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QUALITATIVE MEASUREMENTS OF BUNCH LENGTH AT CLARA USING COHERENT TRANSITION RADIATION

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Abstract

Bunch length is an important metric for user experiments at the Compact Linear Accelerator for Research and Applications (CLARA). A prototype Bunch Compression Monitor (BCM) based on Coherent Transition Ration (CTR) was recently installed and commissioned to support recent user experiments. The intensity of CTR is measured using a pyroelectric detector. A noise cancellation scheme based on a second detector offset from the focus of the CTR was used to reduce the noise caused by the broadband nature of pyroelectric detectors. Qualitative measurements of the bunch length as a function of RF phase are presented, along with an overview of the system design. Plans for an improved system are also presented.

CLARA FACILITY

Compact Linear Accelerator for Research and Applications (CLARA) [1] is a flexible electron beam test facility currently under construction at STFC Daresbury Laboratory. CLARA is designed to test advanced Free Electron Laser (FEL) schemes and technologies that could be later implemented in a future FEL, such as the one being studied as part of the UK XFEL project [2].

CLARA is being constructed in phases, with Phase 1 first commissioned in 2018 to deliver electron bunches at 10 Hz, up to 250 pC bunch charge and at an energy of 50 MeV. Phase 1 comprises of an S-band photoinjector gun (accelerating up to 5 MeV) and an S-band linac. Longitudinal bunch compression was performed in Phase 1 using a magnetic dog-leg and through variation of the linac phase. Phase 1 was used to carry out beam experiments in two periods, taking place in 2018/19 and 2021/22 [3].

Phase 2, which is currently under construction, will install additional linacs and a new photoinjector gun to deliver electron bunches at 100 Hz, up to 250 pC bunch charge and an energy of 250 MeV. The bunches will be delivered to a new flexible experimental hutch called the Full Energy Beam Exploitation (FEBE) hutch. The target comissioning parameters for FEBE are a bunch length of 100 fs at 250 pC and 50 fs at 5 pC. Among the experiments planned for this new facility are novel acceleration experiments, which have demanding requirements for beam parameters [4]. To ensure that the required beam parameters can be delivered, appropriate diagnostics are required [5]. The 6D suite of diagnostics being developed for FEBE is shown in Fig. 2.

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This paper presents the first results of a new diagnostic system being developed as a Bunch Compression Monitor (BCM) for FEBE. The BCM measures the energy of pulses of coherent transition radiation (CTR) released by the bunch when it strikes a polished metal target. A prototype was installed and commissioned during the most recent experimental period on CLARA Phase 1 [1]. This paper first presents the design of the prototype front end, then the results of online measurements taken during the experimental period, and finally future plans for the more advanced system being developed for FEBE.

SYSTEM DESIGN

The system broadly consists of four parts: An aluminum CTR target, the window and optics, detector heads, and the analog front end. The CTR target is a polished aluminum disk, mounted on a motorized stage at an angle of 45° to the beam axis. The resulting CTR is transmitted out of the beam pipe through a fused silica window, and collected with a series of TPX lenses which focus it onto one of two pyroelectric detector heads. Both detector heads are commercially available Gentec-EO QS5-THz-BL pytoelectric detectors [6]. Each detector incorporates a high bandwidth op amp. From the manufacturer's calibrations, the detectors have an almost 30% difference in gain, which was not compensated for with this prototype. The spectral response of the detector system as a whole was not characterised.

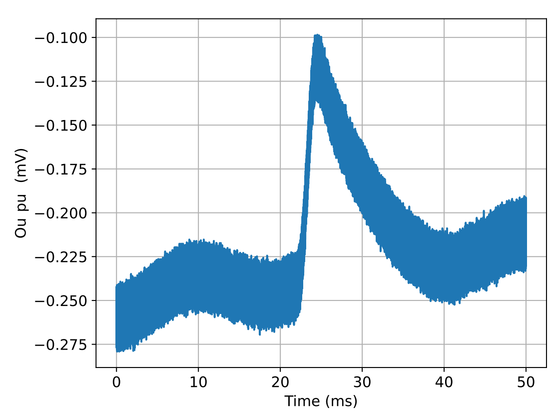

Figure 1: Output of analog front end during bench testing

The analog front end consists of three parts: A feedback network for adjusting the gain of each detector head, an active noise cancellation circuit to improve signal to noise ratio, and an output driver. The feedback network uses relays to allow switching between four different external feedback

