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COMPACT INTEGRATED THz SPECTROMETER IN GaAs TECHNOLOGY FOR ELECTRON BUNCH COMPRESSION MONITOR APPLICATIONS

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Abstract

Bunch compression monitors are essential for the efficient operation of linear accelerators. The spectral distribution of coherently generated THz radiation is a favorable measure for the shape of the electron bunches. Today, THz spectrometers are bulky and costly. Here, the concept of an integrated on-chip semiconductor spectrometer being developed in a joint effort by HZDR and TU Dresden within the scope of the BMBF project InSEl is presented. This potentially low-cost and compact solution based on Schottky diode detectors, integrated on-chip THz antennas and filters fabricated in a commercial GaAs process will not exceed 5 mm in size replacing current single element THz detectors in the bunch compression monitors in the ELBE accelerator at HZDR. Covering the frequency range from 0.1 to 1.5 THz (and more in the future) with a resolution of 5 to 20 points, it could also be of interest for the longitudinal electron bunch diagnostic at other electron linacs such as FLUTE, BERlinPro, FLASH or the European X-FEL. Furthermore, the detector bandwidth in the GHz range will support the high repetition rates of superconducting radio frequency accelerators.

INTRODUCTION

Shortly after the prediction and experimental discovery of the emission of coherent synchrotron radiation (CSR) by accelerated relativistic electrons [1, 2] the easy access to the longitudinal bunch form via the the emitted spectrum was obvious. While for Gaussian-like charge distribution the emitted THz spectra can be directly converted into the longitudinal density distribution (e.g. [3]), in case of a random bunch the THz spectra can still serve as a useful fingerprint of a certain class of bunch shapes. For all of the early experiments performed in synchrotron storage rings, diagnostics on the relatively long electron bunches was carried out routinely by other means (e.g. streak camera). For new linear accelerators allowing electron bunches in the sub ps regime, conventional approaches like streak cameras fail to work or become extremely sophistiated so CSR became a widely discussed alternative as diagnostic tool. Most modern linacs meanwhile investigate into this topic and THz spectra have recently become an essential online diagnostic tool available in the control room at FLASH [4].

The drawback of the currently available spectrometers is their bulky size, high cost and difficult alignment procedures. Thus, they can typically not be installed in the most interesting locations along the accelerator. The standard approach to monitor the bunch compression at linear accelerators is to employ single element GHz/THz detectors that are positioned in the focus of the emitted CSR [5, 6]. Classically, this monitor comprises a broadband detector based on the pyroelectric principle, so that a change in the bunch form factor which is shifting the coherent cut off of the emitted THz radiation is thereby also changing the received integral THz power. The disadvantage of these detectors is their relatively low sensitivity and slow response time allowing to work only at few 100 kHz repetition rates. To extend the bunch compression monitor (BCM) principle to lower bunch charges, relatively narrow bandwidth semiconductor GHz receivers [7] have been employed recently. These detectors can detect much lower GHz intensities but their information on the bunch form is even more indirect as it is purely based on the intensity fluctuation in a narrow frequency band.

We propose to form an array of miniature narrow bandwidth semiconductor GHz/THz receivers covering different frequencies between 0.1 and 1.5 THz on a footprint of less than 5 mm in diameter. Such an integrated GHz/THz spectrometer could replace the classical single element semiconductor detectors at all positions along the accelerator thereby adding one additional dimension (frequency resolution) to the BCM signal. The bandwidth of the receivers shall furthermore be high enough to allow for phase-sensitive detection at the repetition rate of the accelerator. Consequently, the spectrometer would work with the tremendous dynamic range available from Lock-In techniques [8].

SYSTEM DESIGN

An integrated spectrometer as monitoring device for superconducting accelerators should cover a frequency range of 0.1-1.5 THz. Frequency sampling points within that frequency range help to observe the THz spectrum. In a first step, five frequency sampling points are aimed. Figure 1 shows the general principle of the on-chip spectrometer. The THz radiation is received using on-chip antennas and power detectors. A phase sensitive processing of the received signal follows. Therefore, the bandwidth of the power detectors has to support the repetition rate of the accelerator. At ELBE, a repetition rate of 13 MHz and charges of 77 pC will be maintained. Finally, the spectral information will be used for the control of relevant accelerator parameters.

One of the major design decisions is whether to use one broadband antenna or a few narrowband antennas (Figure 3). The desired system properties at the ELBE accelerator at HZDR, i.e. high sensitivity, have to be taken into account.

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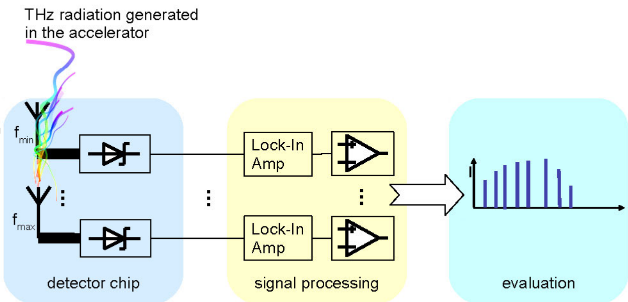

Figure 1: principle of operation for integrated on-chip spectrometer.

