Short Bunch Beam Diagnostics — Source link

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Institutions: Stanford University

Published on: 26 Nov 2002

Topics: Femtosecond, Particle accelerator, Terahertz radiation, Laser and Stimulated emission

SLAC-PUB-9527
September 2002

Short Bunch Beam Diagnostics*

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Invited talk presented at the 10th Beam Instrumentation Workshop 2002, Brookhaven, NY, May 5-9,2002.

* This work is supported under the DOE contract DE-AC03-76SF00515.

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Abstract. With the emergence of 4th generation FEL based light sources there is now considerable interest in both producing and characterizing ultra-short (<100 fs) electron bunches. Knowledge of the extremely high peak current in a short bunch is required to diagnose the SASE (self amplified stimulated emission) process. Measuring the femtosecond duration of the pulse is inherently interesting, particularly for experimenters using the beam to measure fast phenomena (e.g. femto-chemistry). Diagnostic techniques that have the necessary femtosecond resolution will be reviewed: These include high-power RF transverse deflecting structures that "streak" the beam in the accelerator allowing the bunch length to be recorded on a profile monitor. Electro optic crystal diagnostics use the electric field of the electron bunch to modulate light thereby exploiting the femtosecond technology of high bandwidth visible lasers. Coherent synchrotron radiation (CSR) from dipole magnets and optical diffraction radiation (ODR) both result in radiation with wavelengths of the order of the bunch length and hence in the terahertz band which can be detected by a variety of techniques. The role of each of these techniques is discussed in terms of its application at the Linac Coherent Light Source (LCLS) and the Short Pulse Photon Source (SPPS) currently under construction at SLAC.

INTRODUCTION

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 production and tuning of these ultra-short bunches is critical to the performance of the LCLS but the measurement of such short bunch lengths is a considerable challenge that cannot be met, for example, with conventional streak camera technology. The technologies and limitations to various bunch length measurement techniques are reviewed in this paper together with plans for developing and testing these techniques at SLAC.

The new Short Pulse Particle Source (SPPS)[2] at SLAC offers a nearer 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. The locations of the SPPS and LCLS installations are shown in figure 1 in relation to the other accelerators at SLAC. SPPS will only produce spontaneous x-ray radiation from its undulator but the peak spectral brightness from this source, at 10^{24} photons s^{-1} mm^{-2} mr^{-2} (0.1% bandwidth), still exceeds that of any existing x-ray source.

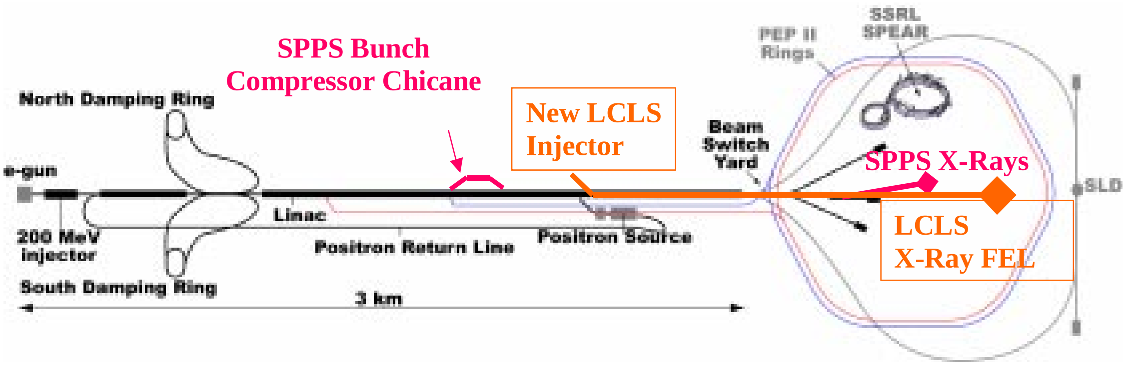

FIGURE 1. The locations of the SPPS linac bunch compressor chicane is shown superimposed on the SLAC site together with the LCLS facility which utilizes the last one third of the linac to generate coherent x-rays from a FEL located downstream of the beam switch yard.

To illustrate the application of the various short bunch diagnostic techniques the accelerator layout of the LCLS is shown in figure 2 with indicators for the locations of the various devices. Bunches of approximately 3 ps rms length are produced in the RF photoinjector and accelerated to 150 MeV where a magnetic chicane compresses the bunches to an rms length of 630 fs. A second bunch compressor is located at the 4.5GeV point where the bunch attains its final bunch length of 75 fs.

