information it will be shown that we can minimally compute a time-resolved centroid of charge.

The proposed layout for a one-axis setup is shown schematically in Fig. 2 with the beam arriving from the left. Here we see the two crystals placed inside the beam pipe in the vicinity of the beam axis.

To date many experiments meant to directly sample the beam in the near field have done so using an arrangement placed in a six-way cross or by the placement of in-pipe

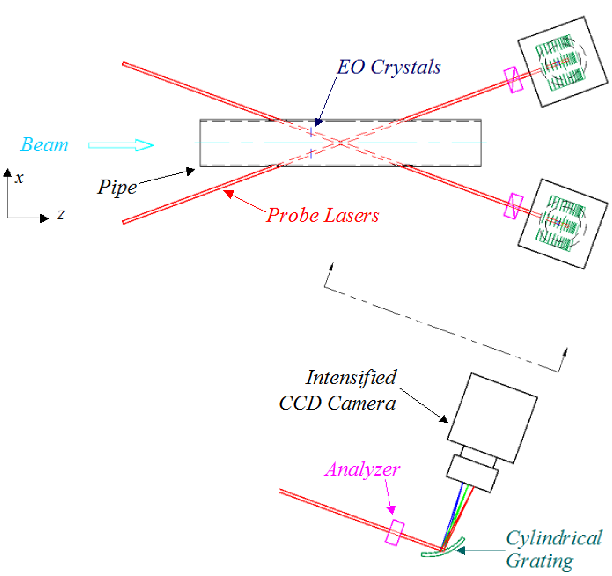

Figure 2: Schematic layout of proposed one-axis optical beam position monitor with side view (*top*) and projected view of final imaging system (*bottom*) shown.

mirrors to deflect the laser path along the beam direction as, for example, in [3, 4]. The drawback to such approaches is the local production of wake fields that EO techniques can be sensitive to, making direct measurement of the beam difficult.

We instead suggest the laser cross pattern demonstrated in Fig. 2. By introducing our two probe laser pulses at an oblique angle, the only required discontinuities in the pipe are small holes to permit the passage of the probe lasers. Depending on the angle of incidence this will introduce an additional temporal skew to the measured image on the order of picoseconds, but this should be easily addressed. Other issues such as refraction and dispersion through the crystal may also be more pronounced, but correctable.

Also suggested is the use of an intensified CCD camera for imaging. Present calculations suggest that the signal produced for crystal positioning about 1 cm from axis will then be at detection threshold for unfocused EO imaging.

Such an approach introduces other barriers. First is determining the applied chirped laser phase space. This is to be measured directly by frequency resolved optical gating in a second harmonic generating (SHG) crystal.

Good synchronization of the laser pulses is required to avoid detection of an artificial bunch skew. A solution to this is in process by way of laser pulse cross-correlation in an insertable SHG crystal.

Picosecond synchronization to the bunch arrival time is also required to ensure the resulting signal is encoded to the time window provided by the chirped laser pulses. The relevant timing experiments are currently underway.

Finally, there are time resolution issues intrinsic in the measurement, one of which can be significant for medium energy beams such as the A0 photoinjector [6].

TEMPORAL RESOLUTION

The laser pulse, EO crystals and electron beam each impose temporal resolution constraints. The contribution Δt_{Laser} is the Fourier-limited pulse length, or ideal unchirped length. At the A0 photoinjector we are using a Ti:Sapph laser presenting a resolution limit of about 30 femtoseconds.

For the crystals the high-frequency cut off can vary from two to several THz depending on the crystal material and thickness. Other experiments have easily achieved resolutions in tens of femtoseconds.

The beam's contribution to the resolution limit comes from the opening angle of the boosted Coloumb field for a charged particle. From this we find the energy-dependent term $\Delta t_\gamma \cong r/2c\gamma$, where r is the perpendicular distance from axis and γ the Lorentz factor of the beam.

For high-energy beams the latter contribution is minimal close to the beam. At the A0 photoinjector, however, with a typical beam energy of 16 MeV, this term is seen as 500 fs image blurring just 1 cm from the beam.

