COHERENT TRANSITION RADIATION TO MEASURE THE SLAC ELECTRON BUNCH LENGTH*

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Abstract

Coherent transition radiation is used to measure the length of the ultra-short electron bunches available at the Stanford Linear Accelerator Center. The results and the limitations of the method are described.

INTRODUCTION

Electron bunches as short as 80 fs (or 24 µm) fwhm length are now available at the Stanford Linear Accelerator Center (SLAC) FFTB facility, and are used for example to produce ultra-short pulses of x-rays [1], and for plasma wakefield acceleration (PWFA) experiments [2]. Retrieving the bunch length and detailed bunch current distribution is particularly important for the PWFA experiments.

Particle bunches emit transition radiation, when traversing a metallic foil (see for example Ref. [3]). This transition radiation is coherent at wavelengths longer than the bunch length; $\lambda>0.6\sigma_z$. The coherent transition radiation (CTR) emitted by a particle bunches carries information about the bunch length. For example, for bunches with a Gaussian longitudinal distribution and a fixed number of particles, the total energy emitted as CTR is inversely proportional to the rms bunch length. Additionally, the CTR can be sent to an interferometer to obtain the autocorrelation trace of the particle bunch electric field, and therefore yield a measurement of the bunch length and shape. We used these CTR measurements to characterize the SLAC ultra-short electron bunches.

The autocorrelation trace is always symmetric and therefore gives limited information about the detailed bunch profile. An autocorrelation trace is also built from many single bunch measurements, and requires these bunches to be similar if not identical. The difficulty in obtaining an accurate autocorrelation trace is that the CTR energy spectrum is very broad, from $\lambda\geq\sigma_z$ to very long wavelengths. The ability to collect, transport and measure this broad spectrum without losses determines the ability of the autocorrelation trace to reflect the real bunch length and shape. Distortions or the autocorrelation trace created by absorption or radiation not collected have been observed [4].

EXPERIMENTAL SET UP

We use at 1 µm thick, 20 mm in diameter titanium foil placed at 45º in the beam path as a CTR radiator. The CTR exits the beam line vacuum through a 12.5 µm thick Mylar window at normal incidence and is collected by a gold plated 90º off-axis parabolic mirror. A 12.5 µm thick Mylar beam splitter at 45º reflects a fraction of the CTR to a Molectron P1-45-CC pyro-electric detector to monitor the total (relative) CTR energy on a bunch-to-bunch basis. This reference measurement is also used to select events that are included in the autocorrelation trace according to their similar CTR energy. The CTR then travels to a Michelson-Morley interferometer. The interferometer beam splitter is also a 12.5 µm thick Mylar foil at 45º. The interferometer is aligned using a helium-neon laser beam that was aligned onto the electron beam location on the CTR foil and on an identical foil located about 1 m upstream. The upstream foil is retracted after the alignment procedure is completed. The electron beam is delivered at a 10 Hz rate with an energy of 28.5 GeV ($\gamma\approx55700$) and $1.5\text{-}1.8\times10^{10}$ electrons. One of the interferometer arms length is changed every second by a control computer. The minimum motion step size is $\Delta z/2=1$ µm, corresponding to a time delay of $2\Delta z/2c\approx7$ fs. The interferometer detector is identical to the reference detector. The recording of the CTR signals is integrated into the SLAC data acquisition system and can be correlated with the accelerator parameters.

CTR INTERFEROMETRY

A typical autocorrelation trace is shown in Fig. 1. Notice that the trace is symmetric and that the ratio between the peak of the trace (Δz=0), and the background ($|\Delta z|>>0$) is approximately two, as expected for a well-aligned interferometer. However, the trace also exhibits some modulation at large delays, and most noticeably, two dips, one on either side of the trace peak ($\Delta z\approx\pm80$ µm). The modulation and dips are the result of the filtering effect that various elements of the collection/interferometer system impose on the broadband CTR signal. In particular, the multiple reflections in the Mylar beam splitters as well as the Mylar decrease in reflection at long wavelengths contribute to this filtering effect. A Gaussian fit to the center peak of the autocorrelation trace leads to an rms width of 18 µm. This would correspond to a bunch length √2 narrower, or of about 13 µm or 43 fs.

The effect of the Mylar beam splitters can be included in a simple calculation of the expected autocorrelation trace. The reflection and transmission coefficients for an electromagnetic wave of wavelength λ on dielectric slab of thickness d and at an angle θ can be calculated from the formulas given in Ref. [5].

