SINGLE-SHOT THZ SPECTROMETER FOR MEASUREMENT OF RF BREAKDOWN IN MM-WAVE ACCELERATORS*

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Abstract

We present a new instrument designed to detect RF pulse shortening caused by vacuum RF breakdown in mm-wave particle accelerators. RF breakdown limits the performance of high gradient RF accelerators. In X-band or S-band accelerators, RF breakdowns are detected by measuring RF pulse shortening, X-ray burst, flash of visible light, vacuum burst, or, if current monitors are available, spikes in the field-emitted currents. However, these methods could not be easily scaled towards much shorter (mm-wave) accelerators. To overcome this limitation, we built a single-shot spectrometer with a frequency range of 117-125 GHz and a resolution of 0.1 GHz. The spectrometer should be able to measure the widening of the spectrum caused by the shortening of nanosecond-long RF pulses. We present design considerations, first experimental results obtained at SLAC, and planned future improvements for the spectrometer.

INTRODUCTION

There is a significant effort at SLAC National Accelerator Laboratory, to push the linac operating frequency into W-band and beyond; with the 100 GHz, and 200 GHz accelerating structures [1,2]. The advantage of higher frequencies is prospective of reaching very high accelerating gradients (> 200 MV/m). Practical operating gradients of these structures are limited by the vacuum RF breakdowns (RFBD) phenomena. During conditioning, the RF fields in a structure is raised slowly over time, to keep the breakdown rate within the acceptable level. Thus detecting and recording RFBD is a critical part of linac testing and conditioning. However, the conventional RFBD detection methods are difficult to apply to mm-wave accelerating structures the charge fluctuations during RFBD are below the noise level, and many RFBD events go unnoticed. RadiaBeam Systems in collaboration with SLAC has developed the new instrument designed to detect RF pulse shortening caused by vacuum RFBD in mm-wave particle accelerators. We built and tested a single-shot spectrometer with frequency range 117-125 GHz and design resolution of 0.2 GHz. The spectrometer intended to measure widening of the spectrum caused by pulse shortening of nanosecond long pulses. Spectrometer parameters are shown in Table 1.

* This work was supported by the U.S. Department of Energy, Office of High Energy Physics, under contract DE-SC0013684

Table 1: Parameters of the Spectrometer for RFBD Diagnostics

Parameter	Value
Central frequency	120 GHz
Frequency range	±0.8 GHz
Frequency resolution	0.2 GHz
Maximum noise equivalent pulsed energy per channel	50 nJ
Maximum reset time	5 ms

In the first stage of the project we have designed and built the mm-wavelength spectrometer source, demonstrated its proof-of-principle performance in the experiment with the beam as planned, identified and proposed solutions for the design problems, and prepared for commercial multi-channel prototype fabrication and testing in next stage.

SPECTROMETER DESIGN

The layout of the Terahertz single shot spectrometer is an adaptation of DESY broadband multi-channel spectrometer [3], and consists of several core elements, as shown in Fig. 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 parabolic mirrors to focus the signal on the detector arrays,
5) Electronic board with pyro-detector to acquire the THz radiation signal

The spectrometer design was enabled by the availability of custom-made linear array of 32 small pyro-detectors from the RadiaBeam Real-time interferometer [4]. Each individual pyro-detector is only 0.5 mm in width and 1 mm in length. 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.

ISBN 978-3-95450-147-2

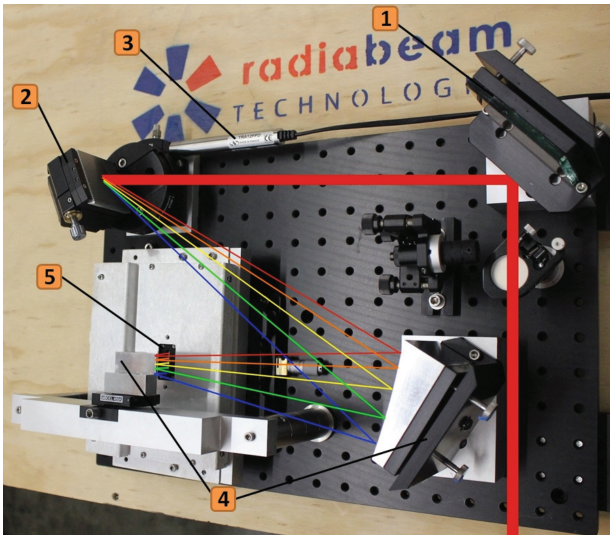

Figure 1: Physical layout of final spectrometer design, shown with dimensions and optical path.

