A REAL-TIME BUNCH LENGTH TERAHERTZ INTERFEROMETER[*]

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Abstract

The recent development of advanced photoinjectors and next generation light sources guides the progression towards high-current, ultra-short beams. The measurement of these short pulses, with sub-picosecond resolution, is essential for successful beam operation and optimization. This paper describes the development of a real-time, shot-to-shot bunch length diagnostic utilizing a novel coherent terahertz radiation autocorrelation technique. The proposed diagnostic is called the real-time interferometer (RTI).

INTRODUCTION

The imminent emergence of x-ray free-electron laser (FEL) facilities, such as the Linac Coherent Light Source (LCLS) [1] and the TESLA x-ray FEL [2], necessitates improved electron beam diagnostics. These short wavelength radiation facilities require bunched electron beams with high current (kA) and ultra-short pulses (sub-ps) typically achieved by chicane bunch compressors or velocity bunching techniques. The measurement of these ultra-short pulses with sub-ps resolution is essential for successful beam operation as beam emittance quality must not be compromised. The detailed longitudinal profile of these beams is required for machine performance optimization as well as beam characterization and benchmarking to computational modeling.

After extensive feasibility studies, RadiaBeam Technologies is currently developing a single-shot, real-time, bunch length diagnostic based on the autocorrelation of coherent terahertz radiation. Beam-based coherent radiation (CR), such as coherent transition radiation (CTR), coherent edge radiation (CER), or coherent diffraction radiation (CDR), is autocorrelated using a novel arrangement of terahertz optics and then analyzed to yield longitudinal information about the beam (Fig. 1). Although many robust methods exist for bunch length determination, such as electro-optical sampling [3], rf deflecting cavities [4], and rf zero-phasing [5] techniques, these methods are either invasive to beam operations, costly, or require multiple-shots for averaging. The real-time interferometer (RTI), presented here, is a relatively inexpensive, self-contained device which can operate in the single-shot mode, and not interrupt regular beam operations (depending on the CR source used).

Studies were conducted on the coherent transition radiation emitted for two cases, the Brookhaven National Laboratory Accelerator Test Facility (BNL ATF) and the LCLS after bunch compression. The interferometer was designed using the respective parameters of these facilities and the concept is described in this paper. The algorithm used to obtain longitudinal profile information from the autocorrelation is briefly described as well.

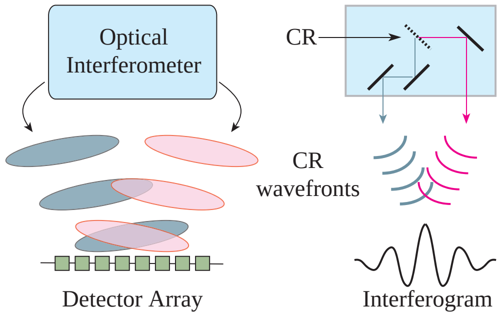

Figure 1: Conceptual scheme of the real-time interferometer (RTI) which autocorrelates the phase fronts of a beam-base CR source to determine bunch length information.

REAL-TIME INTERFEROMETER

The single-shot autocorrelator relies on the spatial autocorrelation of a split signal where the two beams recombine on the plane of a detector array at a small angle. This differs from the standard autocorrelator, where the two beams are split and recombined after introducing a time delay (path length difference) to one of the beam. The autocorrelation function for the single-shot (spatial) interferometer is given by

$$S(x) \sim \int dy \left[\int dt \vec{E}(x,y,t)\vec{E}(x,y,t-\theta x) + \text{c.c} \right] \tag{1}$$

where we consider the detector to lie along the $\hat{x}$-axis, one split beam traverses along the $\hat{z}$-axis and the other at a small angle θ with respect to the $\hat{z}$-axis, and the two beams are focused linearly along the $\hat{y}$-axis. Recall that the real part of the fourier transform of this autocorrelation function yields the spectral fluence according to Parseval's theorem. The goal of the real-time interferometer development is to build a diagnostic that will output the beam-based CR autocorrelation function of Eq. 1.

