SINGLE-SHOT THz SPECTROMETER FOR BUNCH LENGTH MEASUREMENTS*

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Abstract

We present a new diagnostic instrument designed to measure bunch length in RF particle accelerators. Typically, scanning-type Michelson or Martin-Puplett interferometers are used to measure the coherent radiation from a short bunch to deduce the bunch length. However, this requires averaging over several shots, revealing only the average bunch length. We propose to measure the emitted coherent spectrum of a short bunch emission that contains the same spectral information as the bunch shape using single-shot spectrometry. In this paper, we present design considerations and first experimental results obtained at FACET for this instrument that allows shot-to-shot measurement of the spectrum emitted by a short electron bunch.

INTRODUCTION

Electron bunch length monitors are an important diagnostic tool for current and upcoming accelerators. The short bunch lengths of single-pass linacs have traditionally made use of RF transverse deflecting cavities [1,2,3] or interferometric methods [4,5]. RF deflecting cavities streak the electron bunch onto a screen and is a destructive measurement limited by available RF power. Interferometric methods exploit the fact that the emitted coherent spectrum of a bunch contains the spatial information of the bunch structure. This technique is attractive in that it is potentially non-destructive when paired with coherent synchrotron radiation or diffraction radiation. However, scanning-type Michelson or Martin-Puplett interferometers are incapable of shot-to-shot measurements.

A single-shot, non-destructive, high-repetition-rate bunch length monitor is a greatly desired diagnostic. A cascaded multi-stage grating spectrometer has the potential to fill this gap in diagnostic techniques [6].

SINGLE-SHOT SPECTROMETER

Since a single-shot spectrometer allows for reliable detection and measurement of RF pulse shortening, it can be used for identification of occurrences of RF breakdown (RFBD). The first prototype of our THz spectrometer was designed for RFBD detection in 120 GHz high-gradient accelerating sections developed at the SLAC National Accelerator Laboratory [7]. Operations with short pulses required narrow bandwidth (2GHz) and high frequency resolution (100 MHz).

This version of the spectrometer was designed, prototyped and built by RadiaBeam Systems, LLC [8]. It was tested at SLAC and the proof-of-principle operation was demonstrated. It was revealed that the alignment and optics systems must be enhanced, as well as more robust electronics added.

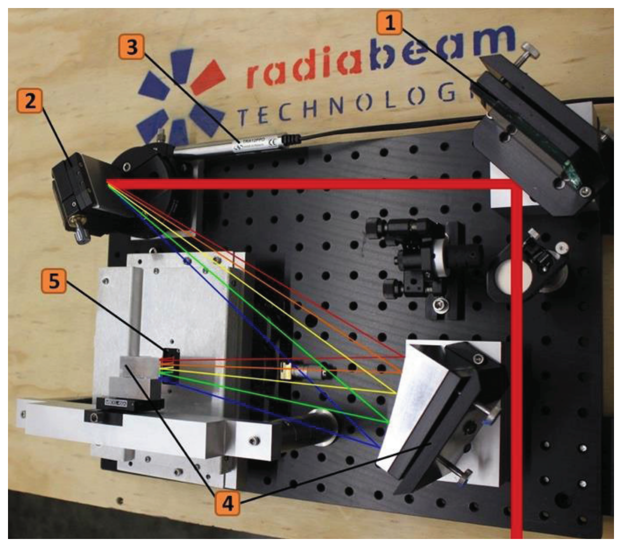

Figure 1: Physical layout of final spectrometer design, shown with dimensions and optical path

The design of the THz single-shot spectrometer is an adaptation of the DESY broadband multi-channel spectrometer [9], and consists of several core elements shown in Figure 1:

1) Reflecting mirror to deflect the signal to the grating,
2) Diffraction grating to spatially separate the signal by frequencies,
3) Motorized mounting to rotate the grating,
4) Aluminum 2D parabolic mirrors to focus the signal on the linear detector array,
5) Electronic board with pyroelectric detector to acquire the THz radiation signal

DESIGN UPGRADE

Unlike the spectrometer for RFBD detection, for which a narrow-band, high-resolution spectroscopy is required, the bandwidth of the spectrometer for bunch length measurements must be much larger than the RFBD design. This upgrade can be accomplished with two simultaneous techniques: adding additional stages with

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cascading central frequencies and increasing the bandwidth of each stage.