At the injector, confirmation of the critical initial longitudinal distribution of the bunch is independently diagnosed with both electro-optic profiling of the bunch and with a short, 0.55 m long S-band transverse deflecting cavity. The electro-optic system can make use of the already available high-bandwidth Ti:Sapphire laser system for the injector to easily achieve the necessary sub-picosecond resolution to characterize the gun pulse. The relatively low 150 MeV energy of the injector means that only a short section of transverse deflecting structure is required to streak the beam on a downstream profile monitor using about 1 MW of power split off from one of the injector klystrons.

A second transverse deflecting cavity is also located in the high-energy linac with a length of 2.44 m and is powered with 25 MW from a separate klystron.

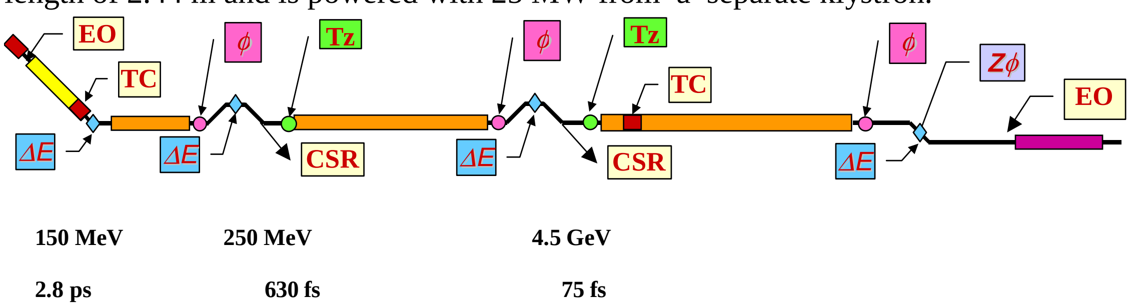

FIGURE 2. A schematic layout of the LCLS accelerator and bunch compressor system showing the types and locations of the various diagnostics to measure bunch length and characterize the longitudinal phase space of the beam: Electo-Optics (EO), Transverse Cavity (TC), Terahertz power monitors (Tz), Coherent Synchrotron Radiation monitors (CSR), Energy spread monitors (ΔE), Beam Phase monitors (ϕ),and Zero-phase measurement locations (Z ϕ).

The energy and energy spread of the beam are measured on beam position monitors and profile monitors at all the dispersive locations where the beam is bent. The very short bunches generate a coherent component to the synchrotron light in the bunch compressor chicane bends so the light will also be diagnosed to monitor the bunch length at these locations. Tuning and feedback control of the chicane bunch compressors is facilitated by rapid, pulse-to-pulse measurement of the CSR power by narrow band terahertz detectors. Beam phase monitors are located at each accelerating sector. The accelerating section downstream of the second bunch compressor will be used for zero-phase crossing measurement of bunch length in conjunction with the profile monitor located in the final bend before the undulator.

The SPPS linac bunch compressor chicane [3] is similarly equipped with short bunch diagnostics to tune and measure its performance.

Each of these techniques will be described in the following sections and their potential for reaching the necessary resolution in the LCLS and SPPS will be discussed. The full temporal characterization of the electron bunch also involves an assessment of the timing jitter and how it can be measured on a pulse-to-pulse basis.

TRANSVERSE DEFLECTING CAVITIES

The principal of the transverse cavities is shown in figure 3 where it can be seen that a strong longitudinal-to-transverse correlation, or crabbing, can be imposed on the bunch when the cavity is operated close to zero phase crossing of the applied RF voltage. This technique of measuring bunch length was in fact used during the early commissioning years of the injector at SLAC[4] and in more recent times has been proposed as a method for measuring very short bunches[5]. In order to test this technique we have just completed recommissioning one of the original SLAC deflecting structures[6] by installing it in the SLAC linac where it can be used with a variety of beams during normal accelerator operations[7].

