

FEMTOSECOND RESOLUTION BUNCH PROFILE MEASUREMENTS

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Abstract

The measurement of ultrashort longitudinal bunch profiles is of growing importance to accelerator development and operation. With requirements of ~ 10 fs time resolution, and a desire for non-destructive and real time diagnostics, the challenges for diagnostic development are significant. Alongside more established transverse deflecting cavity and CTR measurement techniques, new approaches arriving from the field of ultrafast lasers offer significant potential; Ultrafast electro-optic detection has now been demonstrated on several accelerators, and in many distinct forms, although challenges remain in getting to the desired time resolution. Proposed schemes combining ultrafast laser diagnostics with FEL interactions, such as the "optical replica" scheme also have considerable potential. Here, we discuss some of the recent developments in longitudinal diagnostics.

INTRODUCTION

Many different approaches to ultrafast characterization of electron bunches have been explored experimentally, and with the growing importance of such diagnostics to light source machines, more schemes are proposed to be tested in the near future. Here we discuss some of the leading longitudinal diagnostics techniques, with an emphasis on recent demonstrations of their sub-picosecond capabilities; this discussion is not intended to be an exhaustive review of all the latest developments, but rather an examination of some of the experimental issues and challenges facing sub-ps longitudinal profile diagnostics. Furthermore, the longitudinal profile diagnostics are seen as distinct from approaches that aim to provide an empirical 'bunch-length' monitor, which only aims to inform on the first moments of the bunch profile, or on the presence of structure on a particular time scale of interest.

We discuss techniques through a sub-classification of i) spectral techniques, where the bunch profile is inferred from the spectral intensity of a radiated field, ii) electro-optic (EO) techniques where a Coulomb or radiated field is determined through sampling (possibly single shot) with an ultrafast laser, iii) direct electron bunch techniques, where an active change to the electron bunch properties is made in such a manner that the original longitudinal profile can be inferred from the bunch. Here we restrict ourselves to a brief discussion of transverse deflecting cavities, and proposed demonstrations of the 'optical replica' scheme.

SPECTRAL TECHNIQUES

Within spectral techniques we include the spectral measurements of coherent transition, diffraction and synchrotron radiation, and Smith-Purcell radiation (CTR, CDR, CSR and S-P, respectively). Such techniques have been applied to longitudinal bunch diagnostics in a considerable number of laboratories, and here we give selective examples to demonstrate the practical issues of their implementation and interpretation. These spectral techniques rely on causing the Coulomb field of the electron bunch to radiate in a controlled manner, and subsequently inferring the bunch profile from the emitted radiation spectrum. For femtosecond diagnostics it is important to address the temporal distinction in the Coulomb field and the electron bunch itself. At large distances from the bunch ($r \gg \sigma_z/\gamma$) the field will have a spreading angle of $\theta \sim 2/\gamma$, which corresponds to a temporal spreading in the field of $t \sim 2r/c\gamma$. Furthermore, the field strength will fall as $1/r$ at short distances from the electron bunch, and as $1/r^2$ at large distances. It therefore follows that the position of the radiating structure must be sufficiently close to the electron bunch both to retain the fast time structure and to ensure that the radiated field is sufficiently large for detection. As an example, for a $\gamma \sim 1000$ it follows that any measurements that wish to probe the bunch structure with a 10 fs resolution must be able to access the field distribution within a < 2 mm radius of the bunch (this requirement is also present in electro-optic techniques). For low energy machines this may be a deciding factor in the applicability of CDR or Smith-Purcell radiation techniques. A demonstration of the relative signal strength of CTR and CDR has been given by Delsim-Hashemi et al. [1, 2]. For a CTR or CDR screen inserted into the compressed bunch of FLASH, with $\gamma \sim 900$, the CDR energy is approximately two orders of magnitude reduced in power density with respect to the CTR radiation. The CDR screen is intercepting the Coulomb field at a radius of 5 mm from the bunch. They also observe a cut-off in the short wavelength emission for the diffraction radiation at $\lambda \approx 200 \mu\text{m}$, while the transition radiation has a cutoff at the much shorter wavelength of $\lambda \approx 50 \mu\text{m}$. In separate experiments, with a diffraction grating spectrometer they were able to observe CTR at wavelengths as short as $5 \mu\text{m}$, thus identifying the presence of extremely short time structure in the bunch [3]. At SLAC, CTR has also been used to characterize the extremely short bunches available at the FFTB

