BUNCH LENGTH MEASUREMENTS USING COHERENT RADIATION*

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Abstract

The accelerating field that can be obtained in a beam-driven plasma wakefield accelerator depends on the current of the electron beam that excites the wake. In the E-167 experiment, a peak current above 10 kA will be delivered at a particle energy of 28 GeV. The bunch has a length of a few ten micrometers and several methods are used to measure its longitudinal profile. Among these, autocorrelation of coherent transition radiation (CTR) is employed. The beam passes a thin metallic foil, where it emits transition radiation. For wavelengths greater than the bunch length, this transition radiation is emitted coherently. This amplifies the long-wavelength part of the spectrum. A scanning Michelson interferometer is used to autocorrelate the CTR. However, this method requires the contribution of many bunches to build an autocorrelation trace. The measurement is influenced by the transmission characteristics of the vacuum window and beam splitter. We present here an analysis of materials, as well as possible layouts for a single shot CTR autocorrelator.

INTRODUCTION

In the plasma wakefield acceleration experiment E-167 [1], an ultra-relativistic electron beam with a peak current above 10 kA and a particle energy of 28 GeV traverses a lithium vapor cell. The first part of the electron bunch creates a plasma by field-ionization and generates a plasma wake that accelerates the electrons in the back of the bunch. The process depends on the peak current and therefore on the bunch length. Furthermore, the charge distribution in the beginning and end of the bunch have a strong influence on the observed acceleration. It is therefore desirable to determine the longitudinal bunch structure.

Several methods are currently used to achieve this. A transversely deflecting cavity determines the bunch structure before the last compression step, at a bunch length of 50 μm [2]. A measurement of the energy spectrum is compared to a particle tracking simulation using the code LiTrack [3], taking into account the wake fields in the accelerator [4]. A pyroelectric detector records the energy emitted by coherent transition radiation (CTR) on a titanium foil. Finally, this CTR pulse is autocorrelated in a Michelson interferometer. Measurements based on the electro-optic effect are currently being developed [5].

In the present setup, transition radiation is emitted when the electron bunch passes a 1 μm thin titanium foil, which spans an angle of $45°$ to the beam. At wavelengths longer than the bunch length, the radiation is emitted coherently, and its power is increased by a factor equal to the number of electrons in the bunch. Thus, an intense radiation pulse is emitted at wavelengths that correspond to a frequency in the Terahertz region.

Autocorrelation of the radiation is a convenient way to measure its duration. A beam splitter separates the pulse and the two parts undergo a variable delay before they are overlaid again. In the present setup of intensity autocorrelation, there is no nonlinear material or detector present; the electric fields of the two partial beams add to produce a pulse that has twice the intensity for zero path length difference, and the rms width of the autocorrelation is a factor $\sqrt{2}$ larger than the rms pulse length.

A Michelson interferometer has been set up to perform the autocorrelation (Figure 1). The autocorrelation is measured by scanning one of the mirrors. An analysis of the trace is compatible with a bunch length of 18 μm rms. The setup and measurement results are detailed in [6].

NEW DEVELOPMENTS

Material Selection

In the far infrared, traditional optical materials such as fused silica have a relatively high absorption coefficient. Inorganic crystals such as potassium bromide (KBr) or thallium bromo-iodide (KRS5) can be used up to a wavelength of 25 and 33 μm, respectively. Polymers such as polyethene (PE), polytetrafluoroethene (PTFE) or polymethylpentene (TPX) are widely used as dielectrics for radiation up to the millimeter region. However, their absorption changes significantly across the wavelength region of interest here. The present setup uses a beam splitter made from polyetheneterephthalate (PET) and a vacuum window of high-density polyethene (HDPE). HDPE is opaque for visible light, making alignment difficult.