We also ascertained the SLAC footprint and thus had a proper constraint for the size of the spectrometer. As an effort to reduce machining time and complexity, we used two parabolic mirrors that were parabolic about one axis. This was done to focus in each transverse direction separately, instead of one parabolic mirror that was parabolic about two axes. The parabolic grating mirrors were machined from bare aluminum and not gold-coated, as both materials behave identically as excellent THz reflectors. Figure 2 demonstrates the results of ray tracing analysis of the designed optical system the radiation with different frequencies showing the absence of aberrations on the detectors for collimated input signal.

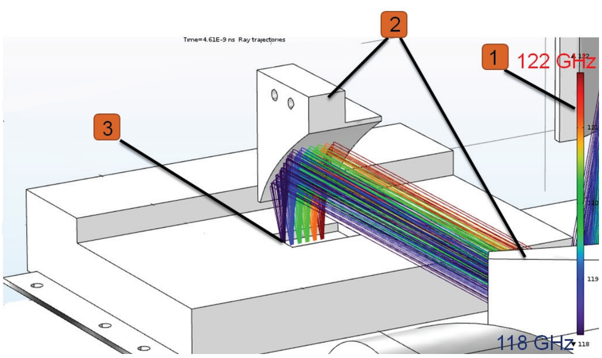

Figure 2: Ray optics simulations in the designed spectrometer with initial assumptions for the incident beam parameters (red: 122 GHz, blue: 119 GHz).

The final design consists of the grating, a flat transport mirror, two parabolic mirrors, the pyrodetector array box, and an internal alignment laser with a flipper mirror. The design also includes an enclosure box to block external noise.

PROOF OF CONCEPT TEST

Conceptual design of the spectrometer was made to pursue the following objectives: observe a signature of RFBD in SLAC mm-wave structure, and gather statistical properties of RFBD. Due to the absence of mm-wave RF source with MW power levels, the structure was designed to de driven by FACET [5] beam with the energy of 20.35 GeV, and about 50 μm of longitudinal bunch length [2]. The structure was excited by single bunch with charge 2.7 nC and 3.2 nC. The structures are open type, composed of two separate movable metal halves as shown in Fig. 3. The gap can be remotely controlled by a mover, and its size defines the central frequency of the signal. The designed spectrometer should be able to measure the spectrum of signal radiated out through antenna horns, and to provide frequency resolution sufficient to detect the pulse shortening.

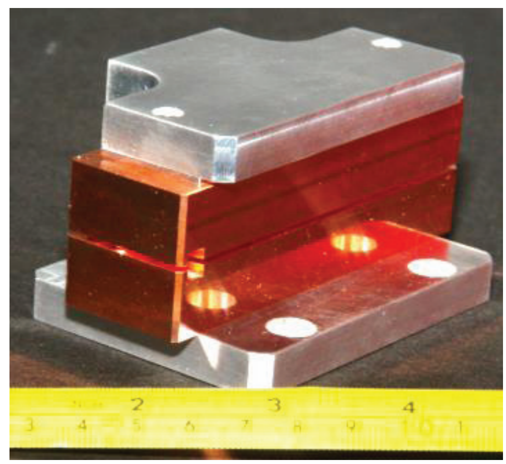

Figure 3: SLAC open mm-wave travelling wave accelerating structure.

When the beam was turned on with a repetition rate of 30 Hz, we started data acquisition from the spectrometer. Two parameters were varied during the experiment: accelerating structure gap, which defines radiated signal frequency, and diffraction grating angle defining the spectrometer central frequency. The diagrams of the acquired signals strength (color bar) at different channels (y-axis) and for different grating angles (x-axis) are presented in Fig. 4. The red spot on these plots indicates the area where signal is strong. The results clearly indicate that the signal reaches the pyro-detectors only for particular combinations of grating angle and number of detector channel, which are different for different frequencies of the input signal. Such behaviour verifies the proof-of-concept operation of the spectrometer. The signal is maximal a particular detector which changes with the angle, and this maximum moves with the change of the input signal frequency. These effects prove that the correlation between detector position, grating angle and input frequency exists and behaves as expected.