facility [4]. Using a Michelson-Morely interferometer the autocorrelation of the CTR radiation was measured, from which the power spectrum of the CTR radiation is determined. In that work, Muggli et al. comment that limitations in the accuracy of the diagnostic arise from the difficulties of transporting and detecting the full spectral range of the far-infrared radiation; these effects limited the ability to infer an actual bunch profile, although bunch lengths of 210fs FWHM were however able to be determined. At the Advanced Photon Source (APS), CTR and CSR diagnostics have been demonstrated for profile reconstruction of sub-picosecond 150 MeV bunches [5, 6]. The spectrum of the CTR/CSR was obtained from a Michelson-Morely interferometer. To determine the profile of the bunch, the phase of the radiation was retrieved from the intensity spectrum from applying a “minimal phase approximation”, a numerical process that is based on Kramers-Kronig relations. For the CTR measurements [5] the retrieved bunch profiles displayed FWHM durations as short as 290fs for leading spikes of the profile.

For Smith-Purcell radiation, the radiator is a periodic structure running parallel to the beamline. In such a structure the radiated power at a specific wavelength can be enhanced in proportion to the number of periods to the structure. It also has the property of acting as a wavelength dispersing element. Korby et al. [7] have determined bunch lengths using S-P radiation of a 15 MeV beam. Their S-P gratings had periods of either 6 mm or 10 mm, and a grating length of 100 mm. Through a moveable mirror directing the S-P radiation out of the beamline, they were able to determine the angular, and hence spectral, intensity of the radiation. Separately, Blakemore and Doucas [8, 9] have undertaken S-P experiments at the FELIX FEL facility in the Netherlands. In their experiments an array of 11 detectors arranged opposite the radiator were able to simultaneously collect the S-P radiation over a large angular range. They collect radiation in the range of $\lambda = 500 \mu\text{m}$ -3 mm, and determine a sub-ps bunch length. In both the above examples of S-P radiation, the bunch shape was not explicitly determined from the data; instead the experimental spectra were compared to calculated spectra based on trial bunch profiles.

In determining the bunch profile from the spectral content a number of issues must be accounted for. These issues can be summarized as i) the Coulomb field temporal profile at the radiator; ii) the propagation of the radiation to the detectors (Absorption, dispersion and diffraction); iii) the detector response, which may include the dispersive characteristics of the spectrometer. Finally, the net result is a power density measurement, and it therefore does not explicitly include information about the phase of the radiation (measurements of CTR or CSR by electro-optic techniques, which do measure the radiation phase, will be discussed separately below).

The propagation issue is one of the significant experimental challenges for spectral techniques. The long wavelength radiation is significantly affected by diffraction, and

there is always some long wavelength cutoff present. The design of transfer lines will usually be specific to the particular experimental conditions (e.g. transport distance from the beamline, available window aperture at the beamline, and the beam properties themselves). These issues, and the analysis of far-infrared (FIR) beamline propagation have been described in detail by Casalbuoni et al [10]; while focused particularly on the the CTR radiation transfer line at the 140m point of FLASH at DESY, the methods and many general results are equally applicable to other experimental situations.