* Work supported by US DoE under grants Nos. DE-FG02-92ER40745 and DE-AC02-76SF00515
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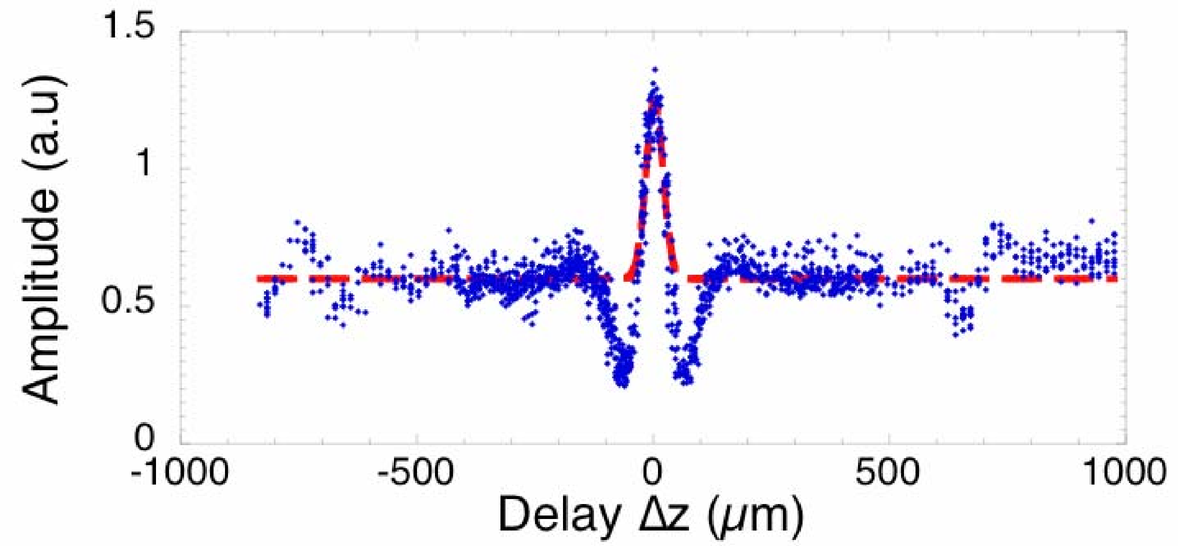

Figure 1: CTR amplitude versus delay of the movable interferometer arm Δz showing the electron bunch autocorrelation trace. The blue diamonds show the measured data points, the red dashed line is the Gaussian fit to the trace peak. Note that the trace was obtained from multiple scans with various Δz steps.

The signal reaching the interferometer detector is given by:

$$C(\tau) = \int_{-\infty}^{\infty} |E(t) + E(t-\tau)|^2 dt$$
$$= 2\int_{-\infty}^{\infty} |E(t)|^2 dt + 2\int_{-\infty}^{\infty} |E(t)E(t-\tau)|^2 dt$$

where $E(t)$ is the CTR electric field, and the time delay is given by $\tau=\Delta z/2c$. The first term in the second equation is the background observed at $\Delta z>>0$, while the second term is the CTR signal autocorrelation. In the case of a Gaussian signal, the autocorrelation trace is also Gaussian with a width $\sqrt{2}$ wider than the bunch length. The reflection $R(\omega)$ and transmission $T(\omega)$ coefficients for the beam splitters are included by using the Fourier transform of the electric field as emitted at the foil. The autocorrelation can then be calculated as:

$$A(\tau) = \int_{-\infty}^{\infty} |R(\omega)T(\omega)E(\omega)|^2 e^{i\omega\tau} d\omega$$

since each beam in the interferometer experiences both reflection and transmission through the beam splitter. For the case described here, the CTR is first transmitted through a window at 0º and another splitter at 45º; these are included in the model. The power spectrum of a Gaussian bunch with σ_z=20 µm as well as the transmission resulting from the three Mylar foils with a relative dielectric constant of 3.2 (assumed to be constant with frequency) are shown in Fig. 2. The autocorrelation trace with and without the Mylar foils effect are shown in Fig. 3. The trace with the foils effects is similar to the measured trace of Fig. 1, and is narrower than the expected trace and has a much lower overall amplitude. Figure 4 shows the real bunch length versus the autocorrelation trace width obtained with and without the filtering effect of the Mylar foils. Assuming the electron bunches that led to the trace of Fig. 1 are Gaussian, their rms width corrected for the foils effects would be ≈27 µm or 90 fs corresponding to FWHM bunch length of ≈210 fs. A trend similar to that of the dashed green curve of Fig. 3 was also observed in the experiment, i.e., the autocorrelation width was weakly dependent on the changes in bunch length expected from the changes in linac parameters in the σ_z≥20 µm. range. Note that for the case of Fig. 1 the accelerator parameters were not optimized to produce the shortest possible electron bunches, but rather those suitable for the PWFA experiments.

