Electron Bunch Length Measurements in the E-167 Plasma Wakefield Experiment

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Abstract. Bunch length is of prime importance to beam driven plasma wakefield acceleration experiments due to its inverse relationship to the amplitude of the accelerating wake. We present here a summary of work done by the E167 collaboration measuring the SLAC ultra-short bunches via autocorrelation of coherent transition radiation. We have studied material transmission properties and improved our autocorrelation traces using materials with better spectral characteristics.

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INTRODUCTION

Beam driven plasma wakefield experiments have a unique need for ultrashort bunches due to the inverse square relationship between bunch length (σ_z) and the wake amplitude (E), where N is the number of electrons in the bunch.

$$E \propto \frac{N}{\sigma_z^2} \tag{1}$$

Although this relationship can be analytically derived only in the case of linear plasma behavior, simulations show that the scaling holds even in the non-linear regime [1,2]. Thus it is important in plasma wakefield experiments to accurately measure the bunch length. In the E-167 plasma wakefield acceleration experiment, the electron beam from the Stanford Linear Accelerator Center (SLAC) linac is predicted to have an RMS bunch length of 10-25 microns, in the 30-80 fs range. A diagnostic appropriate measure bunch lengths in this range is therefore necessary [3].

There are many different methods now available. Streak cameras currently do not have the necessary resolution. Electro-optic measurements, while having the advantage of being single shot, are difficult to perform in the SLAC environment, where jitter in the linac can foil synchronization with the required external laser. Transverse deflection cavities are parasitic, and thus cannot be run simultaneously with a measurement of the plasma response. Currently the E167 collaboration uses pyro-electric detectors to measure the total coherent transition radiation (CTR) energy, which is correlated to the inverse of the bunch length on a shot to shot basis. At the same time the incoming energy spectrum of the bunch is measured and can be matched to the output of the longitudinal phase space simulation code LiTrack to yield the expected current profile of the bunch [4]. However a direct measurement of the bunch length is desired.

Towards this goal we have been concentrating on the use of interferometry with the CTR mentioned above. When the bunch passes from one dielectric medium to another it emits transition radiation which is coherent for wavelengths longer than the bunch length. The spectrum of radiation has the following form:

$$\begin{aligned} I_{tot}(\lambda) &= I_{inc}(\lambda) \bullet [1 + (N-1) \bullet f(\lambda)] \\ f(\lambda) &= \left| \int e^{\frac{2\pi i z}{\lambda}} S(\vec{r}) dz \right|^2 \\ where &\int d\vec{r} S(\vec{r}) = 1 \end{aligned} \tag{2}$$

Here I_{inc} is the incoherent spectrum of N electrons, f is the form factor as defined above and S is the normalized number density of electrons in the bunch [5].

In the long wavelength range ($\lambda > \sigma_\zeta$) this spectrum is dominated by the second term in the rhs of eq. 2. This shows that the CTR spectrum is related to the power spectrum of the bunch profile, and can therefore yield information about the bunch [5]. Then the shape of this Fourier spectrum can be indirectly measured using autocorrelation, which can be achieved through interferometry. We can then estimate the bunch length (σ_z) from the width of the resulting autocorrelation trace (σ_A) for a gaussian bunch profile as:

$$\sigma_Z = \frac{1}{\sqrt{2}} \sigma_A \tag{3}$$

EXPERIMENTAL SETUP AND RESULTS

The CTR energy from a conducting foil is peaked at $\theta = 1/\gamma$ from the longitudinal axis, giving two distinct lobes [6]. However, this translates into a sharp peak at effectively $\theta = 0$ for 28.5 and 42 GeV, meaning the lobes cannot be split. Thus the Michelson Interferometer was chosen for the autocorrelation as shown in Figure 1.

First the electron beam was passed through a 1 micron thick titanium foil, causing it to radiate transition radiation. The CTR was then collected by an off axis parabaloid mirror (OAP) and reflected into the scanning interferometer. The interferometer consisted of two arms, one stationary to serve as the reference arm and the other on a translation stage to serve as the delay arm. The radiation was split at the beam splitter, traveled both arms, then was recombined and focused by another OAP onto a pyro-electric detector on the other side.