Of a different character is the problem of missing phase information for the field. Lia and Sievers [11] have shown that the phase of the field can be determined from the field amplitude (i.e. the power spectrum) using Kramers-Kronig relation (KK). The KK relations relate the imaginary components of an analytic function through an integral function of the real components, with an integration range extending over the full spectral range of the signal. In the context of bunch diagnostics, a fundamental issue arises as to the validity of the KK phase retrieval in the absence of some spectral amplitude information. Grimm et al. [12] have discussed this issue with examples of sub-ps bunch profiles retrieved with different levels of missing data. Specifically, they show the importance of the long wavelength data in obtaining a faithful retrieval of the bunch shape. Earlier, Lai et al. also addressed this question of retrieval validity, and noted (as do Grimm et al.) that for some bunch profiles the underlying assumption of minimal phase employed in the retrieval may not always be appropriate; an example of a truncated Lorentzian with failed retrieval is given. The conclusion of Lai, Grimm, and others, however is that for “reasonable” bunch profiles, and with sufficient extent to the data, a meaningful bunch profile can indeed be obtained.

ELECTRO-OPTIC TECHNIQUES

Electro-optic techniques enable the ultrafast characterization of far-infrared (FIR) pulses directly in the time domain, and as such avoid the possible ambiguities associated with spectral techniques. In electron-bunch diagnostics, through carrying out the EO detection within the electron beamline, it is possible to measure the Coulomb field directly, avoiding the step of first causing the field to radiate; alternatively, the emitted CTR/CDR or CSR radiation can be measured with the EO detection outside the beamline. Unless otherwise stated, we will be referring to intra beamline measurements of the Coulomb field.

It is usual to describe the EO modulation as resulting from an electric field induced refractive index change within an EO material (such as appropriately orientated ZnTe or GaP crystals). This refractive index change can then be probed by optical means; the polarization components of a linearly polarised laser will experience a differing delay in propagating through the crystal, with the emerging pulse therefore becoming elliptically polarized.

This ellipticity can subsequently be converted into an intensity modulation by a suitable arrangement of polarisers. The net result is an intensity change in the optical probe as a function of the FIR field which is dependent on the particular arrangement of polarizers. In the two most commonly used arrangements, which we call “balanced detection” and “crossed polariser detection”, the intensity change is proportional to field or field squared, respectively.

An alternative perspective for describing the EO process has been derived by Jamison et al [13]; the ellipticity induced in the optical pulse is the result of sum and difference frequency mixing of the FIR and optical field. This is a rigorous description, and has the advantage of being a more appropriate formalism for describing the interaction with long duration (few ps) chirped optical pulses such as used in single shot EO techniques. In essence, they have shown that the optical field spectrum exiting the EO crystal, for a given polarisation component, is given by

$$\tilde{E}_{\text{out}}^{\text{opt}}(\omega) = \tilde{E}_{\text{in}}^{\text{opt}}(\omega) + i\omega a \tilde{E}_{\text{in}}^{\text{opt}}(\omega) * \left[\tilde{E}^{\text{Coul}}(\omega) \tilde{R}(\omega) \right] \quad (1)$$

where the coefficient a is dependent on the polarization geometry. $\tilde{R}(\omega)$ describes the material response due to the nonlinear coefficient and phase-matching. From Eqn. 1 it can be said that the far infrared spectrum of the Coulomb field is now ‘upconverted’ into the optical region. A FIR bandwidth of $\sim 100\%$ (if that can be assigned any rigorous meaning) is exchanged for an experimentally easier optical bandwidth of $\sim 5\%$. Importantly, if the EO frequency conversion is done directly on the Coulomb field within the beamline, the shift to optical frequencies allows the information from the DC component to propagate and be detected. Simple Fourier transformation of Equation 1 gives the equivalent expression for the optical field in the time domain,

$$E_{\text{out}}^{\text{opt}}(t) = E_{\text{in}}^{\text{opt}}(t) + a \left[E^{\text{Coul}}(t) * R(t) \right] \frac{d}{dt} E_{\text{in}}^{\text{opt}}(t) \quad (2)$$

We therefore see that the EO interaction has created a new optical pulse with pulse envelope described by the Coulomb field; in borrowing terminology from a quite distinct technique, we have created an “optical-replica” of the Coulomb field.