The broadband version of the spectrometer requires several major changes. First, the grating will be redesigned to provide larger angular spread and thus better resolution of the frequency components. In this case, we will be able to use discrete pyro-detectors that have significantly better speed and sensitivity. Figure 2 shows the upgraded design of the single-shot spectrometer that will be used for bunch length measurements.

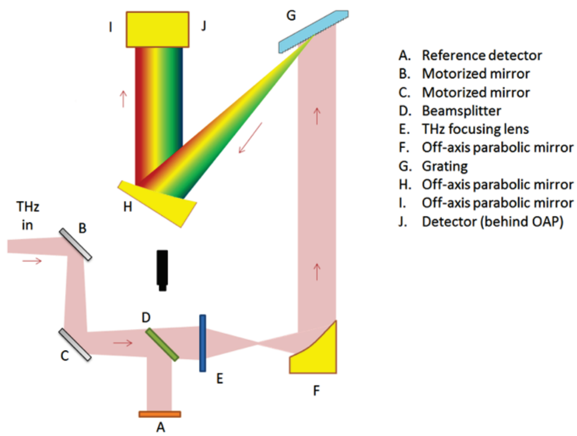

Figure 2: Preliminary broadband spectrometer design for beam length measurements. The linear polarizer is not shown.

The improved spectrometer design includes the following features:

- Collimating system: Polymethylpentene (TPX) THz lens and an off-axis parabola
- Alignment system: one laser beam arrives from both ends of grating
- External alignment system: 2 mirrors
- New detector board with discrete detector
- Linear polarizer to increase extinction ratio

The broad-band spectrometer is currently in the final modelling stage but will not be built until spring 2017. The improved broadband design will be tested using a THz source at the Advanced Photon Source Injector Test Stand [10].

ELECTRONICS SYSTEM

The spectrometer design was made possible by the availability of a custom-made linear array of 32 small pyro-detectors from the RadiaBeam Real-Time Interferometer [11]. Each pyro-detector is only 0.5 mm in width and 1 mm in height. The total span of the array is 32 mm. To spread across the array, the diffracted beam, which has a narrow angular spread, requires only about 55 cm of optical path length. This optical path length is an important parameter for the spectrometer design since the shorter length allows for a more compact spectrometer, and also reduces the total THz power loss due to reflection and atmospheric absorption.

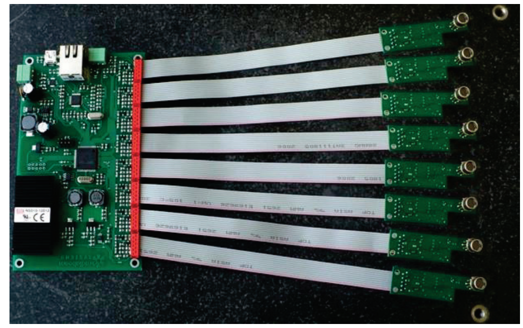

Figure 3: Prototype multichannel data acquisition system.

Since the existing detector board cannot be used for broadband spectroscopy, a new robust discrete-detectors-based electronics board that will be used in future commercial versions of the spectrometer was developed (see Figure 3). Though it was designed for QS5-IL Hybrid Pyroelectric detectors from Gentec Electro-Optics, it can be readily adapted to other discrete pyros. This sensor possesses sufficient sensitivity as a THz radiation spectrometer and fast thermal response. In this configuration, the pyroelectric detector element is combined with a low noise operational amplifier. QS-IL detectors are designed to maximize voltage output at low frequencies and therefore include load and feedback resistors in the 100 GΩ to 300 GΩ range. They are also formed into 8-pin TO packages that allow the addition of an "external resistor" to lower the output and increase the bandwidth.

