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LONGITUDINAL BUNCH DIAGNOSTICS IN THE TERAHERTZ DOMAIN AT TELBE USING FAST ROOM TEMPERATURE OPERABLE ZERO-BIAS SCHOTTKY DIODES*

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Abstract

Modern accelerator-based light sources rely on short bunches to generate intense photon pulses. To achieve this, the electron bunches from the accelerator need to be compressed longitudinally in a magnetic chicane. A valuable tool for the measurement of the signal in the bunch compressor is the use of broadband EM-detectors covering a spectral range from few 100 GHz up to THz frequencies. With this setup, bunch length variations caused by instabilities in the acceleration process can be measured that in turn also affects the secondary photon beam. In this paper we demonstrate the pre-commissioning of broadband, room temperature Schottky THz detectors for the diagnosis of compressed short electron bunches at the ELBE facilities at the Helmholtz-Zentrum Dresden-Rossendorf, Germany. Qualitative bunch compression measurements have been carried out to diagnose the beam to optimize the machine setup and provide feedback to the beam-line scientists for optimum machine operation. These detectors are scheduled to be commissioned at free-electron facilities in near-future.

INTRODUCTION

The history of free electron lasers (FELs) can be dated way back to 1971 when Madey [1] experimentally realized the ability of using undulators for high brilliance emittance from electrons [2, 3]. The kinetic energy of electrons is converted to high brightness photon beam when electrons wiggle through the undulator. The average brightness of coherent synchronous radiation (CSR) generated by FELs is ten orders of magnitude higher than that excited by synchrotron radiation [4]. Accelerator sources can generate pulses in the range from a few fs to ps and cover a spectral bandwidth all the way from Terahertz to hard X-ray region [5]. The precise tuning of the machine parameters to adjust the properties of the electron bunches is crucial for the emission of photons with high brightness [6–9].

Third generation linear accelerator facilities are capable of producing electron bunches in sub-ps down to fs range. Diagnostic measurements require bunch compression monitors delivering ultra-fast response time. Traditionally pyro-electric detectors are employed for power measurements with response times in microsecond-scale. Faster repetition rates in range of few kHz to MHz range as for FELs demand for an ultra-fast, ultra-sensitive and broadband diagnostic tool. The III-V semiconductor based high mobility devices such as zero-bias Schottky diodes (ZBSDs) [10, 11] and high electron mobility based transistors (HEMTs) [12] are suitable detector devices. ZBSDs are the most prominent member due to their high sensitivity at sub-ns or even ps response times compared to their slower thermal counterparts such as Golay cells, Pyro-electric, Hot-electron bolometer, etc. Another solution to measure the longitudinal bunch shape would be a THz spectrometer comprising a set of narrow-band array detectors, which might have lead to the limited THz bandwidth [12]. Having a compact, cost-effective, robust, broadband and ultra-fast detector would offer a suitable solution for beam diagnostics directly next to the accelerator beam-line inside the cave.

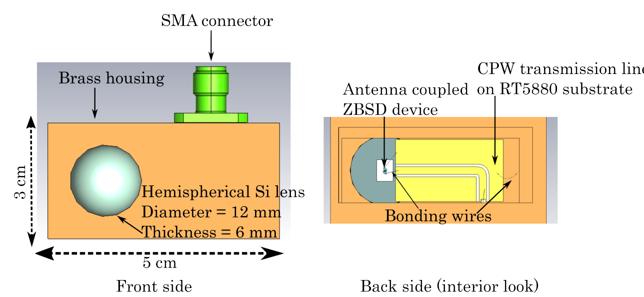

Figure 1: Schematic of developed ZBSD THz detector, left:depicts the front and right: illustrates the interior look into the detector along with Schottky diode and packaging technique.