Although the RTI is advertised as a non-destructive bunch length monitor, for initial development work, CTR (radiation generated from a thin foil intercepting the beam) will be used as it has been well-characterized in prior studies at the BNL ATF. As part of work performed for the prototype development, the CTR signals have been calculated for a number of cases using the classical approach [6].

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The energy levels for these signals for the BNL ATF case (300 pc, 60 MeV, 28 μm rms bunch length) are on the order of 10 μJ; for the LCLS bunch compressor 1 case (1 nC, 250 MeV, 180 μm rms bunch length), the CTR signal is approximately 1 μJ. The energy levels for these cases are not abundant. Therefore, careful consideration of the detectors and components are required before use in the RTI application.

Diagnostic Layout

The diagnostic layout of the interferometer exploits the radial polarization properties of the CTR. The incoming radiation is first collimated by an off-axis paraboloid mirror (OAP) to a manageable spot size. It is then split with a wire-grid polarizer, which yields a linearly polarized beam of half the intensity (the other half of the radiation is not used by this interferometry but can be used, for example, with another interferometer to increase the confidence of the measurement). The linearly polarized radiation is then split by a knife-edge splitter, which is currently under design study. The two beams, which now have the same polarization but opposite sign, are then focused by astigmatic mirrors which have the property of only focusing in one dimension (to a line). These two beams are then autocorrelated on the pane of the detector array. Figure 2 displays a draft of the conceptual assembly with the major components.

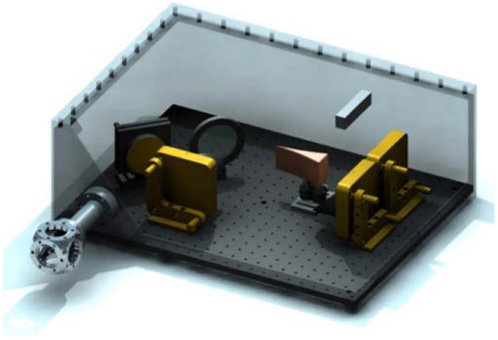

Figure 2: Conceptual assembly draft of the components for the real-time interferometer. The knife edge splitter splits the lobes of the radiation on the plane parallel to propagation and the autocorrelation occurs on the perpendicular plane (detector plane).

Since power losses are a major concern for CTR signals at terahertz frequencies, only reflective optic components are permissible for the RTI. Absorptive coefficients for the components (wire-grid polarizer, OAPs, etc.) must be taken into account when conducting the final analysis. The final device will be vacuum compatible (for easier integration into existing beamlines as well as mitigation of water absorption effects during transport), therefore all components will be tested for ultra-high vacuum operability. Telescoping optics will also be used to achieve manageable transverse spot sizes in the layout, therefore care must be taken when selecting such components as well.

Detector Considerations

The RTI concept is based on the spatial autocorrelation of terahertz pulses on a detector plane for single-shot operation. One of the biggest challenges for the development of this device is the construction of a suitable terahertz detector array. The preliminary requirements for the array are presented in Table 1. The parameters are reasonably achievable with pyroelectric detector technology [7], except for the fast time response. However, it should be noted that slower time responses are adequate if the detector meets the sensitivity criteria (suitable signal-to-noise ratio). Other techniques devised to reach the sub-nanoJoule sensitivity requirements have been explored such as the electronic reduction of the integration time-window of the detector (thereby reducing the accumulated noise collected and increasing the signal-to-noise ratio). This method has been successfully used to achieve single-element detectors with 300 pJ sensitivity at other facilities [8].