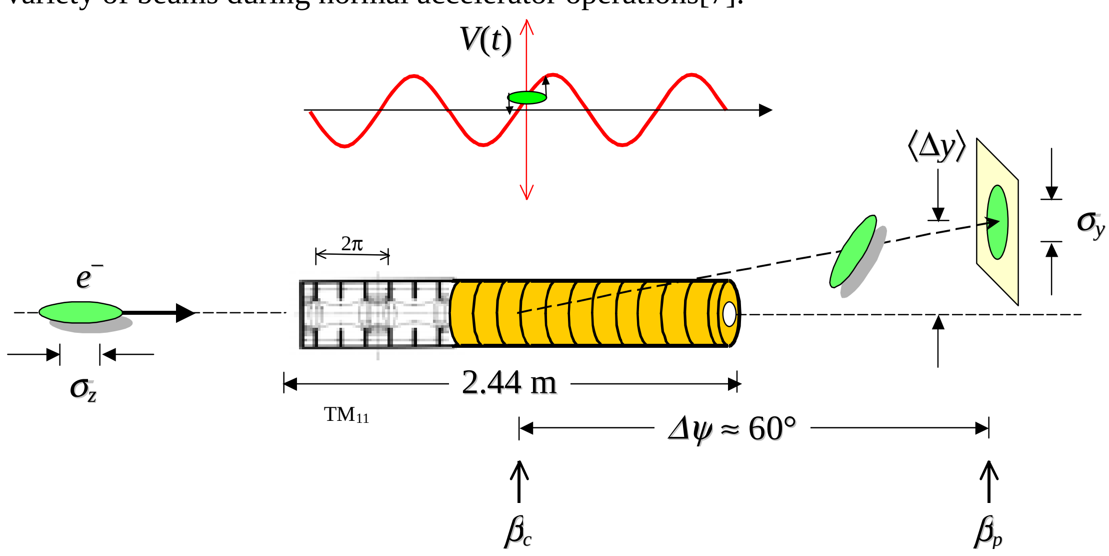

FIGURE 3. The transverse deflecting cavity can be used to crab the bunch so that its projected transverse beam size measured on a downstream profile monitor is proportional to bunch length.