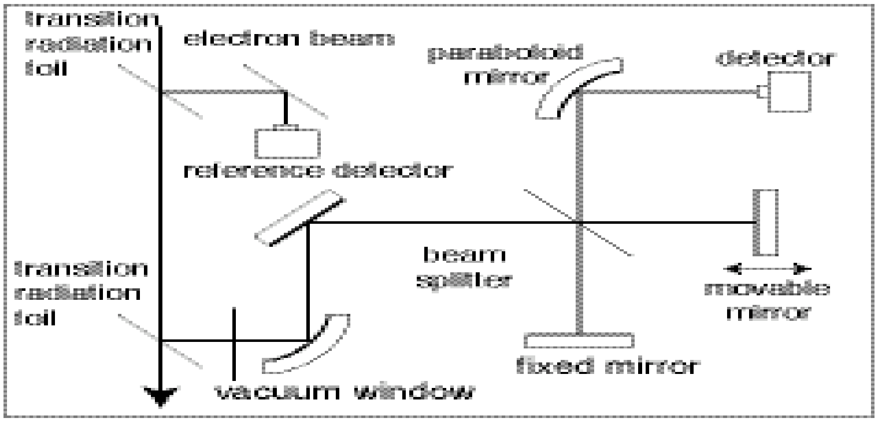

FIGURE 1. A Schematic of the experimental setup. Note that the reference detector, used for monitoring pulse length jitter (via total CTR energy measurement) in the beam was set up approximately 1m upstream of the rest of the apparatus. This auxiliary measurement allowed us to select similar events for analysis.

It was realized that the materials chosen for the interferometer parts played a large role in the resulting shape of the autocorrelation trace. Originally the beam splitter was a 12.5 micron thick mylar sheet and the vacuum window either another 12.5 micron thick mylar sheet or 1.5mm thick TPX window. The mirrors had a first surface of uncoated gold and the detectors, both interference and reference, were pyro-electric. The measured traces showed dips indicative of long wavelength attenuation [3]. This problem was traced to the choice of mylar as a beam splitter and vacuum window. Material studies aimed at finding a more suitable candidate with better spectral transmission characteristics resulted in pure silicon being chosen as a replacement (see Figure 2) [7].

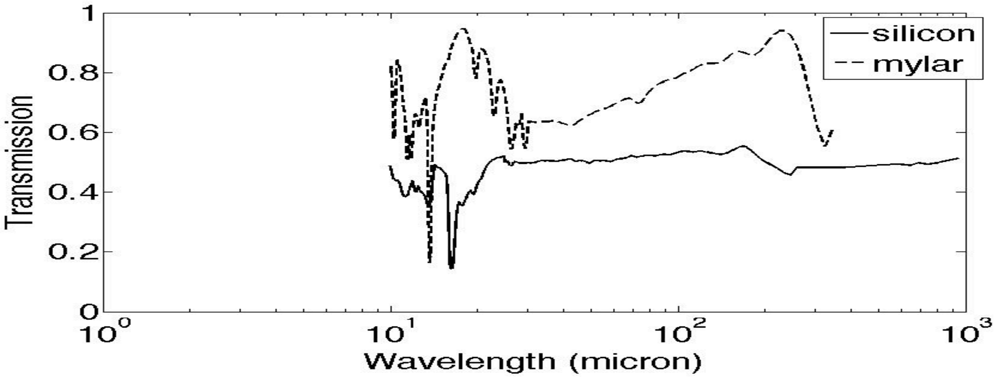

FIGURE 2. A comparison between the spectral response curves for mylar and silicon shows that, while both have similar issues at short wavelength with dips and humps, silicon is better suited for use

in the interferometer due to its generally flatter response. It is also mechanically suitable for a vacuum window, and given its approximately 50% transmission, ideal for a beamsplitter at long wavelength.

The current setup uses a 1.5mm thick silicon vaccum window and a 300 micron thick silicon beam splitter. The mirrors and OAP all had a first surface of uncoated gold and the detectors were still pyro-electric.