In this paper, we present the results of pre-commissioning beam diagnostic experiments performed at TELBE by using in-house developed ZBSD based THz detectors. For this application we developed single pixel ZBSD and HEMT-based ultra-broadband and ultra-fast THz detectors that measure the electromagnetic signal emitted by the charged bunch when passing by the detector or likewise synchrotron-, diffraction- or transition radiation which all scale with its compression factor. ZBSDs operate at room-temperature and handy use of detectors eases as well as speed up the diagnostics process by applying it directly next to the beam-line in the cave.

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DEVELOPED THz DETECTOR

Figure 1 shows the schematic of the ZBSD detector. The Quasi-vertical Schottky diodes [10, 14] used in ZBSD detector were purchased from ACST GmbH. Integration and packaging of the detector was done in-house. A high-resistive hemispherical silicon lens (HRFZ Si) focuses the incident THz radiation on the Schottky diode mounted on the backside of the silicon lens. The frequency independent characteristic of the silicon lens makes it an excellent option for THz signal coupling to Schottky diode as compared to waveguide coupling, as wave guides can only be used within a very specific and limited frequency range. The signal read-out path is routed from Schottky diode contact pads via co-planar wave guide (CPW) transmission line that is milled on Rogers substrate RT5880, which has a substrate thickness of 0.508 mm ($|\epsilon_r| = 2.2$) to the SubMiniature version A (SMA) connector.

Table 1: Machine Parameters during Measurements at TELBE

Parameters	Values
FEL type	Single pass
FEL repetition rate	101.56 kHz
Linac fundamental frequency	1.3 GHz
Electron source	SRF Gun
Photocathode	Cs_2Te
Bunch energy	28 MeV
Bunch length	≈200 fc
Magnetic bunch compressor	≈500 mm
Operation mode	Continuous wave
FEL Terahertz frequency	0.7 THz
Pulse energy	<8 µJ
# periods	8

EXPERIMENTAL SETUP

ELBE is an abbreviation for Electron Linear accelerator with high Brilliance and low emittance [10, 11], which is a FEL facility at HZDR, Dresden. TELBE is the Terahertz photon source as a part of ELBE. We used the dipole diffraction signal in this work for pre-commissioning characterization of the ZBSD detector. The superconducting radio frequency photo electron injector (SRF gun) was used due to its capability to produce high quality electron beams and high bunch charge in CW operation mode. Investigated ZBSD detector was installed inside the cave directly next to the beam-line. Figure 2 shows the experimental setup used in this work. The detector was aligned using an alignment laser which can be switched on remotely from the control room and the motorized parabolic mirrors installed inside the beam-line are used to guide the laser spot to the diagnostic mounting post next to the beam-line (the red visible spot on detector in Fig. 2 is the visible laser). The machine parameters are summarized in Table 1.

The generated wavelength (frequency) from FEL is given by Ref. [7] as:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right), \quad (1)$$

where, λ is the generated wavelength from FEL, γ is electron beam energy, λ_u is the undulator period and K is scaled magnetic field intensity. The undulator period was adjusted to match the output radiated frequency of 0.7 THz. The rectified signal was recorded by Rhode & Schwarz R&S®RTO6-B94 oscilloscope, which was connected to ZBSD detector via ≈30 m long LDF1-50 cable. The measurement equipment and detector specs are summarized in Table 2.

RESULTS AND DISCUSSION

Figure 3 shows the time-domain trace of the electron bunch having bunch charge (q_B) of 28 pC, which was recorded at repetition rate of 50 kHz. We note here that this measurement was performed at a different time compared to all other results shown in following figures. The full width half maximum of 487 ps has been observed with the rise time (τ_r) of 163 ps. The repetition rate range of TELBE is 10 to 500 kHz, which means for diagnostic purposes the