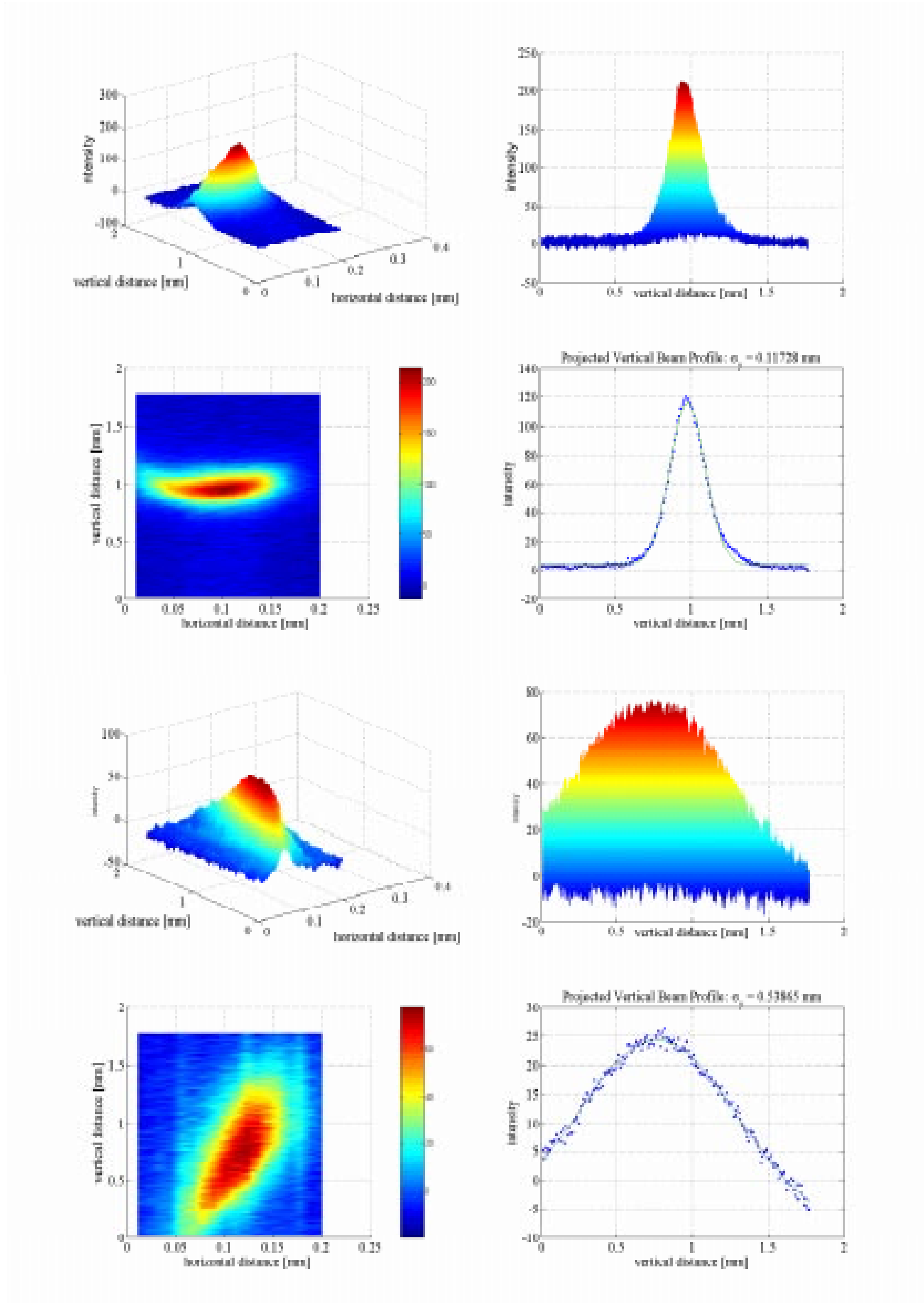

FIGURE 4. Profile monitor images and projected vertical image profile with the RF transverse cavity off (left) and with the RF on (right) showing how the beam is streaked.

A profile monitor screen (p) is positioned at a suitable transverse betatron phase advance from the deflecting cavity (c). The beam size measured on the screen is the quadrature sum of the initial vertical beam size, $\sigma_{y0}^2=\beta p\varepsilon_{y0}$ and the RF induced crabbing.

$$\sigma_y = \sqrt{\beta_p \varepsilon_{y0} + \sigma_z^2 \beta_c \beta_p \left(\frac{2\pi e V_0}{\lambda E_0} \sin \Delta\psi \cos\varphi \right)^2} \qquad (1)$$

The advantage of this technique is that a large deflecting voltage, V_0 can be achieved at short RF wavelength, λ by applying high peak RF power supplied by the same type of klystron as is used to power the normal accelerating sections.

A recent test of this technique with a 2.44 m long 2856 MHz device at SLAC[7] showed that 10 μm bunch length resolution could be achieved with a RF deflecting amplitude of 17.5 MV on a bunch with a normalized vertical emittance of 3*10-5 m rad. Images of the streaked beam are shown in figure 4.

In addition to measuring the rms bunch length, information can also be gained on the bunch length distribution. The measured profile is a convolution of the actual longitudinal distribution in the bunch with the vertical beam size at the screen as determined by the transverse emittance. When the longitudinal distribution is non-Gaussian, due to the bunch being over compressed for example, the measured profile is also non-Gaussian. Particle tracking[8] of the LCLS beam show that quite complex longitudinal bunch distributions are to be expected as a result of the compression dynamics together with the strong wakefields experienced in the linac that are excited by the short bunch. Simulation[9] of the transverse beam profile from the RF deflecting cavity shows that adequate resolution can be achieved to reveal most of the details of the complex longitudinal distribution of the LCLS bunch.

The RF deflecting cavities offer such a powerful resolution of the beam properties along the longitudinal z-coordinate of the bunch that it is reasonable to consider measuring other properties as a function of the “longitudinal slice” position along the bunch. Consider, for example, that the horizontal width of the beam can be measured at different vertical positions on the screen and hence at different positions along the bunch, as shown in figure 5a. If this is combined with a standard emittance measuring technique such as varying the strength of an appropriate upstream quadrupole then the horizontal emittance of each of the slices along the bunch can be determined.

Another technique is to use a profile monitor screen in a region of large horizontal dispersion, after a bending magnet, so that the horizontal beam size becomes a measure of energy spread in the beam. Recording the horizontal beam size along the vertical axis of the profile monitor gives a measurement of what is referred to as the slice energy spread of the bunch. The slice emittance and slice energy spread together with the bunch length and charge are key parameters in the performance of an FEL.

Although this bunch length measurement technique disrupts the beam it is possible to power the device on and off on a pulse-by-pulse basis so that it can operate with a 1% or less duty cycle and minimize the impact to the downstream users.

