

A SINGLE-SHOT, BUNCH LENGTH DIAGNOSTIC USING COHERENT TERAHERTZ RADIATION INTERFEROMETRY*

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Abstract

The generation of high peak current, high brightness beams routinely requires compression methods (e.g. four-bend chicane), which produce coherent radiation as a by-product, such as synchrotron radiation. Characterization of the emitted radiation, coupled with interferometric methods, yields crucial longitudinal bunch length and bunch profile information. This paper presents the progress in the development of a real-time terahertz interferometer (RTI) used for longitudinal beam profile diagnosis.

INTRODUCTION

The recent progress on x-ray free-electron laser (FEL) programs, such as the Linac Coherent Light Source (LCLS) [1], the EU-XFEL [2] and SPARX [3] demonstrates the necessity to create and diagnose electron bunches with high peak current (kA) and ultra-short pulses (sub-ps). These short bunches are typically obtained by bunch compression via magnetic chicanes (4-dipole magnets). The measurement of ultra-short pulses with sub-ps resolution is essential for successful beam operation as beam quality, or beam emittance, must be maintained. Detailed longitudinal characterization of the beam, and bunch length monitoring, are required for machine performance optimization and computational model benchmarking. The measurement of these bunches on a single-shot, real-time basis is extremely attractive for both accelerator operators, to monitor key beam parameters, and for end-users, to obtain consistent radiation delivery.

There are many robust techniques for longitudinal beam profile characterization, such as electro-optic sampling, deflecting cavities, and RF zero-phasing. The electro-optic sampling method works on a single shot basis, however is costly depending on the nonlinear crystal used and requires alteration of the existing beam and laser transport lines [4]. Deflecting cavities offer superb resolutions, however they are invasive to the beam trajectories and require additional RF power sources [5]. The zero-phasing technique does not require any additional hardware, but is disruptive to regular beam operations [6]. Another standard method of bunch length measuring involves the interferometry of the coherent radiation emitted by the beam. Depending on the coherent radiation employed, this method can be non-destructive and relatively cost-effective. Examples of beam-based co-

herent radiation used for interferometric include coherent transition radiation (CTR), coherent diffraction radiation (CDR), coherent synchrotron radiation (CSR).

In this paper, we describe the development of a real-time, terahertz interferometer (RTI), a self-contained diagnostic which autocorrelates the coherent radiation of compressed bunches to output bunch length and profile information in a single-shot basis. The diagnostic is described with particular attention to the detection scheme. The experimental tests for this device will culminate with a measurement of the bunch length at the Brookhaven National Laboratory Accelerator Test Facility (BNL ATF).

DIAGNOSTIC DESIGN

Traditional interferometers, such as the Michelson-type, rely on a moving delay stage to create a time delay, or path length difference, between two pulses. In an autocorrelator, the two pulses are split from a single pulse and recombined with a path length delay to yield an interference pattern. The post-processing of this interferogram yields longitudinal information about the pulse. This method is robust and well-proven, however it relies on an averaging technique of multiple shots to acquire an interferogram. The real-time terahertz interferometer extends this idea to the single-shot regime.

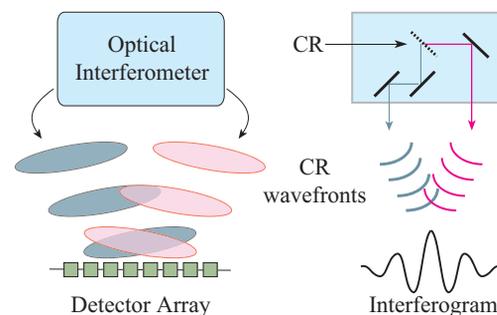


Figure 1: Conceptual scheme of the real-time interferometer which autocorrelates the phase fronts of beam-based radiation to determine bunch length information.

Concept

For single-shot autocorrelations, the averaging method of multiple shots of the scanning Michelson-type interferometer can not be used. Rather, the diagnostic must rely

* Work supported by U.S. DOE Grant Number DE-FG02-07ER84814

on a spatial, not temporal, autocorrelation. The spatial autocorrelation of the split signal occurs as the two beams recombine at a small angle, on the plane of a segmented detector, producing an interferogram in a single-shot. The autocorrelation function for the spatial interferometer is

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

where the detector lies 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. The real part of the Fourier transform of this autocorrelation function yields the spectral fluence according to Parseval's theorem.

For the proof-of-concept experiment, CTR will be used to characterize the device. Subsequent tests will include non-invasive radiation sources such as CDR.

Table 1: CTR Energy levels at the BNL ATF.

	BNL-ATF
Beam Energy [MeV]	60
Bunch Length, rms [μm]	28
Bunch Charge [pC]	300
Spot Size, rms [μm]	100
Aperture [cm]	2.5
CTR pulsed energy [μJ]	11.5
CDR pulsed energy (a=1mm) [μJ]	7.7

We have considered the BNL ATF test case (Table 1) to get an understanding of the CTR energy levels involved. The layout (terahertz optics) and the detector are very important because the CTR energy levels are very low. Although inherently an invasive radiation mechanism, CTR will be used because it has been well characterized by previous experiments at the BNL ATF [7].