Table 1: Preliminary Detector Specifications

Parameter	**Design Value**
Dimensions	1mm x 16mm
No. of Channels	32
Arrangement	linear
Coating	broadband
Spectral Response	0.2 - 3 THz
Sensitivity	$\geq$ 1nJ per channel
Dynamic Range	$\geq$ 6bit per channel
Time Response	$\leq 0.5\mu$sec

Other detector considerations include in-vacuum capabilities, or cryogenic operations, if mandated by terahertz signal degradation due to atmospheric contamination.

RECONSTRUCTION TECHNIQUE

The output of the RTI is an autocorrelation of a beam-based CR pulse. Useful information is only garnered after subsequent analysis of this autocorrelation curve. There are two approaches for this analysis. The first method utilizes the Kramers-Kronig approach of Lai and Severs [9]. The autocorrelated data is Fourier transformed to yield the frequency spectrum and form factor. Then applying the Kramers-Kronig relation yields the minimum phase which is used to determine the longitudinal profile of the pulse. This method has its limitations due to the assumptions made about the frequency spectrum at both small and large frequencies (asymptotic assumptions must be made to fill in the gaps where there is no spectral data). This approach may also be computationally intensive and not work well for shot-to-shot operations, however, it can yield extremely detailed longitudinal profile information about the beam employed.

The second method uses a multi-Gaussian fit with appropriate parameters. This approach may be computationally faster if suitable initial conditions about the beam are known (e.g. approximate bunch length). Ideally, one would use the Kramers-Kronig approach for an initial detailed study, and once beam parameters are well established, use the guassian fit model for bunch length monitoring.

As with any mathematical reconstruction technique, a sound error analysis should point out the limitations. For the RTI, there are a number of sources of error for bunch length determination. The loss of long wavelengths due to diffraction at the source is a problem solved using a mathematical formalism (asymptotic assumption) [9]. Also, the loss of short wavelengths due to finite transverse beam size, or finite apertures, can be corrected using a mathematical function based on previous electron beam measurements. Additional spectral corrections originate from the beam transport optics, RTI component response, and absorption efficiency of the detector and associated windows. These factors are associated with the finite sensitivity and dynamic range of the detector therefore careful treatment of each component through analysis, calibration, simulation and experimentation will allow for meaningful, informative data reconstruction.

CONCLUSIONS

The real-time interferometer (RTI) is an electron beam diagnostic that has the capability to measure the bunch length of compressed beams using the autocorrelation of emitted coherent radiation. The RTI will yield accelerator facilities the capability to perform longitudinal characterization of compressed electron beams in a non-destructive, single-shot manner. The anticipated benefits of such a device include improved beam characterization as well as reduced downtime for facilities with users with stringent demands on beam properties.

This device is under development at RadiaBeam Technologies and fabrication and initial testing is underway at the RadiaBeam terahertz laboratory. The terahertz lab at RadiaBeam uses a tabletop CO2 laser for 10.6 μm radiation and a calibrated blackbody source for broadband terahertz studies. Subsequent tests are slated for the BNL ATF. This facility uses beam-based CER and CTR for characterization of compressed pulses from a chicane bunch compressor. Previous data has shown that characterization and reconstruction of the pulses is achievable with a typical Michelson scanning interferometer. The RTI will be tested with the same CR sources and the accuracy and resolution of the RTI will be compared to the prior results. The design of the hardware components and the reconstruction algorithm will then be optimized based on these results.

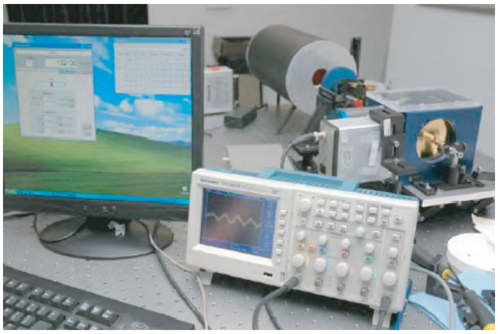

Figure 3: Photograph of the RadiaBeam Terahertz laboratory setup where the RTI is under initial testing and development.

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