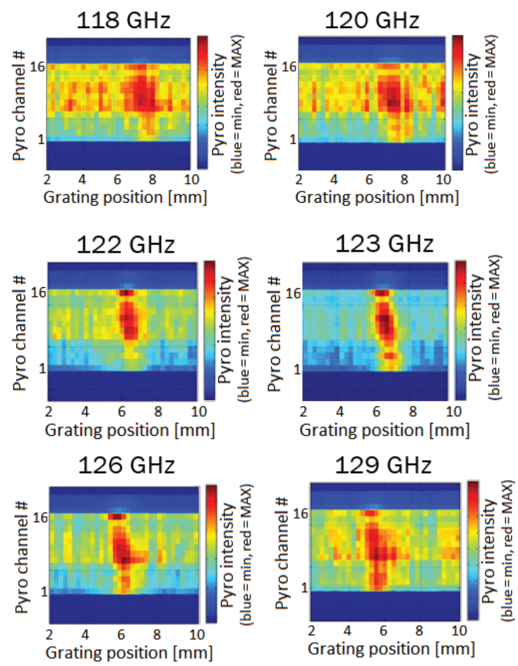

Figure 4: Signal intensity (in color) at separate pyro-detectors (y-axis) as a function of grating angle position (x-axis) and radiation frequency (numbers below the plots).

DESIGN UPGRADE

The following problems have been identified during the calibration and proof-of-principle tests:

- ***Alignment***. We noticed that it is problematic to align the diffraction grating precisely, since the alignment laser beam is not reflected from the grating and we cannot visually track it from the source to the detector array. In current design we had to use a spare detector in order to trace the beam from the source to the detector board. Obviously, such method is extremely time consuming, inaccurate and impractical in for field operations. In the next version of the spectrometer we will use the system with the built in laser for rapid alignment and validation of the spectrometer geometry.
- ***Calibration***. The collimation system should also solve the problem with the weak signal from the reference oscillator used for the system calibration, since it will prevent the signal from being divergent and thus intensity drop. We also plan to use a new calibrated source with frequency control for precise calibration of the spectrometer frequency response without moving the optical elements.
- ***Noise cancellation***. Finally, a completely new electronics system which implements a discrete reference detector and programmed logic will be designed and built to improve signal-to-noise ratio of the spectrometer and allow single-shot measurements even for weak signals just above the noise level.

OTHER APPLICATIONS

The spectrometer has additional applications as a TWT, gyration, and other sources test devices. In fact, further testing of the device will take place with the RadiaBeam THz source recently commissioned at the Injector Test Facility at Argonne National Laboratory [6].

In addition, such a single-shot THz spectrometer lends itself well to bunch length measurements. The coherent emission of a short bunch contains the same spectral information as the bunch shape; thus, knowledge of the emitted coherent spectrum can yield the bunch length. Scanning-type Michelson or Martin-Puplett interferometers are typically used to measure the coherent radiation from a short bunch [7], but these require averaging over several shots over several minutes and only thus report the average bunch length. A single-shot device such as presented here allows shot-to-shot measurement of the bunch length but the bandwidth of the spectrometer must be much larger than the RFBD design. This can be accomplished with two simultaneous techniques: by adding additional stages with cascading central frequencies and by increasing the bandwidth of each stage. A commercially available single-shot bunch length monitor has appeal in various high-brightness and high-current accelerators and the presented spectrometer can be extended to fulfill this need.

CONCLUSIONS

We built and field tested first prototype of single-shot high resolution mm-wave spectrometer. We identified necessary improvements. Successful implementation of these improvements will allow RadiaBeam System to deliver a useful instrument for RFBD detection and suppression to several THz accelerator and FEL projects and facilities such as SLAC, where developing 100 GHz and 230 GHz accelerating structures represents a potential application for such spectrometer production. The proposed effort will continue our ongoing work to support the accelerator community in the area of novel instruments, which would enable a better understanding of the breakdown physics in mm-wavelength accelerating structures as key for any future design of high gradient accelerators.

ACKNOWLEGMENTS

We thank efforts of SLAC FACET team that enable field test of the spectrometer.

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