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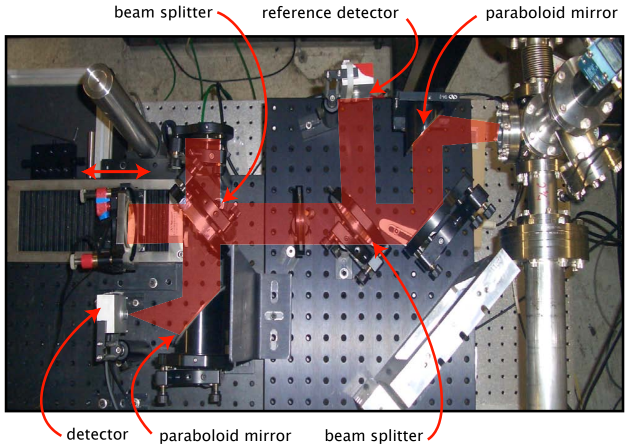

Figure 1: The scanning Michelson interferometer, used to measure the length of the electron bunches in the FFTB.

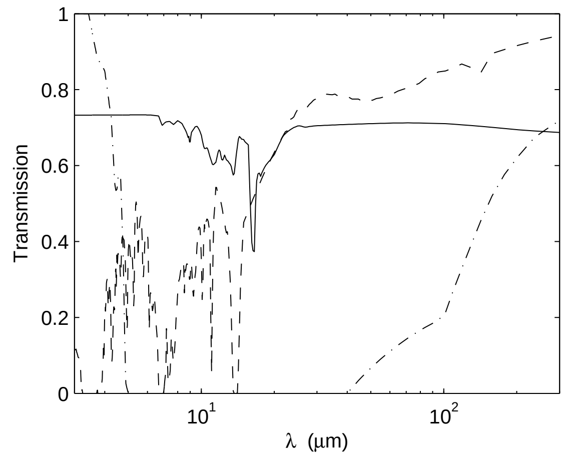

Figure 2: Transmission of possible vacuum windows for THz radiation. Fused silica (- · -), High-density polyethene, (- - -) Silicon (—), each with a thickness of 1.5 mm.

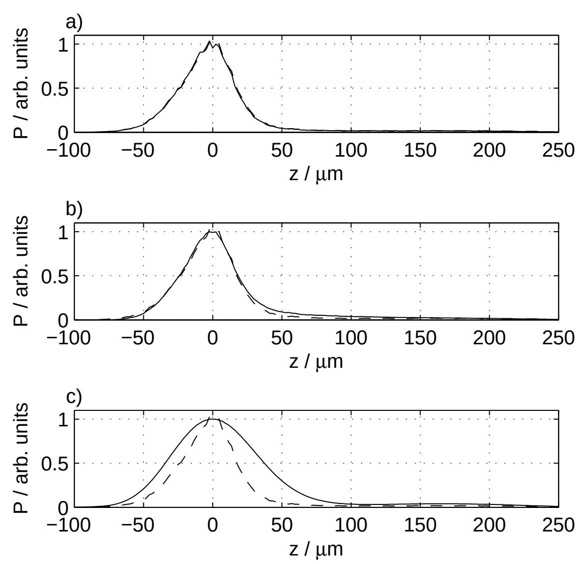

Figure 3: Effect of the window transmission on the shape of the radiation pulse: original pulse (- -) and transmitted pulse (—). a) Fused silica (quartz) b) High-density polyethene, and c) Silicon.

Semiconductors have a low absorption coefficient for photons with an energy below the band gap. For high purity materials, the transmission can extend to wavelengths of several hundred micrometers. Apart from a narrow absorption band around 16 μm, silicon shows low absorption in the FIR spectrum [7]. However, no data is available between 30 and 60 μm. Its refractive index is 3.42, leading to a reflection of 30% on every surface. Another possible material is synthetic diamond. While it is more expensive than the other three materials considered here, it has the advantage of being transparent for visible light, making the alignment of the autocorrelator easier. For silicon, an infrared laser has to be used.

Figure 2 shows the transmission through three materials suitable for vacuum windows, namely fused silica, high-density polyethene and silicon. The effect of these filters on a CTR pulse is shown in figure 3. The simulation includes the propagation of the electrons through the accelerator up to the CTR foil and the transmission of transition radiation through 1.5mm of the window material.

Detector

Quantum detectors such as photodiodes or photomultipliers do not respond to the low photon energies of THz radiation. Therefore, a radiometric detector such as a pyroelectric crystal has to be used: it reacts to temperature changes and its response to incident radition energy should in principle be independent from the wavelength. In the present setup, $LiTaO_3$ detectors[1] are being used. However, the interference between the reflections on the surfaces of these pyroelectric crystal cancels the electromagnetic field in the crystal for certain wavelengths, which leads to a significant wavelength dependency of the detector response [8]. This effect could be mitigated by anti-reflective coatings on the crystal [9].

