PROGRESS REPORT ON THE DEVELOPMENT OF THE REAL TIME INTERFEROMETER FOR BUNCH LENGTH DETERMINATION

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Abstract

The real-time interferometer is a single-shot, autocorrelator that outputs the interferogram of coherent radiation emitted from compressed, high-brightness beams. The device uses all-reflective terahertz optics as well as a highly sensitive pyroelectric-based detector array. For initial testing, coherent transition radiation is used; however, the diagnostic can be used in a non-destructive manner if coherent edge or synchrotron radiation is employed. A benchtop prototype has demonstrated the proof of concept with calibrated sources. This paper reports on the progress of the development of a bunch length diagnostic for high-brightness beams.

INTRODUCTION

The diagnosis of electron bunches with high peak current and ultra short bunch lengths is imperative for present and future light sources [1]. There are many methods currently available to measure the longitudinal bunch length of the beam such as electro-optic sampling [2], RF zero-phasing [3], and deflecting cavities [4]. Another typical method to gather longitudinal profile measurement is coherent radiation interferometry. The coherent radiation emitted by the beam (such as transition or synchrotron radiation) carries information about the longitudinal profile; interferometric methods employing this radiation, coupled with mathematical reconstruction techniques, adequately provide useful longitudinal profile information.

The real-time interferometer is a diagnostic that operates in the single-shot mode, and may operate in a non-destructive manner if edge or synchrotron radiation is considered. The device is appealing because in the single-shot mode it does not interrupt beam time and provides real-time feedback for users.

PROTOTYPE DESIGN

Michelson-type interferometers employ a translation stage to impose a time delay between two pulses. Post-processing the interference pattern (or interferogram) from an autocorrelator (which splits a single pulse, then recombines them) yields longitudinal information about the pulse. The drawback of this scheme is that it requires multiple shots to generate an interferogram. The real-time interferometer operates on the same principle but in the single-shot regime by imposing a linear overlap at a small angle.

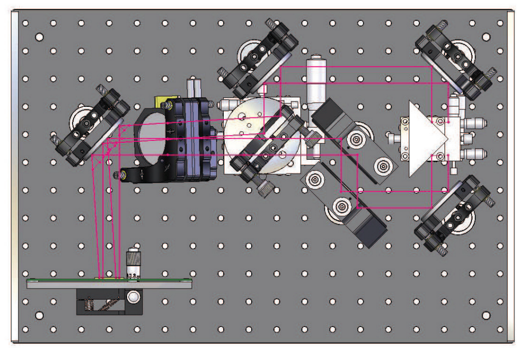

Figure 1: A rendering of the interferometer layout using commercially available components where possible. The beam is split at the wedge splitter and subsequently travels through two identical arms. The interference occurs at a small angle determined by the orientation of the beamsplitter (which reflects one component and transmits the other). The detector array is positioned at the focal point of the final cylindrical lens (out of plane).

Layout

The diagnostic employs reflective optics due to the low power levels and frequency range of the emitted radiation. For the prototype version, coherent transition radiation (CTR) is considered. Due to the radial polarization of CTR, a wire-grid polarizer is used to select one component of polarization. The pulse is sent through the interferometer input where it meets a wedge splitter that separates the pulse into two lobes. The two lobes then travel through two identical length legs, and the pulses are recombined at a small angle with the aid of a terahertz (THz) beamsplitter. The beamsplitter allows for arbitrarily small angles and is currently designed to accomodate angles between 0.1° and 3.3° (Figure 1). A cylindrical mirror focuses the beams in one dimension to create a linear focus. The angle of overlap determines the path length difference between the pulses necessary for the interferometry.

For the benchtop test, all optics were aligned on a breadboard using an expanded HeNe laser (approximately 25mm spot size). The calibration CO_2 laser was co-aligned to the HeNe laser and expanded to 25mm. A Golay cell or a single-channel pyroelectric detector where mounted on translation stages to simulate the forthcoming detector array (Figure 2). The Golay cell and pyroelectric device produced similar signals and were used interchangeably.