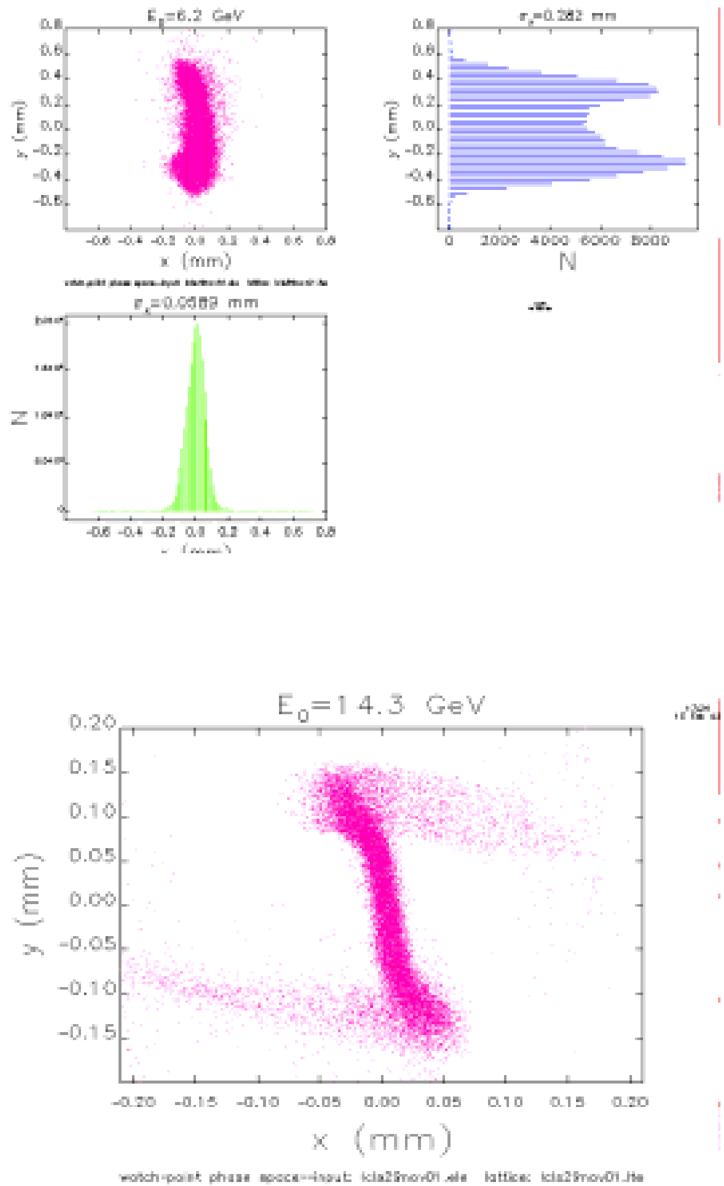

FIGURE 5. a. Expected longitudinal slice profile for the LCLS beam (from P. Emma, ref. 1and 9) from which the horizontal slice emittance could be reconstructed, and b. the slice energy spread obtained by viewing the streaked beam at a high dispersion profile monitor location (ibid).

ZERO-PHASE CROSSING MEASUREMENTS

A more invasive measurement of the bunch length distribution uses the RF accelerating cavities that are part of the linac. Rather than accelerate the beam on crest the bunch is moved to the RF zero-phase crossing where the accelerating field seen by each particle changes rapidly along the bunch length thereby inducing a correlated energy spread, or chirp, along the bunch, as shown in figure 6. The bunch length which was first rotated onto the energy axis by the RF is now transformed into the spatial coordinate by observing the transverse beam profile on a down-stream high-dispersion profile monitor.

The measured horizontal beam size σ_x at a profile monitor location where the dispersion is η_x is the quadrature sum of the beam size σ_{x0}, with the RF off, and the contribution from the energy spread:

$$\sigma_x = \sqrt{\sigma_{x0}^2 + \sigma_z^2 \eta_x^2 \left(\left(\frac{dE}{dz} \right)_0 + \frac{2\pi e V_{rf}}{\lambda_{rf} E_0} \cos\varphi_{rf} \right)^2} \qquad (2)$$

where $(dE/dz)_0$ is the initial energy spread in the beam.

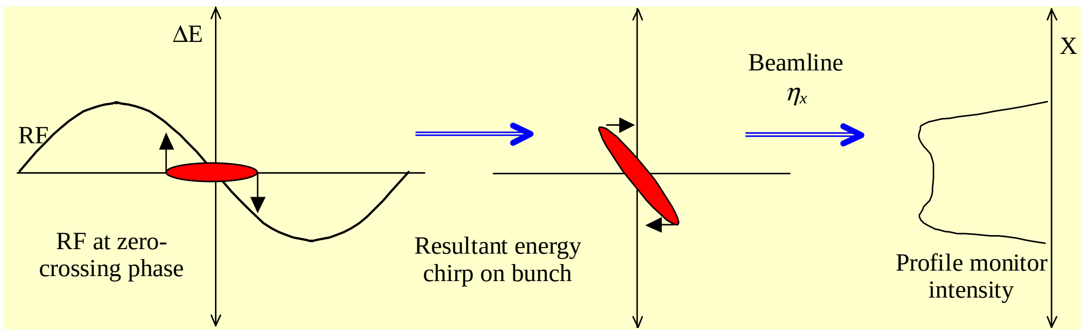

FIGURE 6. A rotation in longitudinal phase space is induced by moving the bunch off crest to the zero-phase crossing where the resultant correlated energy spread is measured on a high-dispersion location profile monitor.