As an illustration, Fig. 3 shows the summed projection to the time axis of ideal images that would be measured for the same simulated 1,000-macroparticle noisy bunch at two energies. This projection is related to the

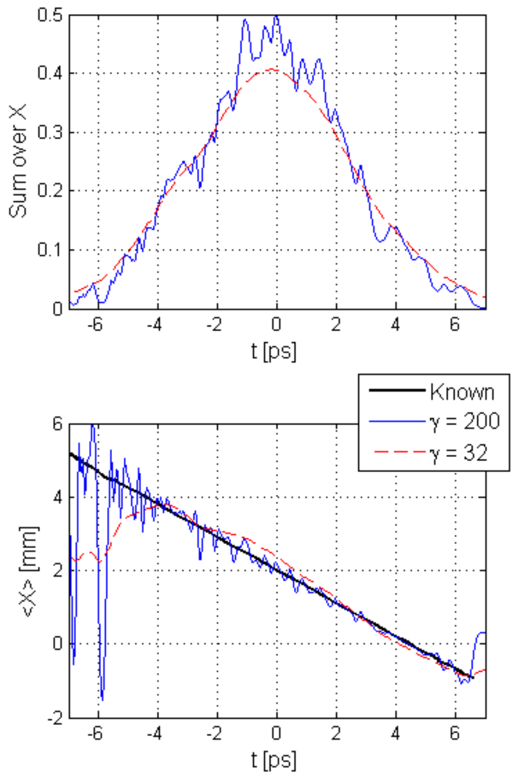

Figure 3: Projection for the sum over x (*top*) and first moment $< x >$ (*bottom*) from simulated images taken as the Coulomb field of the same bunch for two energies.

longitudinal profile of the bunch. Here we can clearly see the blurring effect the lower energy electrons have on the encoding of bunch information to the Coulomb field.

DECODING OF TRANSVERSE FIELD IMAGES

In processing an "ideal image" taken to be the transverse Coulomb field of a bunch with the central region removed, one can theoretically reconstruct a full three-dimensional bunch profile with sufficient information. What information is actually extracted from the field images depends, however, on one's choice of assumed bunch geometry and resolution constraints.

We consider as an example a bunch assumed to have longitudinal and radial transverse Gaussian distributions with all transverse slices centered on an axis parallel to the propagation axis. For large γ we can model the transverse field of this on-axis bunch using a transverse radial normal distribution of instantaneous σ_r, x-offset μ_x, and charge ρ_z to find in the region $|x-\mu_x| > 2.35\,\sigma_r$

$$E_x(X,t) \cong \frac{\gamma}{4\pi\varepsilon_0}\cdot\frac{\rho_z(t)}{\sigma_r^2(t)\sqrt{2\pi}}\cdot\exp\left[\frac{-1}{2}X^2(t)\right]\cdot\frac{1}{X(t)}\cdot\mathrm{Ei}\left[\frac{1}{2}X^2(t)\right] \quad (1)$$

with the time slice-dependent coordinate normalized as

$$X(t) = \frac{x-\mu_x(t)}{\sigma_r(t)} \quad (2)$$

and Ei(x) is the Exponential Integral. We neglect y-offset for the case of our 1-axis system. If one considers only the beam centroid, the Ei(X^2) and Gaussian term both even functions, so <X> is clearly zero. Thus the field centroid corresponds to the modelled bunch centroid. In terms of a fit function this works well in the stated region as compared to direct integration of a bunch. As one introduces a beam centroid that changes with time or goes to lower energy, the approximation folds

Currently we can at best present a first order moment analysis resolving the tilt and offset of the bunch. Figure 3 shows the sum over x and first moment in x for images simulated by direct integration of the Coulomb field. At both energies shown, the same 1,000-macroparticle bunch was used. This was normally distributed in z with $\sigma_z = 2.5$ ps, x offset of 2 mm and -0.45 mm / ps tilt.

The Coulomb field was integrated over all particles over the ranges 8 mm > | x | > 15 mm, representing the regions probed by two 6 mm laser spots.

While this first moment may be expected to represent the local x centroid of the field and bunch, we see this is not the case. What we do see is that the first moment is correlated to the longitudinal distribution. Further, this correlation scales with the distance from the axis. From information about these projections we can reconstruct a linear tilt for the bunch.

For the given resolution of our experiment and using bunch lengths of a few picoseconds, the offset and tilt will be the limit of meaningful information that can be extracted. However, the analysis suggests significant information can be retrieved from extended data fitting for future experiments on high-energy beams.

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