[1]Coherent P1-45CC

Single-Shot Autocorrelator

Modest timing variations in the accelerator have a considerable impact onto the bunch length. For example, a bunch timing variation of 500 fs in the first part of the linear accelerator gives rise to a bunch length change of 15% at the experiment. Therefore, it is desirable to measure the length and shape of every bunch. A scanning interferometer cannot achieve this, as different path length differences are measured with different bunches.

In a Michelson interferometer, the two partial beams are always parallel when they overlap, independent of the

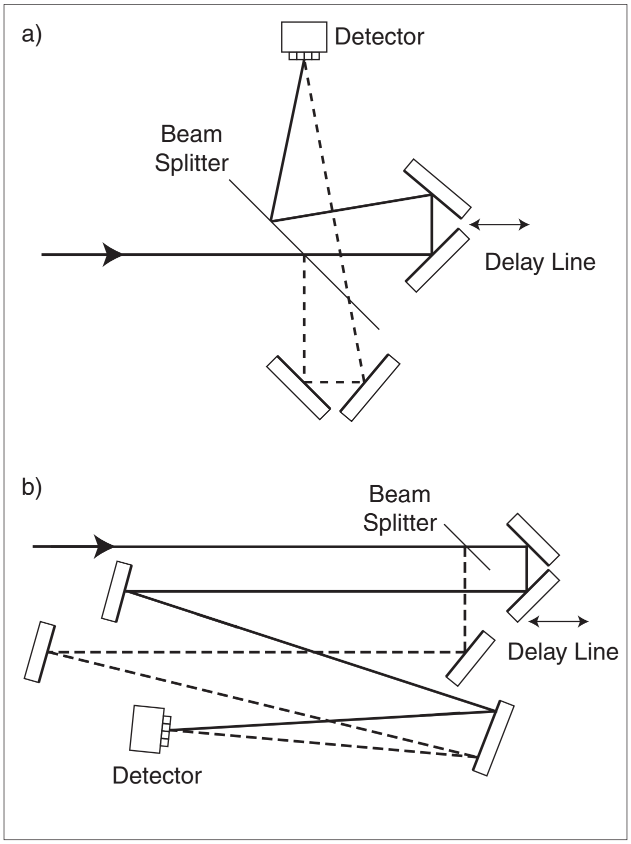

Figure 4: Two layouts are being investigated for a single-shot autocorrelator. The two partial beams interfere at a small angle.

alignment of the mirrors. Possible configurations that overlay the beams at a small angle are shown in figure 4[2]. The path length difference depends on the transverse position, thus a segmented detector[3] can detect the complete interferogram in one shot. It has to be verified whether its sensitivity is sufficient to detect the transition radiation, and whether it shows the same wavelength-dependent effects as the single pyroelectric detectors.

In a single-shot autocorrelator, transverse differences in the intensity are interpreted as interference effects. It is therefore important to separate these from spatial patterns on the beams themselves. Most notably, the near-field pattern of transition radiation raises the problem of a vanishing intensity in the middle of the beam[4]. This is particularly unfortunate since one expects constructive interference at zero path length difference, i.e. in the middle of the beam. Therefore, spatial filtering of the radiation prior to the autocorrelator seems appropriate. The effectiveness of such measures will be determined experimentally.

[2]For lower beam energies, it is possible to mitigate the problems of a dielectric beam splitter by separating the two partial beam spatially with two adjacent mirrors [10]. Due to the small opening angle of the radiation at electron energies of 28 GeV, this is not possible in the present setup.

[3]e.g. the Spiricon Pyrocam

[4]The spatial distribution predicted by near-field diffraction theory has been confirmed by measurements [11].

FUTURE IDEAS

The disadvantage of CTR autocorrelation for bunch length measurements is that the beam scatters on the CTR foil. The emittance growth is not a problem for the plasma wakefield acceleration experiments, but limits its use in other applications. Fortunately, there are other mechanisms where a relativistic beam radiates coherently, for example coherent diffraction radiation at an iris and coherent edge radiation at the entrance or exit of a dipole magnet. A single-shot autocorrelator would be of great interest at these devices.

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