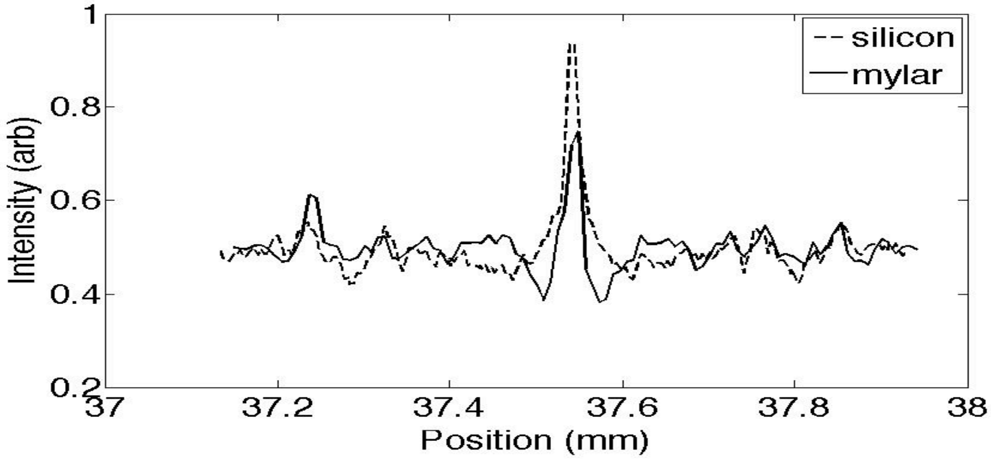

FIGURE 3. The silicon trace has clearly improved over the mylar one. The dips are no longer present, and wings on either side of the main peak, which are indicative of a head or tail on the bunch can now be seen. Structures are visible at large delay on both traces, indicating either poor response of the detector and/or absorption in air that must still be resolved.

Figure 3 shows a comparison between the mylar optics and those made from silicon. The large dips present in the trace using mylar optics are no longer present when silicon is used. Additionally, features indicative of a head or tail on the beam are also observed (see Figure 3).

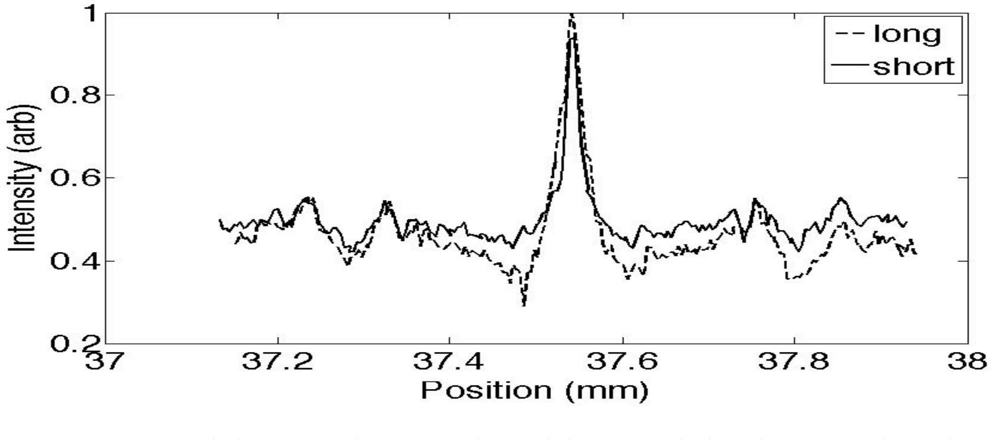

FIGURE 4. Autocorrelation traces for two settings of the magnetic bunch compression. The expected longer bunch, with R_{56}=1.4mm, yielded an RMS trace width of 14.4 micron and the shorter one, with R_{56}=3.2mm yielded an RMS trace width of 8.7 micron.

Furthermore, we find that the trace widths scale with the R_{56} of the beamline (see Figure 4). With R_{56}=1.4mm, the RMS trace width was 14.4 micron, yielding a gaussian bunch length of 20.36 micron (as every micron in our scan is 2 micron of path length). With the R_{56}=3.2mm, the RMS trace width dropped to 8.7 micron, yielding a gaussian bunch length of 12.3 micron. It is of note that the longer bunch trace appears to have some asymmetry. This is due to the fact that the interferometer was aligned to the short bunch and the R_{56} change steered the beam slightly on the foil. This effect was mitigated by the presence of the OAP, but was not totally eliminated.

These results match our theoretical expectations. We expect bunches on the order of 10-25 microns, which is what we measure. As well, the simulation code LiTrack predicts that for our operating conditions we should see a head or tail on the bunch, evidence of which is also present in the traces.

CONCLUSION AND FUTURE WORK

We have shown that, using interferometry and educated choices in our window and beamsplitter materials, we can measure the bunches of 10-25 micron that we expect to be produced by the SLAC linac. There are, however, still some experimental issues that need to be corrected. We must be sure that we are using the best materials and that we fully understand our detector response. To that end, spectral studies of the materials and detectors are still ongoing. We will also attempt to improve the measurement on the current setup using a gas purge environment.

As well, the current scanning setup is of limited use in the experiment as a whole due to the fact that it is not single shot. The jitter in the SLAC linac is enough to cause significant variation in the plasma response, and so single shot capability is at a premium. When a suitable THz camera is found, we will begin construction of a single shot autocorrelator to meet this goal.

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