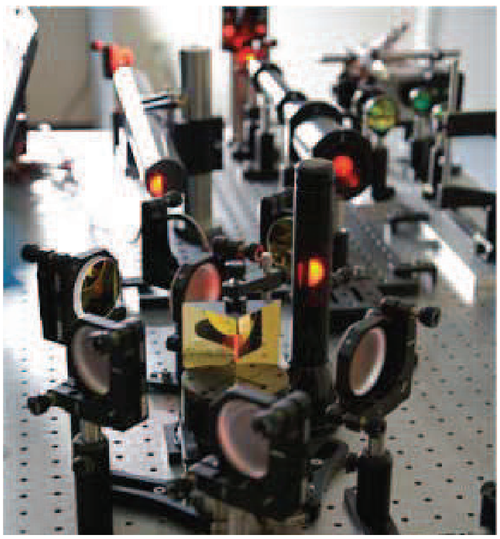

Figure 2: A photograph of the interferometer layout on the laboratory bench top. Pictured are the alignment HeNe laser, the CO_2 laser, the beamsplitting wedge, optics, and the recombining beamsplitter. The detector is not pictured.

Benchtop results

The interferometer was tested with a 10.6 μm calibrated CO_2 laser. The first iteration used all-reflective optics and two long-focal length cylindrical mirrors to focus in one dimension and provide an overlap of 3.5°. The detector was translated along the focal plane of the cylindrical mirror in 20-30μm steps. Figure 3 shows the raw autocorrelation data and the subsequent Fourier transform for a scan of 5.75mm in 20μm steps. This scan accurately reproduced the frequency of the calibration laser with wavelength of 10.6μm (recall for coherent narrowband sources, the interference occurs on the scale of the source wavelength). The initial result demonstrated the robustness of the single-shot interferometer and is used as a benchmark for subsequent measurements.

The next design iteration aimed to test the capabilities of the beamsplitter, which needed incorporation to allow for arbitrary angles. The previous device iteration was constrained by the physical optics and only allowed angles as small as 2.7°. The linear focusing was accomplished with a single cylindrical mirror, with a considerably shorter focal length at the detector plane. A secondary goal was to simulate the detector array by stepping the detector through a range of 16mm. Figure 4 shows the result with 30μm steps. Although the spectral reconstruction is not as accurate at the low frequency end, the peak is centered at 10.5μm, verifying the accuracy of the device with the beamsplitter.

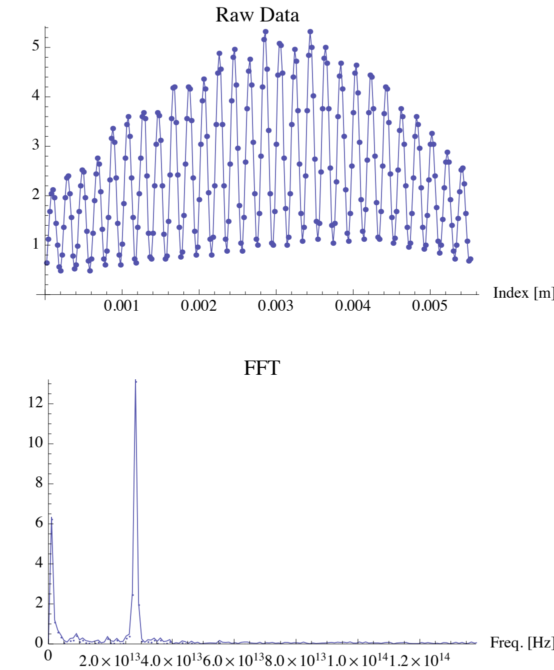

Figure 3: Top: Raw interferogram for benchtop test with calibrated CO_2 laser (10.6μm) using all-reflective optics (no beamsplitter). Bottom: Processed FFT with peak at 28.1 THz (10.6 μm) demonstrates the accuracy and reproducibility of the prototype.