An important factor in the ultimate time resolution of EO techniques is the bandwidth of the response function, and the degree to which it is known. Fortunately, materials are available for which the response is approximately constant over the spectral region of interest. For the most commonly used crystal, ZnTe, $\tilde{R}(\omega)$ has an approximately flat spectrum from 0-2.5 THz. Sufficiently thin GaP crystals may have a cutoff as high as 8 THz ($\lambda \sim 37 \mu\text{m}$). Other EO materials with even broader response functions are known, although to date they have not been used in electron-bunch diagnostic experiments. In using materials with such a flat spectral response, time resolutions of < 150 fs can potentially be obtained without the need for explicit calibration of the response; this assertion has recently been examined

through EO benchmarking experiments (as discussed below).

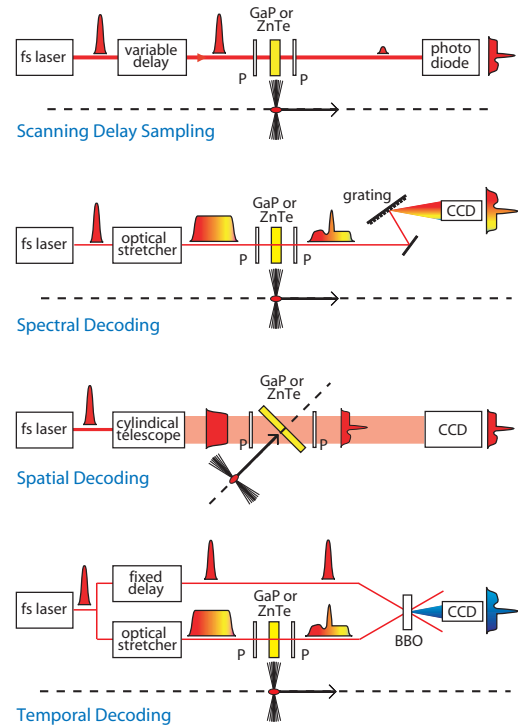


Figure 1: Schematic representations of the four EO detection techniques that have been demonstrated for detection of the bunch Coulomb field.

The above discussion describes the encoding of the Coulomb (or CTR/CSR) field into an optical pulse. The ellipticity introduced into the probe laser is converted into an intensity change with a suitable arrangement of polarisation optics. There are several demonstrated methods for observing this intensity change, each with particular merits. These methods, shown schematically in Fig. 1 are discussed in turn:

Scanning delay sampling: This is the simplest and first demonstrated example EO bunch diagnostics [14]. A short (sub-50fs) laser is used to sample fixed parts of the FIR pulse, and an integrated intensity change in the optical probe is measured. Scanning the relative delay between laser and electron bunch allows the build up of the profile. Multi shot measurements such as this do suffer from time jitter between the laser and electron bunch; however, in even the first demonstration, scanning rates of 2ps per μs were achieved, and over such short measurement periods very small timing jitter (< 50 fs) can be achieved. The time resolution is in the first instance determined by the sampling pulse duration, although for very short laser pulses (< 30 fs), group velocity dispersion of the optical pulse may become the dominating factor [15].