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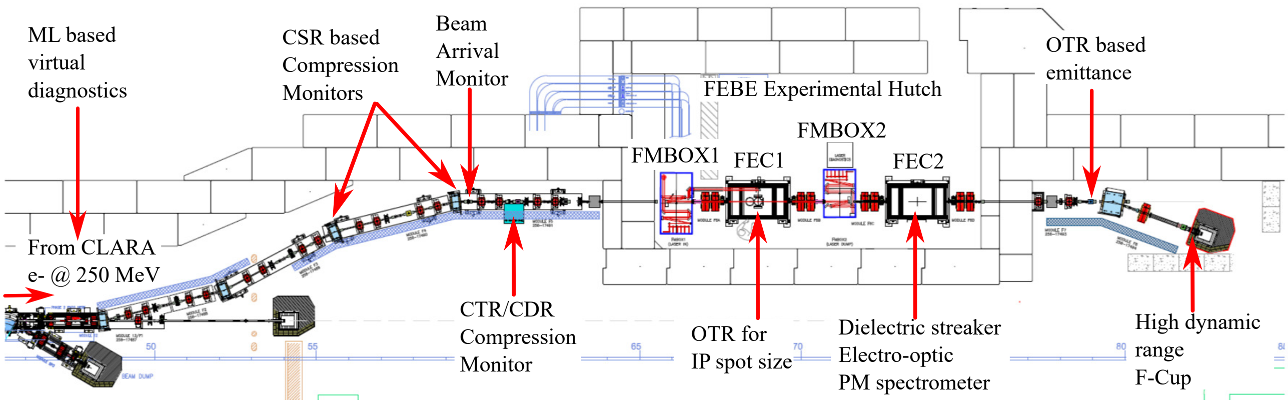

Figure 2: 6D Diagnostics currently undergoing R&D for installation in FEBE. Adapted from [5].

networks for each detector head, which allows the gain of the detector to be adjusted to compensate for bunch charge when installed. The active noise cancellation circuit consists of a high bandwidth, unity gain instrumentation amplifier. One detector is connected to the non-inverting input and the other to the inverting input. The output buffer is necessary due to the length of cable between the analog front end in the machine hall and the digitization equipment located in the rack room outside the radiation shielding.

An example output, generated in a laboratory using a low power, pulsed laser as a test signal, is shown in Fig. 1. Additional electronic filters were added after installation to remove the high frequency noise seen in the lab. The peak-to-peak voltage of this signal is proportional to the total energy of the incident CTR. During bench tests the 95% confidence interval of the peak-to-peak voltage over 250 shots was found to be around 10%.

ONLINE MEASUREMENTS

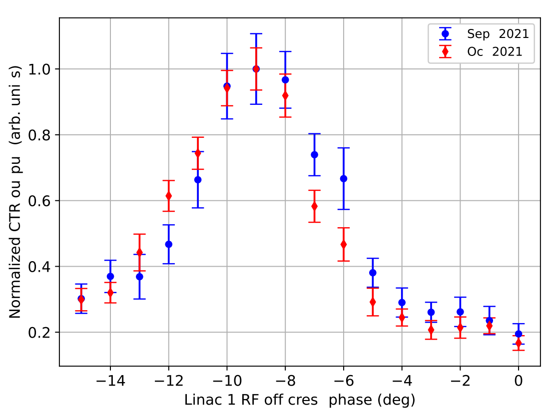

Figure 3: Bunch Compression Monitor output during Linac RF phase scans

The prototype was installed between CLARA Phase 1 and the experimental area in use for the two experimental periods, Beam Area 1 (BA1), and was used to determine the linac off crest phase for maximum longitudinal beam compression. Figure 3 shows two scans of the linac RF phase from crest to -15 degrees off-crest. Error bars show 95% confidence interval across the measurement. The blue scan is from September 2021, and the red scan is a similar scan from October 2021. The bunch charge in both instances was 100 pC, and during comissioning it was found that accurate measurments could obly be achieved above 75 pC. Both scans found the off crest phase of peak signal to be -9° relative to the crest. This phase is likely to be beyond the point of shortest bunch length and the peak signal is due to over-compression and non-linearity within the bunch compression dog-leg. When the bunch is over-compressed the peak current at the head of the bunch is increased, whilst a long tail forms behind the head, this spike in peak current produces high frequency CTR which is transported with less losses and focussed to a smaller spot on to BCM than lower frequencies. Figure 4 shows the output of the prototype system over 20 seconds, with +/- 10% 95% CI.