Figure 2 shows a beam profile measured at HZDR using a toroidal mirror with focal length f =150 mm. It can be seen that the focal area in the millimeter range fits the typical chip size.

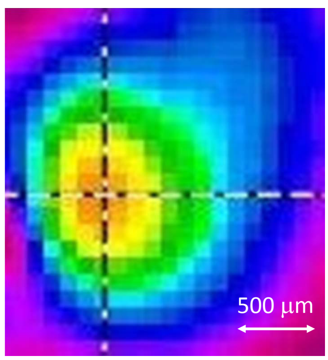

Figure 2: Image of CDR beam in the focus of a toroidal mirror with f =150 mm.

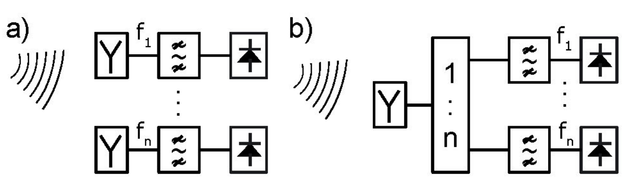

Figure 3: system options for on-chip-spectrometers: a) multiple narrowband antennas, b) one broadband antenna.

The narrowband antennas can be designed more easily: No broadband matching is needed and the development of an extremely broadband power divider (0.1-1.5 THz) is omitted. However, the larger number of antennas requires a larger chip area causing higher manufacturing costs. For a large number of frequency sampling points that would have more drastic consequences than for our intended application. This means, the solution with one broadband antenna is more scalable. Figure 4 shows the relative footprint of narrowband antennas compared to one broadband antenna. It was assumed for the calculation that the dimension of the broadband antenna is determined by the longest wavelength being detected $\lambda_{\max}$

$$A_{\text{broadband}} = \left(\frac{\lambda_{\max}}{2}\right)^2 . \qquad (1)$$

The required area for the narrowband antennas is estimated by the number of antennas n and the wavelength range $\lambda_{\min} \ldots \lambda_{\max}$

$$A_{\text{narrowband}} = \frac{1}{4}\sum_{i=1}^{n}\left(\lambda_{\min} + (i-1)\frac{\lambda_{\max}-\lambda_{\min}}{n-1}\right)^2 . \qquad (2)$$

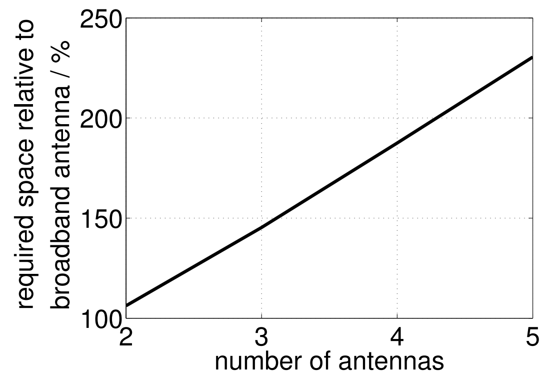

Figure 4: Required relative chip area of narrowband antennas compared to one broadband antenna (without splitter network).

For five antenna elements, the narrowband antenna approach just consumes about 2.5 times more chip area than a broadband antenna. In the end, the difference in footprint is further reduced because for the broadband antenna a power divider has to be integrated. Moreover, the narrowband antennas can be electrically short further reducing the required chip area. The disadvantage of crosstalk between the narrowband antennas remains. In contrast, the succeeding bandpass filters are easier to design because the antennas serve as prefiltering stages. Thus, lower demands can be set for filter steepness and the rejection of unwanted bands. Another fundamental advantage of the multi antenna approach is the higher expected sensitivity because with multiple antennas (also because of the higher area) more power can be collected. Summarizing, the approach with multiple narrowband antennas will be followed (Figure 3 a)).

MANUFACTURING TECHNOLOGY

The choice of an adequate manufacturing process is crucial. Analyzing commercially available options, the BES process of UMS suits best our application. This process provides mixer / Schottky diodes (serving as power detectors) up to a frequency of 3 THz. For antennas and the filters, passive structures such as resistors, capacitors, inductors, air bridges and vias are available. A multi project wafer (MPW) run is offered lowering the prototype chip costs. The metal layer of the process will be used to shield the detectors from incoming THz radiation. Using the process design kit (PDK) of UMS, first electromagnetic simulations will be carried out for the different elements of the on-chip spectrometer (antenna, bandpass filter, detector).

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CONCLUSION

We have presented a concept for an integrated on-chip GHz/THz spectrometer that can be used as a frequency resolved bunch compression monitor in accelerators. Options for the system concept were discussed and an outlook to the manufacturing was given.

ACKNOWLEDGMENT

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