Good bunch length resolution can be obtained if the induced correlated energy spread is much greater than the incoherent energy spread in the bunch. For this reason it is usually necessary to use a large portion of the linac in this off-crest mode.

This technique has been used extensively in short bunch applications such as FEL injectors to measure the bunch length[10,11]. The same technique described above for measuring the slice emittance with the transverse cavity can also be used in conjunction with the zero-phase crossing measurement.

This technique relies on a rotation in longitudinal phase space of the bunch, induced by the RF. In order to distinguish this from wakefield-induced energy correlations in the bunch it is possible to rotate the bunch in opposite directions by performing the measurements on the two zero-phase crossings of the RF in turn. The wakefield contribution will be seen to either aid or oppose the RF induced energy spread and can thus subtracted out of the bunch length reconstruction.

The more invasive nature of zero-phase crossing measurements means they are usually only performed during initial tune up of the accelerator or to cross check other bunch length measuring techniques.

ELECTRO OPTIC TECHNIQUES

At extremely short bunch lengths where the previous techniques begin to give out through lack of RF power we can move to other technologies. It is possible to take advantage of the advances in laser science where femtosecond technology has been developed. Very short electron bunches have very high electric fields associated with them which can be used to modulate a laser pulse. The problem of measuring the electron bunch length then moves to one of measuring the laser pulse modulation, for which several techniques exist.

As an illustration, we consider the setup shown schematically in figure 7, where an electro-optic (EO) crystal responds to the electric field from the electron bunch.

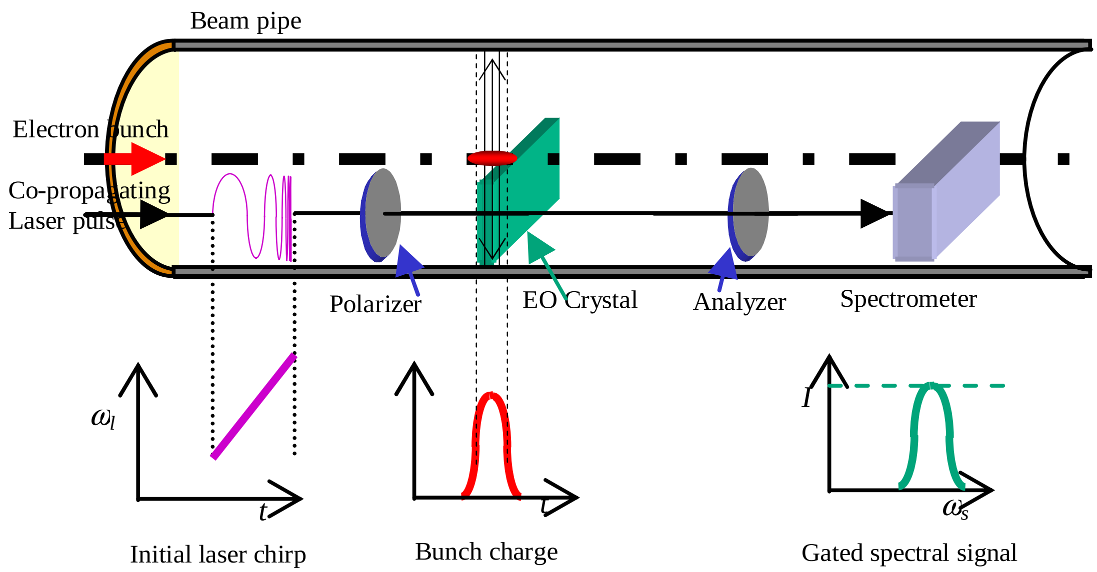

FIGURE 7. The electric field from a bunch modulates the polarization in an electro optic crystal and gates the transmission of a chirped laser pulse.

The electric field of the bunch alters the optical retardation along one axis of the birefringent crystal according to

$$P = \varepsilon_0 \left[\mathcal{X}_1 E + \mathcal{X}_2 E^2 + \mathcal{X}_3 E^3 + \ldots \right] \qquad (3)$$

The optical transmission through a polarizer-analyzer pair is modulated as the polarization vector in the crystal rotates under the influence of the electric field of the bunch. By superimposing a chirp on the incoming laser pulse the time structure of the electron beam induced modulation can be measured in the frequency domain with a spectrometer.