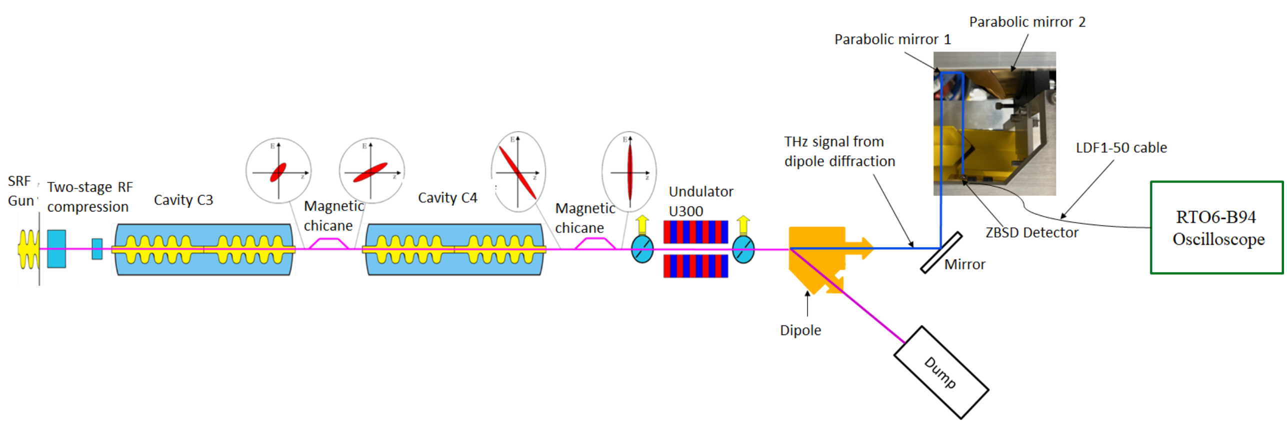

Figure 2: Schematic of experimental setup used in this work (partially adapted from [13]). Effect of bunch compression are shown in circular inset before and after each magnetic chicane. The THz signal used for diagnostics is shown in blue after the dipole, which is guided to ZBSD detector via mirror and two parabolic mirrors. (Note: not to scale or align)

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Table 2: Measurement Equipment and Detector Specs

Equipment	**Specs**
Measurement type	Single shot
ZBSD THz detector	0.05 - 2 THz
R_{diff} of ZBSD	7.14 kΩ
Read-out Oscilloscope (Osci)	R&S®RTO6-B94
Sample rate	10 Gsamples/s
Resolution bandwidth	40 ps
Osci rise time/fall time	104 ps
Record length	1 kpts
Read-out cable	LDF1-50

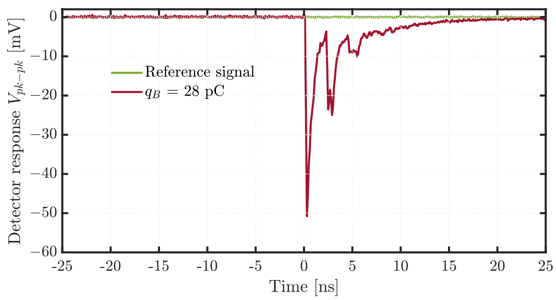

Figure 3: ZBSD detector response recorded at 50 kHz FEL repetition rate.

detector response time must be 100 to 2 µs, at least which is fulfilled by the ZBSD. The secondary peak observed at 2.9 ns might be due to the internal reflections in detector circuitry or due to the interface between silicon lens and Schottky diode device itself. A similar kind of trend in detected signal was also observed in [12].

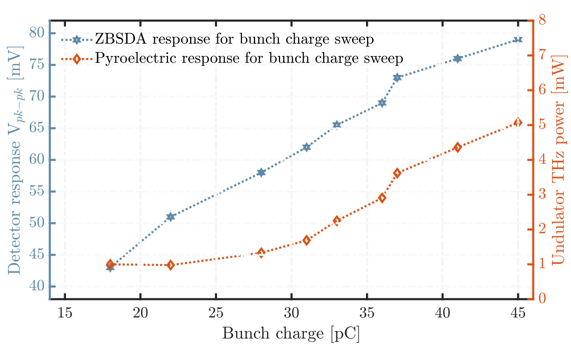

Figure 4: Linearity measurement result by varying the THz power by bunch charge sweep, left y-axis represents ZBSD detector response and right y-axis represents measured THz power with pyro-electric detector. (Note: the THz power seen by pyro-electric and ZBSD is not 1:1).