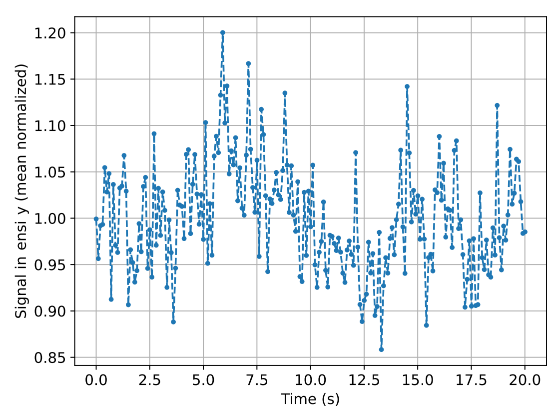

Figure 4: Time series of Bunch Compression Monitor output

FUTURE WORK

For FEBE it is planned to install additional optics, including low and high-pass filters to enable the BCM to act as a rudimentary spectrometer and to fit a non-invasive coherent diffraction radiation (CDR) target [5]. To enable these mea-

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surements a new detector, analog front end and digitization system is being developed.

This new system will be designed to be modular, allowing the components to be reused in other devices in the future. Onboard digitization and signal processing will also be used, including integrating a Xilinx Zynq 7000-series FPGA in each detector. This will enable faster and more complex signal processing, especially for shot-by-shot data, as well as improvements in the active noise cancellation circuitry. Each detector will consist of three boards, stacked using board-to-board connectors: A detector board, an analog processing board, and a digital processing board.

The detector board will mount the pyroelectric detectors and the external feedback network for the integrated op amp in each detector. The relays used in the prototype presented in this paper will be replaced with solid-state switching and additional gain settings will be implemented. Adjustable attenuation will be added to compensate for differences in gain between the two detector heads.

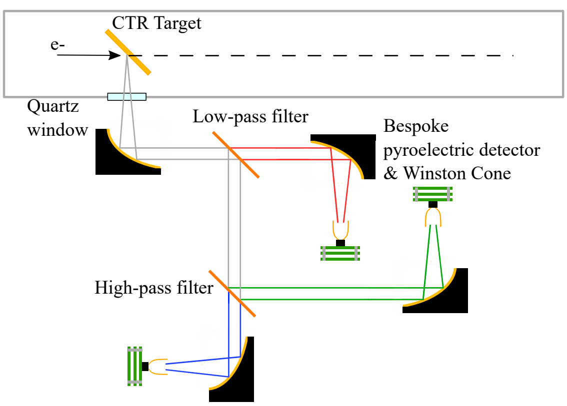

Figure 5: Schematic of the planned BCM spectrometer to be installed on FEBE. Adapted from [5].

The analog processing board will include an improved version of the circuitry used for noise cancellation in the prototype, as well as additional filtering and signal processing to remove noise, and the analog-to-digital converter. The digital processing board, in addition to an FPGA and I/O for data and controls, will process data from the analog-to-digital converter.

The upgraded system will be used in conjunction with a Transverse Deflecting Cavity (TDC) and an improved electro-optic (EO) bunch length monitor [7] to provide a robust variety of longitudinal diagnostics on CLARA Phase 2. It is expected that by comparing against quantitative measurements from the TDC and EO, the improved system can be calibrated to provide quantitative shot-by-shot measurements for certain beam setups.

CONCLUSION

This paper has presented the design of a prototype bunch compression monitor designed at Daresbury Laboratory, and early results of qualitatively measuring the bunch length on CLARA. Peak CTR signal was found to be at -9° relative to the RF crest of the first linac. To address the limitations of the prototype and better support the planned experiments for CLARA Phase 2, an upgraded system is being designed that will act as a crude spectrometer and be able to provide shot-by-shot measurements. This future system will implement on-board digitization, improved analog and digital signal processing, and is expected to complement other longitudinal diagnostics planned for CLARA Phase 2.

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