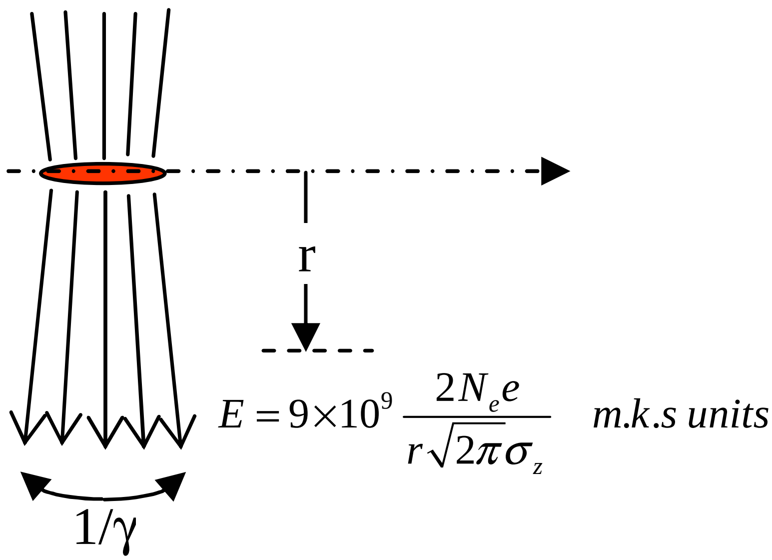

FIGURE 8. Point charge approximation for the electric field at a distance r from a short, relativistic bunch.

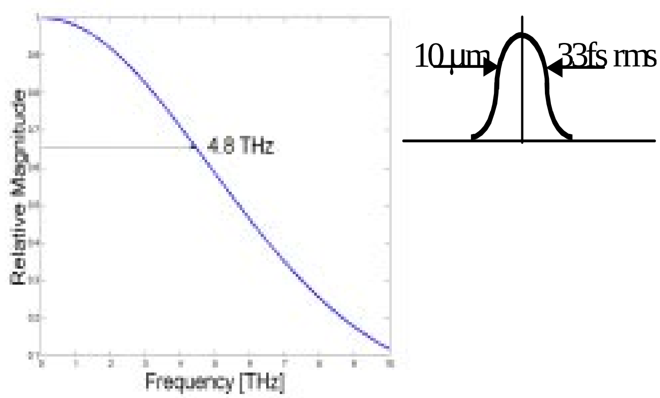

FIGURE 9. The bandwidth of a Gaussian bunch extends into the THz band for short (10μm) bunches.

The electric field of an ultra-relativistic bunch of N_e electrons at a distance *r*, from the crystal is shown in figure 8 for a Gaussian bunch of length σ_z[12].

At high energies the opening angle, $1/\gamma$, is very small so the crystal can be placed some distance from the beam without loss of bunch length resolution. The field is also quite strong, for example a 10 μm long bunch with 1 nC charge will generate a 72 MV m^{-1} field at a distance of *r* = 10 mm. At low energies around the gun and injector the crystal needs to be brought into closer proximity with the beam to maintain good bunch length resolution.

In a beam pipe the high frequency component of the wakefields contain the bunch length distribution information. The bandwidth of radiation produced from a Gaussian bunch, given by its Fourier transform,

$$F(\omega) = e^{-\frac{\omega^2 \sigma^2}{2}} \tag{4}$$

extends into the terahertz region for the ultra-short bunches considered here, as shown in figure 9.

COHERENT RADIATION FROM A SHORT BUNCH

Terahertz radiation is generated by the bunch through a variety of means. Special cases of wakefields for short bunches are coherent transition radiation and coherent diffraction radiation. In addition, the synchrotron radiation from an ultra-short bunch in a bending field has a pronounced coherent component at wavelengths comparable to the bunch length.

Coherent synchrotron radiation

The power spectrum of the incoherent synchrotron radiation is proportional to the number of electrons, N, in the bunch whereas the coherent term is enhanced by N^2, as indicated by equation (5) from reference[13]

$$\begin{aligned} P(\lambda) &= P_0 N \{1 + NF(\lambda)\} \\ F(\lambda) &= \left| \int_{-\infty}^{+\infty} S(z) e^{2\pi i/\lambda} dz \right|^2 \end{aligned} \tag{5}$$

The power spectrum, taken from Wang [13], shown in figure 10, peaks in the terahertz band. It is strongly dependant on bunch length so that a power meter tuned on a narrow wavelength band, for example 0.2 mm in the case shown in figure 10, would produce a clear signal inversely proportional to bunch length. A number of detectors are available for THz radiation, including Schottky devices and germanium photodetectors whose band can be extended into this range. Bandpass filters can also be fabricated at these wavelengths, which should be centered at a wavelength corresponding to the nominal bunch length for an application.