Measurements of the bunch charge sweep were taken in the diagnostic beam mode, which involves macro-pulsing the electron beam and an average beam current in the order of few µA. The bunch charge sweep was performed to test the linearity and sensitivity of the ZBSD THz detector. Figure 4 shows the linearity results. We note here that the THz power seen by pyro-electric and ZBSD is not 1:1 becuase pyro-electric detector got incident THz power from undulator while ZBSD detector sees THz power after dipole. The bunch charge was varied from 18 pC to 45 pC, which directly varies the THz power as well. A linear response of the ZBSD detector was observed (Fig. 4). The THz power from undulator was measured by a pyro-electric detector. However, the direct proportionality was observed in signal change for both detectors (interesting in Fig. 4 the proportionally step-like increase in signal from 36 pC to 37 pC in both detectors).

The FEL power gain length in one-dimension is given by Ref. [4] as:

$$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}\,, \tag{2}$$

where ρ is the one-dimensional FEL parameter or Pierce parameter [4]. Compressing the electron bunches result in an increase in the electron beam's peak current (I_{peak}), which can be used to realize higher FEL gain. Bunch compression leads to higher RF sensitivity. The required phase stability of a single compression stage is given as follows [4]:

$$\Delta\phi \leq \left|\frac{\phi_0}{C_0}\frac{\Delta I_{pk}}{I_{pk}}\right|\,, \tag{3}$$

where C_0 is the compression factor, $\left|\frac{\Delta I_{pk}}{I_{pk}}\right|$ is tolerable relative peak current jitter and ϕ_0 is nominal RF chirp phase. Bunch compression measurements were performed at q_B=45 pC. The cavity C3 & C4 were used to introduce the longitudinal energy chirp in order to compress the electron bunches. Figure 5 shows the results from ZBSD (left y-axis) and pyro-electric detector (right y-axis). LA2 is the offset phase (used as a reference while compressing the bunches) and having arbitrary numbers. At strong negative LA2 phase where the THz power is low, there is excellent agreement. Close to phase matching, where the THz power strongly increases saturation in ZBSD detector is observed before the pyro-electric. This also indicates that electron bunches were highly compressed at that instant. Due to time limitation of beam-time we were not able to measure completely by

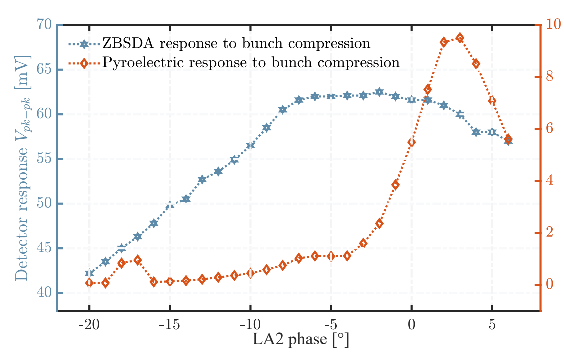

Figure 5: Bunch compression measurement results at q_B = 45 pC where left y-axis illustrates ZBSD detector response and right y-axis illustrates measured THz power with pyro-electric detector. LA2 is the offset phase and arbitrary number. (Note: the THz power seen by pyro-electric and ZBSD is not 1:1).

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compressing the bunches in opposite direction (going more positive in LA2 phase).

CONCLUSIONS AND OUTLOOK

In this work we demonstrated the use of ZBSD THz detectors as a beam diagnostics tool for particle accelerator facilities such as FELs in the fast emerging THz domain. The detector shows similar results in terms of power detection compared to commercially available pyro-electric detector, but at a much shorter detector time constant and consequently orders of magnitude better temporal resolution. The detectors sensitivity to detect bunch charges is as low as 18 pC (without any amplifier). The bunch compression measurements shows sensible results for machine diagnostics and synchronization. Rigorous tests on detector are planned in near future along with improvement in operational bandwidth as well as post-detection electronics (for example employing pulse shaping amplifier).

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