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A SINGLE SHOT THz SPECTROMETER FOR THE FEBE EXPERIMENTAL FACILITY

E. Shackleton[1]*, J. Jones[1], V. Malconi[1], S. Mathisen[1], T. Pacey[1]
ASTeC, STFC Daresbury Laboratory, Sci-Tech Daresbury, Warrington, UK
C. Armstrong, K. Federov, C. Hernandez-Gomez
Central Laser Facility, STFC Rutherford Appleton Laboratory, Oxfordshire, UK
P. Huggard and E. McCormack
RAL Space, STFC Rutherford Appleton Laboratory, Oxfordshire, UK
[1]also at The Cockcroft Institute, Sci-Tech Daresbury, Warrington, UK

Abstract

After current upgrades are completed, the Compact Linear Accelerator for Research Applications (CLARA) at Daresbury Laboratory (UK) will be capable of producing femtosecond-scale electron bunches, which will be used in the full energy beam exploitation (FEBE) experimental area. CLARA will employ multiple techniques to manipulate the longitudinal beam profile, including a variable bunch compressor (VBC). Optimisation procedures for the CLARA modules must be devised, which will require longitudinal diagnostics. Previous longitudinal diagnostics used on CLARA were multi-shot, but for user experiments a single-shot diagnostic operating at the machine repetition rate of 100 Hz is needed. Here, we present a single-shot, four-channel spectrometer to measure THz coherent transition radiation (CTR) produced by electron bunches, which will be used to deduce information about the bunch profile. In the device, a set of frequency-selective elements designed at STFC RAL Space (UK) distribute specific bandwidths onto single-shot pyroelectric detectors based on earlier wideband THz diagnostics on CLARA. The frequency-selective elements have been characterised using both simulations and THz time-domain spectroscopy. A start-to-end computer model of the spectrometer was created, and simulations were performed showing that the spectrometer can be used for both sextupole tuning on the FEBE arc and optimisation of the compression of the CLARA VBC. The instrument is currently being assembled and tested, and commissioning with beam is planned for the summer of 2024.

INTRODUCTION

The FEBE experimental facility is a dedicated user experimental area of CLARA at STFC Daresbury Laboratory [1]. Users of FEBE will require high-charge (~250 pC), femtosecond-scale length electron bunches for experiments such as testing novel acceleration schemes [1]. To deliver compressed bunches to FEBE, CLARA will utilise a variable-angle magnetic dipole chicane, referred to as VBC, and a four-dipole dog-leg transport arc, referred to as the FEBE arc. The VBC and FEBE arc have opposite sign R_{56} components and therefore the parameters of these modules must be optimised in tandem so that high compression may be achieved at FEBE while maintaining a good bunch profile. The arc has a significant T_{566} component which must be cancelled with sextupoles to prevent skewing of the longitudinal bunch distribution. Further detail on the CLARA lattice can be found in [1]. Simulated optimisation of this kind is shown in Fig. 1, where the full width at half maximum (FWHM) of a simulated electron bunch at the FEBE interaction point (IP) is minimal at 60 fs for a VBC angle of 0.113 rads with the sextupoles set to their optimal strength for $T_{566} = 0\,\mathrm{m}$.

To perform this compression optimisation experimentally, a longitudinal diagnostic is needed after the FEBE arc from which information about shape of the bunch profile can be deduced, and relative measurements of bunch length can be made. The longitudinal profile of a bunch may be determined via measurement of the amplitude and phase of the THz CTR frequency spectrum generated when the bunch traverses a thin foil [2, 3]. The CTR phase may be recovered using techniques such as computation with the Kramers-Konig relation or iterative phase retrieval, but these techniques can be difficult to implement. A simpler method is to deduce information about the bunch profile from only the amplitude of the CTR with knowledge of the beam dynamics of the accelerator. Previously this has been achieved on CLARA using a Martin-Puplett interferometer, but this was time-consuming to implement and required multiple shots, which made measurements sensitive to jitter. In contrast, another technique previously used on CLARA is to make an ‘integrated’ measurement of the total CTR spectral power, from which relative comparisons of the bunch length can be easily made. This method however, while simple to implement, provides no information about the shape of the bunch profile beyond an estimate of length. Presented here is a single-shot, four-channel spectrometer, which will provide more information about the bunch profile than an integrated measurement while still being easy to implement, low-cost and robust.