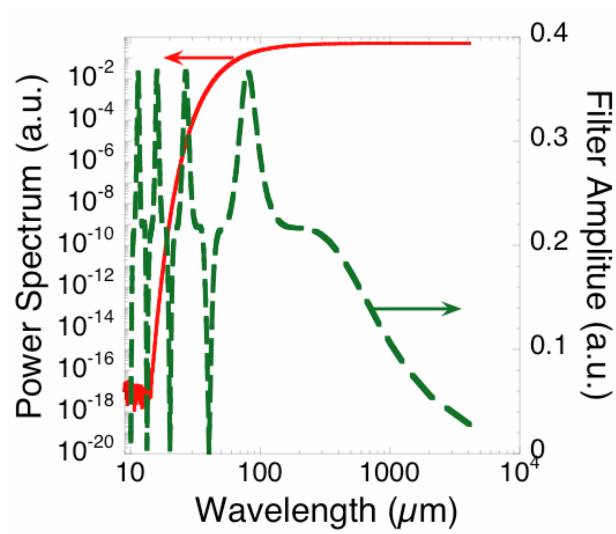

Figure 2: Power spectrum for the CTR of a Gaussian bunch with σ_z=20 µm (red continuous line) and total transmission spectrum (dashed green line) for the three Mylar foils (see text).

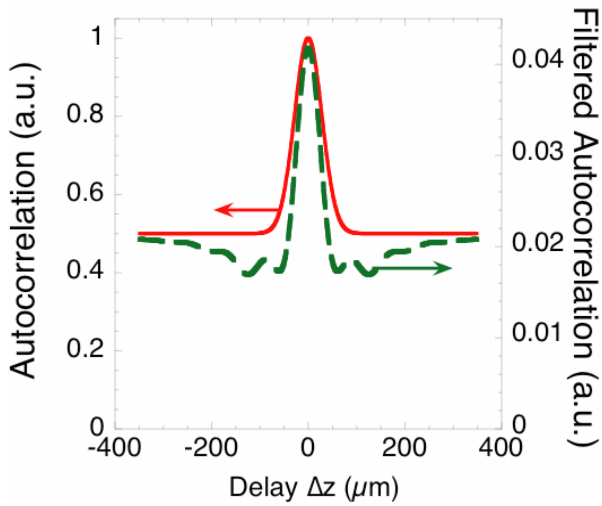

Figure 3: Autocorrelation traces ($C(\tau)$ in the text) calculated without (continuous red line) and with (dashed green line) the effect of the Mylar foils.

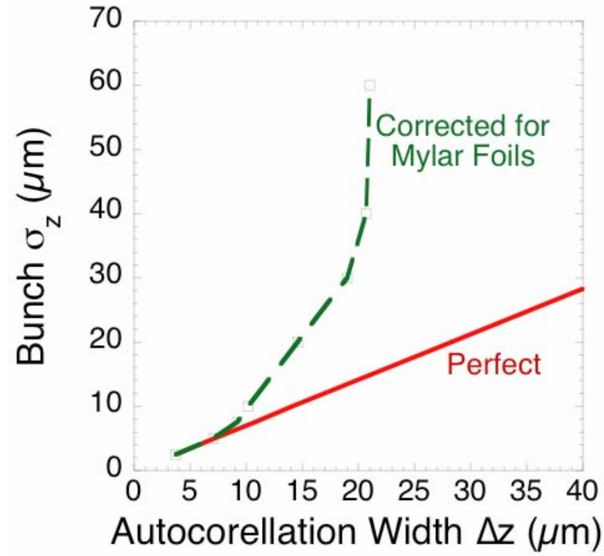

Figure 4: Bunch length as expected from a perfect autocorrelation trace (continuous red line) and corrected for the Mylar foils reflection and transmission (dashed green line). The calculations are done with Gaussian bunch shapes.

FUTURE WORK

Limitations in the ability of the experimental set up to transport and preserve the broadband CTR spectrum limited the accuracy of the diagnostic. In future measurements, some of these limitations may be overcome, for example by using thick ($>>\sigma_z$) silicon windows and beam splitters instead of the thin Mylar and avoiding the Fabry-Perot filtering effect at short wavelengths and the loss of reflection at longer wavelengths. The alignment of the interferometer will be performed using an infrared laser beam instead of the helium neon beam previously used. Another limitation may come from the ability of the detector to respond to long wavelengths. Recent measurements performed at the UCLA Neptune Laboratory show that the sensitivity of the pyro-electric detector to 343 µm radiation is orders of magnitude less than at wavelengths near 10 µm. Development of a single shot CTR autocorrelator is also planned [6].

SUMMARY

Coherent transition radiation (CTR) interferometry was used to measure the length of the SLAC ultra-short bunches. The results show that the bunches are short (210 fs fwhm). Losses in the interferometer limit the ability of the autocorrelation trace to yield the exact bunch width and shape. CTR energy measurements remain a powerful tool to monitor the relative bunch length on a shot-to-shot basis and to understand the bunch compression process. These results will be published elsewhere.

ACKNOWLEDGMENT

We would like to thank Dr. Sergei Tochitsky from UCLA for the detector calibration at 343 µm.

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