Spectral decoding (SD): The measurement of the optical spectrum can be used to directly infer the field temporal profile if a chirp is first applied to the optical pulse, so

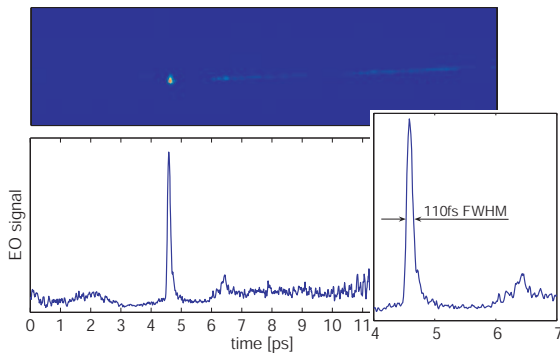


Figure 2: Single shot temporal decoding measurements at FLASH. These measurements are described further in Berden et al. [26].

that there is a known time-frequency relationship in the sampling laser pulse. A lower limit on the bunch duration for which this technique is suitable arises from the intrinsic connection between the temporal modulation of the chirped pulse, and the distortion of the initially known chirp (this limitation can also be shown to be a consequence of the convolution in Eqn. 1). For bunches shorter than this limitation, the measured bunch profile may contain significant artifacts, producing a misleading bunch profile. The limitation can be given approximately as $\tau_{\text{lim}} = 2.6\sqrt{T_c T_0}$, where T_c and T_0 are the FWHM of the chirped and transform limited optical pulse durations, respectively [16]. SD characterization of the in-beam-line Coulomb field has been demonstrated at several facilities, including FELIX [17], NSLS [19], and FLASH [20]. The technique has also been demonstrated for single shot characterisation of CSR [21, 22], and CTR [23].

Spatial encoding: This approach has many similarities to the scanning delay line approach, but instead allows for a single-shot measurement. By sampling the Coulomb field with an optical pulse obliquely incident to the EO crystal and the Coulomb field propagation direction, there is a spatial to temporal mapping introduced for the relative delay of the laser arrival time at the crystal. Imaging the EO crystal, and the intensity changes as a function of spatial position, therefore allows the determination of the field induced intensity changes as a function of relative arrival time at the crystal. An important requirement for spatial encoding is spatially uniform EO materials. The tolerances of this requirement can be difficult to satisfy, with even stress induced birefringence potentially adding significant experiential difficulty. This approach has been demonstrated at SLAC FFTB [24] and at DESY on FLASH [25]. At the FFTB EO signals of 270 fs FWHM were measured, while at FLASH ~ 300 fs FWHM signals have been obtained.

Temporal decoding (TD): Referring to the time domain description of Eqn. 2, it is apparent that for a long duration optical probe, an intensity modulation will be imposed only on portions of the the pulse envelope. TD temporally

resolves this intensity modulation through a process of optical second-harmonic generation, using a non-colinear geometry. Just as in spatial encoding, a time-space mapping is therefore achieved, although in TD this is purely with the optical fields, and is done outside the beamline. TD has been demonstrated at FELIX [18], and more recently at FLASH [26]. In these later experiments an electro-optic signals with FWHM duration of 110 fs were observed. An example of these ultrashort TD measurements is shown in Fig. 2

Benchmarking of Electro-Optic Signals

An important recent advance in electro-optic diagnostics has been the benchmarking of the measured signal with other diagnostics. In recent experiments at FLASH, a variety of longitudinal diagnostics were used to make concurrent measurements. The EO signal has been measured by Temporal Decoding, Spectral Decoding, and Spatial Encoding, together with simultaneously transverse deflecting cavity measurements of the electron bunch immediately following in the bunch train. CTR measurements were also made during the experiments, although not generally simultaneously. The Temporal decoding and transverse cavity measurements have in particular provided explicit confirmation of the exceptional time resolution achieved in the latest TD experiments, and in the faithful reproduction of the bunch profile.

DIRECT ELECTRON BUNCH TECHNIQUES

Direct electron bunch techniques rely on a change to the electron bunch phase space so that the longitudinal projection is converted to a more easily observed projection, such as transverse profile or energy.

Transverse Deflection Cavities: Lola

In RF transverse deflecting cavities, a transverse kick is applied to the bunch which is dependent on the relative phase of the RF with respect to the electron arrival time. Extremely fast temporal resolution can be obtained with a sufficiently rapidly varying deflecting force. Cavities capable of producing such a rapidly varying deflecting force were developed at SLAC in the 1960's, and were prosed for particle separates, as well as for fast bunch diagnostics.