INSTRUMENT DESIGN

A diagram of the optical design of the spectrometer is shown in Fig. 2. The CTR produced as the beam passes through a thin foil is redirected out of the beamline and through a crystal quartz window. The THz radiation is collimated and refocused, and is incident on three frequency-

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* emily.shackleton@stfc.ac.uk

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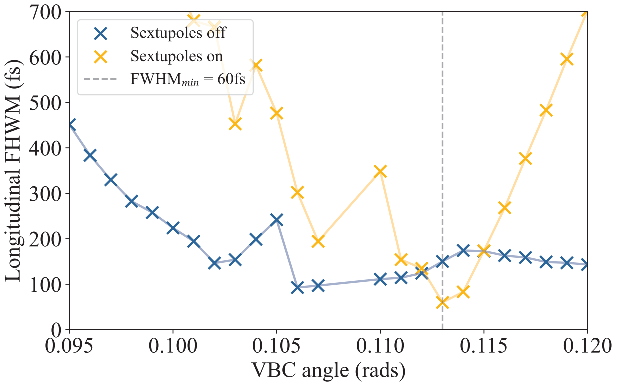

Figure 1: Full width at half maximum of the longitudinal bunch distribution of simulated electron bunches at the FEBE interaction point.

selective mesh filters and distributed onto four broadband pyroelectric detectors. Three filters to create four channels were chosen to give good resolution of the CTR spectrum while keeping the spectrometer compact in size. The total power of each frequency band is recorded by the detectors, and then sent to a data acquisition system. The design is versatile and may be adapted for different purposes; the filters can be switched with other filters if different frequency channels are desired.

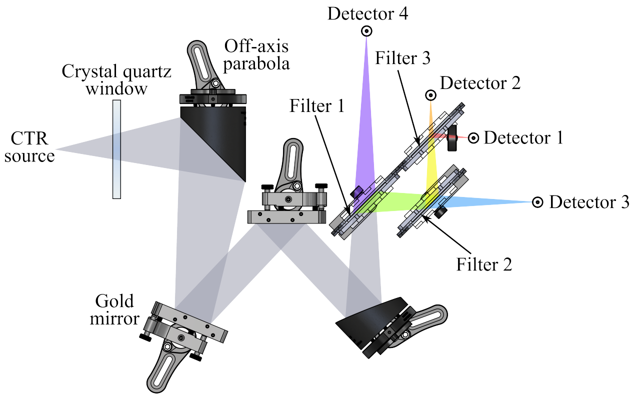

Figure 2: Diagram of the optical layout of the four-channel THz spectrometer.

Several frequency-selective mesh filters were designed at STFC RAL Space, and their transmittances were simulated using physical measurements of the filter properties such as the grid spacing. The filters were then characterised at Manchester University with a broadband THz source, and a good agreement was observed between the measured and simulated transmittances. Three filters were selected based on the corresponding approximate frequency channels for the spectrometer as seen in Fig. 3. Two example CTR spectra generated from simulated bunches at the FEBE IP for a given VBC angle are shown with the arc sextupoles on and off respectively. Poorly-tuned sextupoles will result in bunches with a skewed Gaussian longitudinal distribution, from which CTR spectra with high-frequency tails are produced, compared to the pure Gaussian spectra produced by non-skewed bunches. The spectrometer filters were therefore chosen to correspond to frequency channels that can distinguish spectra with high-frequency tails from those without.

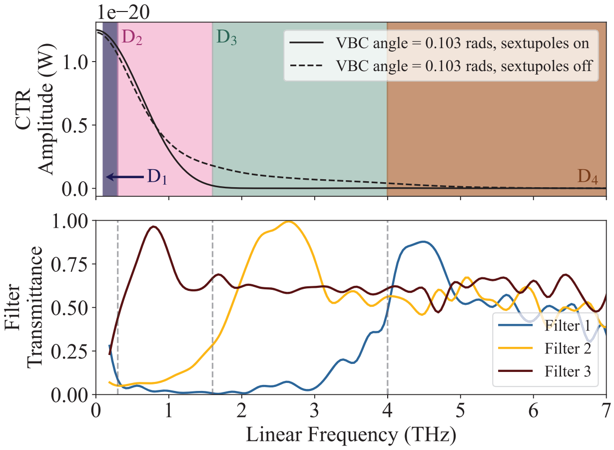

Figure 3: Top: Two example CTR spectra from simulated electron bunches at the FEBE IP for a VBC angle of 0.103 rads, with the arc sextupoles on and off respectively, and spectrometer detector channels indicated as shaded regions. Bottom: Measured transmittance of the spectrometer filters.

COMPUTATIONAL MODEL

A model was written in Python and was configured to take an array of simulated particles and their associated parameters as input. A histogram of the particle distribution in time was then created. Using this binned data, a kernel density estimator (KDE) was used to calculate a quasi-continuous estimate of the longitudinal 2D projection of the 3D bunch distribution. The CTR power spectrum produced by the simulated bunch was calculated up to a constant of proportionality using Eq. 1 from [2]:

$$P(\omega) = P_0(\omega)N[1 + (N - 1)f(\omega)] \qquad (1)$$

where N is the number of electrons in the bunch, and $P_0(\omega)$ is the radiated power from one electron. The form factor $f(\omega)$ is given by

$$f(\omega) = \left| \int e^{i\frac{\omega}{c}t} s(z) dz \right|^2$$

where $s(z)$ is the longitudinal particle distribution. The transverse component of the form factor may be neglected here as it tends to unity over the frequency range of interest. The spectrometer's measurement of the CTR is then modelled. The CTR spectrum is first multiplied by the transmittance of the vacuum chamber window. The subsequent spectrum is then multiplied by the appropriate combination of transmittances and reflectances for each filter to obtain the signal incident on each detector. These experimentally obtained transmittances are shown in Fig. 3. The output from each calorimeter is estimated by calculating the numerical integral of the spectrum incident on that detector.