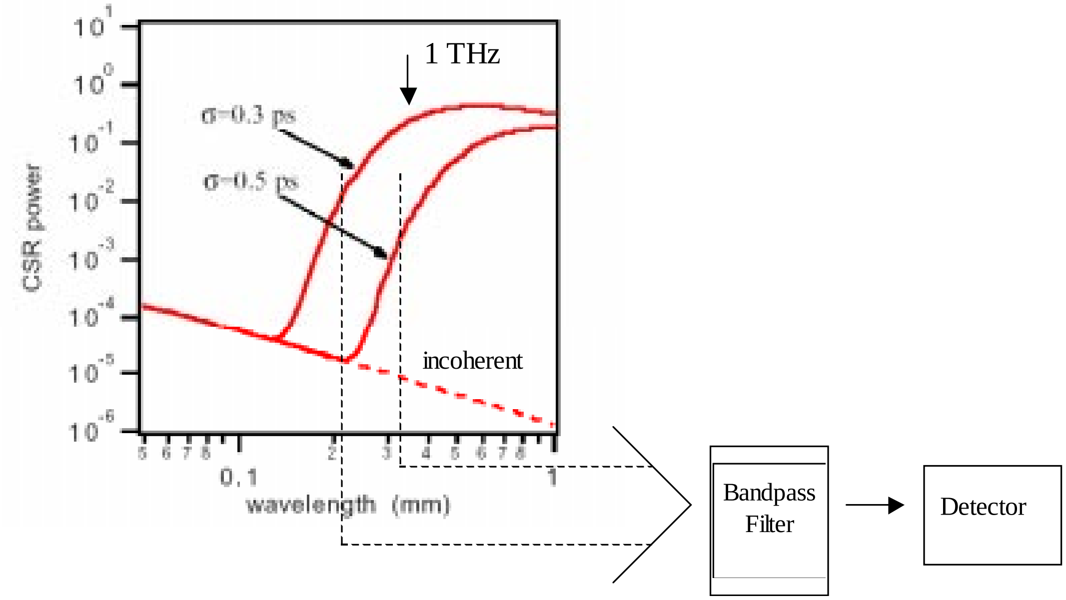

FIGURE 10. Power spectrum of coherent synchrotron radiation calculated for two different bunch lengths (after Wang [13]).

Measurements of the power in the THz band with detectors such as these, or bolometers, do not yield any phase, or bunch shape, information. The measurement still performs the useful function of providing an rms measurement of the bunch length, which is useful in tuning applications along the length of the accelerator.

The phase and arrival time of the bunch can, however, be measured by a fast gating technique using femtosecond laser technology. The output from a Ti:Sapphire laser, for example, is directed onto a semiconductor substrate of GaAs or radiation damaged Si-on-sapphire, generating photo electrons. Metallized electrodes on the surface forming a Hertzian dipole at THz wavelengths allow current to flow when the laser pulse and THz radiation are coincident in time. Such devices, shown in figure 11, are referred to as Auston switches [14] and are used in THz pump probe applications.

Coherent diffraction radiation

The THz detection techniques described above for CSR can also be applied to the detection of coherent diffraction radiation in the beam pipe. It is anticipated that a number of these relatively simple devices would be used along an FEL accelerator to aid in bunch length tuning and feedback control. CSR power would be monitored at the bunch compressor bends and CDR at the diagnostic station preceding the undulator. Pump probe timing measurements with THz radiation could be conveniently made where high bandwidth laser light is already available, at the injector for example, or at the undulator entrance where FEL experiments also employ femtosecond lasers for pump probe characterization of the radiation.

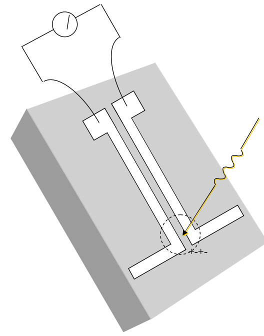

FIGURE 11. An Auston switch comprises of metallized electrodes forming a dipole on a semi-conductor substrate.

ACKNOWLEDGMENTS

The contributions of Paul Emma to the beam dynamics of short bunch production, tuning and diagnostics are gratefully acknowledged.

This work is supported under the United States of America Department of Energy contract DE-AC03-76SF00515.

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