More recently these original SLAC cavities have been installed and operated at the SPPS facility, and at FLASH. The transverse deflection cavity at FLASH, known as "Lola" after its original developers, is currently producing the highest time resolution of all the longitudinal diagnostics. Lola operates in a hybrid mode for which the net deflection produced by the combination of electric and magnetic fields is independent of the transverse position of the beam within the cavity (although the individual contributions from magnetic or electric fields does vary across the cavity aperture). The RF-bunch phase is operated at the

zero-deflection point, so that the longitudinal phase space of the bunch is streaked transversely, but does not have a mean deflection. At FLASH the Lola cavity is preceded by a kicker that adds an additional mean deflection, so that a single bunch can be deflected onto an off-axis OTR screen. An example of the Lola image, and the projected longitudinal profile is shown in Fig. 3. The temporal resolution of TDC is ultimately restricted by the unstreaked transverse beam size on the OTR screen; for Lola this is $\approx 200 \mu\text{m}$ in normal SASE operation conditions, and the maximum streak is 72 fs/mm, from which an ultimate resolution of 15 fs has been inferred [27].

Transverse deflecting cavities such as Lola are intrinsically destructive measurements. They also have large infrastructure requirements, and may require significant beamline space; the Lola cavity is 3.6m in length, compared to the requirement of $\sim 10\text{cm}$ for CTR or electro-optic diagnostics. However, the added capability for measuring slice parameters, such as emittance, energy, or z-y correlations, makes them a more versatile diagnostic than longitudinal profiling by itself.

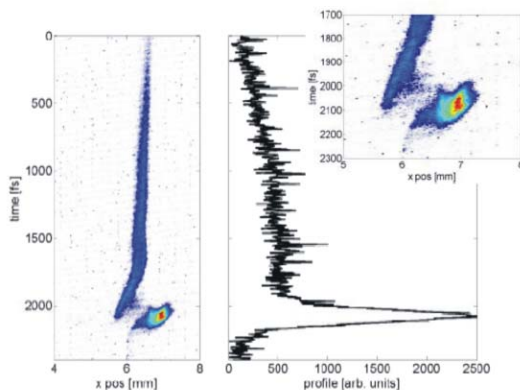


Figure 3: An example of a Lola transverse deflecting cavity measurement (from Hüning et al. [27]).

Optical Replicas

A new technique known as ‘optical replicas’ has been proposed as a means to obtain femtosecond resolution longitudinal profile diagnostics[28]. The basic concept of the scheme is to impose an optical wavelength density modulation on the electron bunch under investigation, and then cause the bunch to radiate optically by passing this modulated bunch through a resonant undulator.

The full scheme consists of i) an initial undulator resonant at $\lambda = 800 \text{ nm}$, which is synchronously seeded with an 800nm TiS laser pulse. The interaction of the bunch with the seeded undulator will result in an energy modulation on the bunch with a period of 800nm, or 2.7 fs. The bunch is taken through a drift space to allow the energy modulation to develop into a longitudinal density modulation, again with a period of 800nm. This modulated bunch then

enters a second undulator also resonant at $\lambda = 800 \text{ nm}$. The pre-modulated bunch will therefore coherently radiate at 800nm, with a radiated intensity dependent on the local charge density of the bunch. Simulations indicate that there will be sufficient intensity in the radiated optical pulse for it to be separately diagnosed with standard ultrafast laser diagnostics. An ultimate time resolution to this technique will be associated with the slippage length of the bunch with respect to the radiation field in the second undulator.

Experimental implementation of a demonstration of the optical replicas concept is currently underway[29]. The system will be installed on FLASH. With a proposed 5 period undulator the achievable time resolution will potentially be 5 cycles of the 800nm resonant wavelength, or 13fs.

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