SIMULATED SEXTUPOLE TUNING

The computer model was used to investigate the possibility of performing sextupole strength optimisation using the THz spectrometer. The spectrometer can distinguish between skewed and non-skewed Gaussian profiles for a given bunch length and so the optimum sextupole strength, k_2L, may be determined. Simulated bunches for a range of FEBE arc sextupole strengths were used as input to the spectrometer model. The value of the T_{566} after the arc was also recorded for each simulated bunch. The signals from each detector channel as calculated by the model are shown in Fig. 4. Each of the detectors' simulated outputs peak very near to the sextupole strength corresponding to the minimum T_{566} for the FEBE arc. In particular detector three has a sharp peak; this is because (as seen in the example signals in Fig. 3), there is the largest difference between skewed and non-skewed bunches in this frequency region. This demonstrates that the THz spectrometer can successfully be used to tune the sextupoles on the FEBE arc.

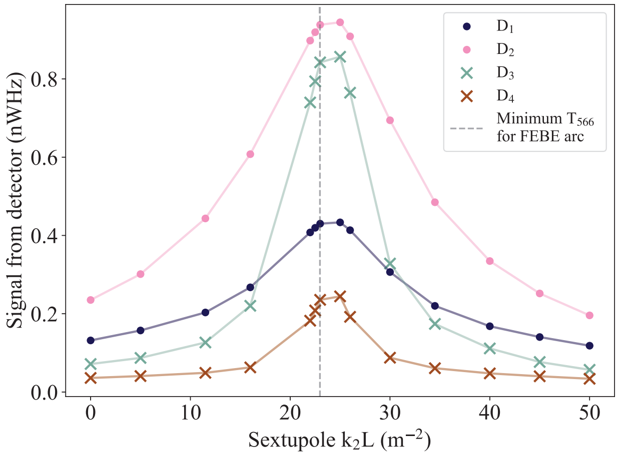

Figure 4: Modelled spectrometer channel outputs for simulated bunches for different arc sextupole strengths.

SIMULATED COMPRESSION SCAN

The optimisation of compression using the VBC on CLARA was also investigated. With the sextupoles tuned, it is possible to determine the VBC angle that corresponds to the minimum bunch FWHM after the FEBE arc. This is because shorter bunches generate higher-frequency CTR which is picked up on the higher-frequency detectors. Simulated bunches were generated for a range of VBC angles, corresponding to different amounts of compression, and then were input to the model. The FWHM of the KDEs of the bunch distribution in time as created by the computer model were also recorded. The output of the model for these data can be seen in Fig. 5. As for the sextupole tuning, the detector outputs peak strongly at the minimum FWHM bunch length of 60 fs, with detector three having a sharp and narrow peak. Figure 5 also illustrates the benefit of having four detector channels compared to one broadband 'spectrally integrated' measurement. Depending on the exact longitudinal profile, the peak for an integrated measurement may not occur at the VBC angle corresponding to minimum FWHM. This can be seen when a compression scan is performed when the arc $|T_{566}| \gg 0$. Additionally, the integrated detector would have a much larger uncertainty in estimated FWHM of the bunch, which would significantly impact potential compression optimisation. An integrated measurement would be equal to the sum of each of the detector channels here, minus the effect of the non-perfect transmission of the filters. A much broader peak would therefore be seen, corresponding to a larger uncertainty in estimated FWHM than that of e. g. detector three, where the signal peak spans 348 fs.

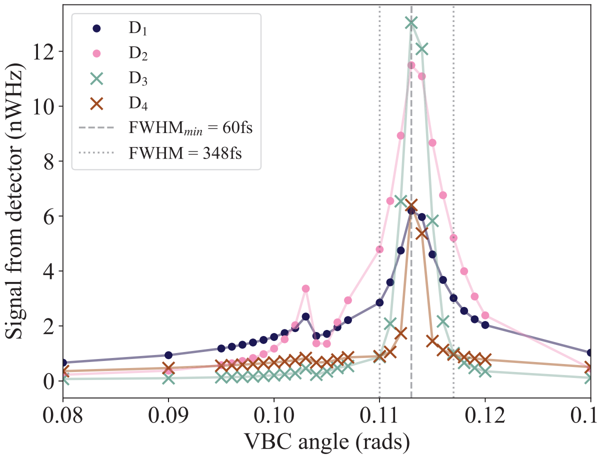

Figure 5: Modelled spectrometer channel outputs for simulated bunches for different VBC angles.

SUMMARY

A single-shot, four-channel THz CTR spectrometer has been designed that will allow the parameters of CLARA to be optimised to deliver short bunches for FEBE users. Compared to other methods of measuring the longitudinal bunch profile, it offers a unique combination of benefits such as being easy to implement, cost-effective, compact in the beamline and robust. The spectrometer design is also versatile and could be adapted for other applications. Start-to-end simulations and numerical modelling have been implemented to demonstrate the tuning of the FEBE arc sextupoles, as well as the optimisation of longitudinal compression using the VBC.

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