Detector Array

The major challenge for the fabrication of the final device is the development of a suitable terahertz detector array. The emitted CTR is peaked around 1 THz, which is a regime where there are few detector options. Pyroelectric-based arrays provide a readily available solution with adequate sensitivity in the THz regime. The real-time interferometer detector array consists of 32 channels (500μm by 1mm each) coated to increase the sensitivity in the 0.2-3.0 THz range. The crystal used in the area is 9μm thick $LiTaO_3$ similar to Figure 5. The theoretically achievable sensitivity (Noise Equivalent Energy) for these crystals is 140pJ, limited by the feedback resistor, amplifier current and voltage noise.

DATA ACQUISITION

The interferometric data requires post-processing for useful bunch length information. The method employed utilizes the Kramers-Kronig approach first developed for electron beam applications by Lai and Sievers [5]. The autocorrelated data is Fourier-transformed to yield the frequency spectrum and form factor. The Kramers-Kronig relation then yields the minimum phase which, coupled to the form factor, determines the bunch profile of the beam.

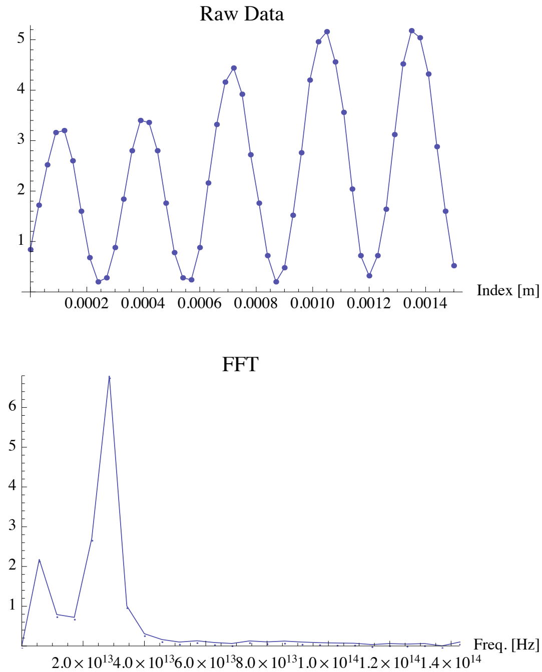

Figure 4: Top: Raw interferogram for benchtop test with CO_2 laser using THz beamsplitter for improved overlap at small angles. Bottom: Processed FFT with peak at 28.5 THz (10.5 μm) to compare the accuracy of the prototypes.

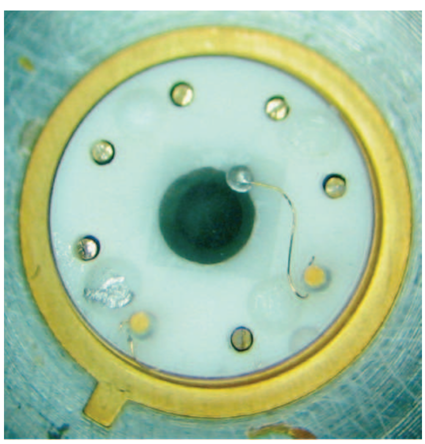

Figure 5: A photograph of the crystal used for the pyroelectric array. The crystal is 9μm thick $LiTaO_3$.

The interferometer has been analytically modeled using test cases to determine the optimum overlap angle for interference. Depending on the beam parameters, the optimal angle is between 0.5°-3.0°.

STATUS AND OUTLOOK

The prototype proof-of-concept is currently in the second stage. The first stage was the demonstration of autocorrelation with the interferometer components without the detector array on a benchtop using a calibrated source as described in this paper. The second step is a similar demonstration using a terahertz source with similar characteristics to the emitted coherent radiation from compressed bunches. This stage will take place at the UCLA Pegasus facility, where recent experiments in optical rectification of ultrashort laser pulses have demonstrated up to 1μJ of radiation peaked at 1 THz [6]. This demonstration will also test the detector array sensitivity, consistency, and reliability. The final stage of testing will take place at the Brookhaven National Laboratory Accelerator Test Facility [7]. Recent results from this facility include CTR from multi-bunch trains [8]. The CTR source will allow for cross-calibration and complete characterization of the diagnostic.

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