After the input action, the signal voltage from the output of QS5-IL pyroelectric sensor is stored by the peak detector and then digitized by a 16-bit ADC. The peak detector can operate at frequencies much higher than those for which there are ADCs. Using the peak detector with a programmable threshold avoids the omission of an observable signal. The threshold level can be set above the noise level. The 12-bit ADC is used for viewing QS5-IL detector output signals and simplifying the tuning of the THz-spectrometer. The sensor boards are connected to the control board via flat ribbon cables up to one meter in length.

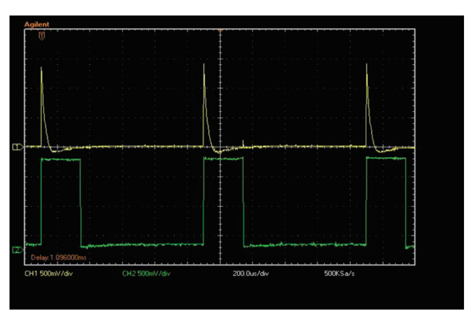

Figure 4: Response of peak detector (yellow) to a series of xenon lamp pulses (green) – right.

The developed system was tested by radiating the detectors with a series of Xenon lamp pulses. Figure 4 demonstrates the response of a peak detector to this radiation, which is clear and demonstrates the operational principle of the electronics.

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MULTISTAGE SPECTROMETER

The wideband spectrometer will be limited in frequency span to about a GHz, which is insufficient for bunch length measurements. To further extend the frequency range of the spectrometer, several stages can be cascaded. Such a technique has been used at DESY [12] with success. In this technique, the THz pulse is sent to the first stage grating and the zeroth-order reflection (containing longer wavelengths) is forwarded to the next level. Successive spectrometer stages use a grating with a central frequency shifted to successively longer wavelengths. This cascaded spectrometer scheme is shown in Figure 5. Only the available pulse energy limits the total device bandwidth.

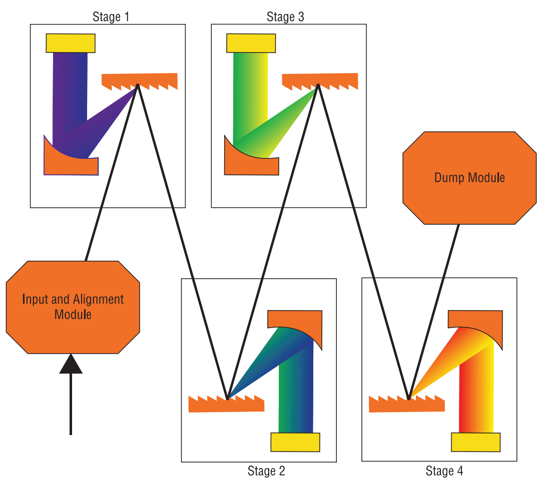

Figure 5: A cascaded spectrometer is shown with four stages, an input module, and an exit module. Additional stages can be added to expand the range of wavelengths covered or to allow smaller wavelength steps.

The spectrometer will make use of a remotely actuated alignment and collimation mechanism for ease of use in changing conditions. The collimating mechanism will use an adjustable beam expander to adjust the convergence of the incoming beam. The additional alignment mechanism, while not strictly required, was prompted by the difficulty in aligning the system during prototype testing; systems installed in a radiation-free environment could easily omit this module.

SUMMARY

We built and field-tested the first prototype of single-shot high-resolution, wide-bandwidth THz spectrometer. This device, with modifications discussed, allows shot-to-shot measurements of bunch lengths by increasing the total bandwidth. The bandwidth is widened by adding additional stages with cascading central frequencies and widened individual bandwidths. A turnkey single-shot bunch length monitor has applications in various high-brightness and high-current accelerators and the spectrometer is being extended to fulfil this need. A possible realization of the commercial product is shown in Figure 6.

Figure 6: Rendering of the commercial envisioned device.

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