Layout

The diagnostic layout employs reflective geometric optics due to the frequency range of interest (terahertz) and the low power levels. Telescoping optics will also be used to achieve manageable transverse spot sizes in the layout. For the current description of the interferometer, we will examine 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 (10 μm thickness, 25 μm spacing), which yields a linearly polarized beam of half the intensity. The other half of the radiation is not used by this interferometer but will be used, for example, with another interferometer to provide transverse beam information. The linearly polarized radiation is then split by a knife-edge splitter (or rooftop mirror) 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

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autocorrelated on the plane of the detector array at the given small angle. Figure 2 displays a draft of the conceptual assembly with the major components. An alternative to using

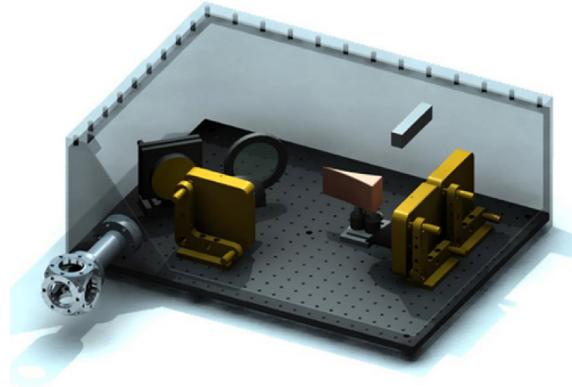


Figure 2: Conceptual assembly draft of the components for the real-time interferometer.

a polarizer and splitter is also under study, in case the power levels are too low or detection. The alternative design uses the entire pulse and Lloyd-type mirrors, which resemble half-wedges. These custom mirrors reflect half of the pulse at shallow angles, and rotate the phase by 180 deg. The incorporation of these elements will be straightforward due to the modular approach of the diagnostic development.

DETECTOR ARRAY

The RTI concept is based on the spatial autocorrelation of terahertz pulses on a detector plane for single-shot operation. The main challenge for the development of this device is the construction of a suitable terahertz detector array (or segmented detector). The target requirements for the multi-channel array are presented in Table 2. The spectral response of 200 GHz-3THz was chosen to efficiently diagnose bunches on the order of 30-100 μm . The parameters are reasonably achievable with pyroelectric detector technology [9]. Other techniques devised to reach the sub-nJ 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 [10].

Table 2: Pyroelectric detector array target specifications.

Parameter	Design Value
Dimensions	1mm x 16mm
No. of Channels	32
Spectral Response	0.2 - 3 THz
Sensitivity	sub-nJ per channel

The main considerations for achieving a sub-nJ sensitivity on the broadband terahertz detector are the noise limitations in the circuit. The prominent noise sources are the

feedback resistor, the amplifiers input noise current, and the amplifier input noise voltage, which unlike the other sources has a frequency response. The accurate accounting of this noise involves the rms sum of the noise response in each frequency region. The theoretical resulting noise equivalent energy for the designed circuit is 140 pJ.



Figure 3: Example of a 10 channel joulemeter fabricated by Spectrum Detectors including DAQ and controller. The segmented detector for the real-time terahertz interferometer requires significant enhancements in size and sensitivity.

DAQ CONSIDERATIONS

The raw data from the interferometer is not enough to deduce information. Two approaches are needed for post-processing the data. The first method utilizes the Kramers-Kronig approach of Lai and Severs [11]. 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 pulse longitudinal profile. This method has limitations due to the assumptions made about the frequency spectrum at both small and large frequencies (to fill the gaps where there is no spectral data). This approach is computationally intensive, however, it will yield detailed longitudinal beam profile information.

The second method uses a multi-Gaussian fit with appropriate parameters. This approach is computationally faster pending initial conditions about the beam are known (e.g. approximate bunch length). Ideally, a Kramers-Kronig approach would be used for initial detailed studies, and once beam parameters are established, the gaussian fit model is employed for bunch length monitoring.

Other sources of error that must be accounted for include the loss of long wavelengths due to diffraction, the loss of short wavelengths due to finite transverse beam sizes or apertures, and spectral effects originating from beam transport optics.

SUMMARY AND OUTLOOK

The real-time terahertz interferometer 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 interferometer will allow accelerator facilities the capability to perform longitudinal characterization of compressed bunches in a non-destructive, single-shot manner. The anticipated benefits of such a device include improved beam characterization and real-time bunch length monitoring.

The proof-of-concept experiment will take place in three stages. First, the device components will be tested individually in the in-house terahertz laboratory using a tabletop CO₂ laser and a calibrated blackbody source. The second stage of testing will include a complete system test at the University of Georgia laser facility, with a TEA laser. The testing will culminate with the final stage of testing at the BNL ATF with the compressed beam as described above.



Figure 4: Photograph of the RadiaBeam Terahertz laboratory setup where the interferometer and detector are being tested with a calibrated blackbody source and a 10.6 μm CO₂ laser. The results are compared to the standard Michelson scanning interferometer.

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