14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL160

HIGH-BANDWIDTH ELECTRO-OPTIC BPMS AND AN OPTICAL TIME-STRETCH TECHNIQUE

S. M. Gibson*, A. Arteche, John Adams Institute at Royal Holloway, University of London, UK
T. Lefèvre, T. Levens, CERN, Geneva, Switzerland

Abstract

An electro-optic beam position monitor is in development for the HL-LHC to enable high-bandwidth monitoring of crabbed bunch rotation and intra-bunch instabilities. Following in-air beam tests of a prototype at HiRadMat and the CLEAR facilities at CERN in 2021 and 2022, a new in-vacuum version is being prepared for operation in the SPS during LHC Run 3. We report on progress toward the design aims and investigate a novel method of readout of single shot pulsed bunch signals at high bandwidth, while acquiring data at lower bandwidths using an optical time-stretch technique.

MOTIVATION

Electro-optic crystals exhibit rapid response times to the passing field of a relativistic particle bunch, making them well suited to high-bandwidth, intra-bunch beam diagnostics. Electro-optic techniques are particularly applicable at electron beam lines, at which the typical bunch length is several orders of magnitude shorter than at hadron machines. The short of $\ll 1$ ps length of the relativistic electron bunch and correspondingly high longitudinal charge density generates a very high transverse field ($\gg$ MV/m) at the location of the crystal, which is inserted within the evacuated beam pipe, where radial proximity to the bunch further increases the signal strength. Due to the high field creating a strong electro-optic response, the crystal can be very short in length, $\ll 1$ mm. Thus the variation in charge profile of the electron bunch creates an optical analogue encoded in an ultrafast probe pulse from a synchronised laser, mode matched to the co-propagating field. A range of standard ultrafast optical techniques can then be used to decode the laser pulse to extract the time-resolved longitudinal charge distribution.

In contrast, at hadron machines such as the High Luminosity Large Hadron Collider (HL-LHC), the bunch length is much longer, $4\sigma \approx 1$ ns, and the beam pipe radius is larger (typically 40 mm) thus reducing the Coulomb field to $\approx$ kV/m at the crystal, which cannot be placed very close to the beam due to impedance considerations. The challenge in developing electro-optic beam position diagnostics for the HL-LHC [1–9] has therefore been in obtaining sufficient signal strength, given a field that is many orders of magnitude less than at electron machines.

In the past two years, an electro-optic pick-up design has been produced and beam tested, which addresses these fundamental limitations, by employing electro-optic waveguides in place of bulk crystals. Two such pick-ups were combined into an Electro-Optic Beam Position Monitor (EO-BPM), and the first results of the in-air beam tests of these prototype pick-ups were presented at IBIC22 [10] and are reviewed in the next section. The beam tests at HiRadMat demonstrate a major enhancement in the signal, that has enabled a demonstration of single shot beam position measurements for the first time.

A remaining challenge to develop an operational EO-BPM system for the HL-LHC is the high bandwidth read-out required to meet the design target of 6-10 GHz, to be able to monitor crabbed bunches and intra-bunch motion. While direct digitisation of the fast signal may be achievable, this paper focuses on an initial investigation of a novel optical time-stretch method to detect the electro-optic difference signal, such that the data may be recorded at a slower rate and bandwidth. This has the potential advantage of using lower noise, high gain photodetectors, coupled with efficient and more affordable off-the-shelf data acquisition system.

ELECTO-OPTIC BPM TESTS

Waveguide EO Pick-Up

The operating principle of an EO-BPM has been detailed elsewhere [1, 4–6], and essentially consists of replacing the capacitive pick-ups in a conventional button BPM by electro-optic crystals. The passing Coulomb field of the particle bunch generates a near instantaneous change in the refractive index such that the phase of transitioning coherent light is modulated according to the bunch charge. For the reasons described above, electro-optic waveguides were manufactured in collaboration with UK industry, which serve to enhance the Coulomb field. A microscope image of the waveguide prior to installation in the pick-up is shown in Fig. 1.

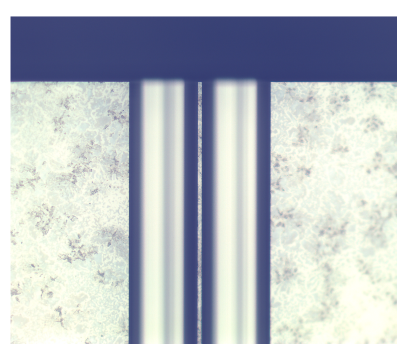

Figure 1: Microscope image of the lithium niobate waveguide, prior to fibre-coupling. The $< 10\,\mu$m waveguide is design to transmit $\lambda = 780$ nm single-mode polarised light.

* stephen.gibson@rhul.ac.uk

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL160

The waveguide was fibre-coupled with single-mode polarisation-maintaining fibre, and incorporated into the pick-up shown in Fig. 2.

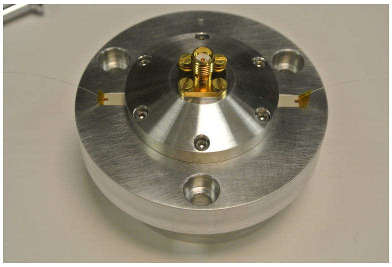

Figure 2: Fibre-coupled electro-optic waveguide pick-up.

An EO-BPM was created in the horizontal plane from two such pick-ups on opposite sides of a 61 mm diameter beam pipe. The body of the EO-BPM was part of a coaxial line that was used for VNA bench tests of the pick-ups prior to shipping to CERN. A set of three interferometers were created, two around each waveguide and one between the opposing waveguides, by connecting a series of fused bi-conic taper fibre couplers to split and combine the light before and after the waveguides. In-line phase modulators were incorporated to enable fine remote control of the working point in the side interferometers, while the main interferometer was controlled by frequency tuning the laser.

In-Air Beam Tests

The EO-BPM was installed in August 2021 at the HiRadMat extraction line from the CERN SPS for in-air beam tests as in Fig. 3. The device was mounted on a stepper motor, so that the BPM could be translated across the extracted proton beam, to assess the positional sensitivity of the response. Further details on the setup can be found in [10].

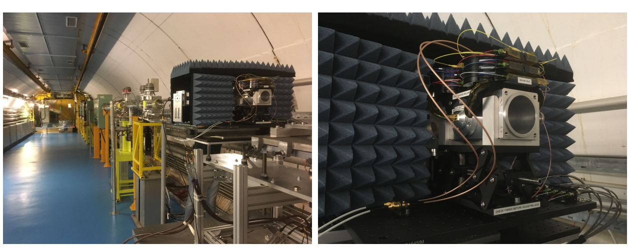

Figure 3: EO-BPM installed in the HiRadMat beam line

Single shot measurements of the extracted proton bunches were recorded, typically over several hours and for multiple beam conditions. An automatic procedure was developed to stabilise the working point of the interferometer during SPS cycles. For each extracted bunch the amplitude of the temporal response of the electro-optic interferometric difference signal was calculated, and is plotted versus the translation stage position in Fig. 4. Despite some limitations of the photodetectors and acquisition system used in these first tests, good linearity of the signal amplitude with position is observed, demonstrating the principle of single-shot position measurement. The same EO-BPM was later tested at the CLEAR facility and high-bandwidth eo signals were observed for a train of short electron bunches separated by 666 ps. For further details see [10, 11].

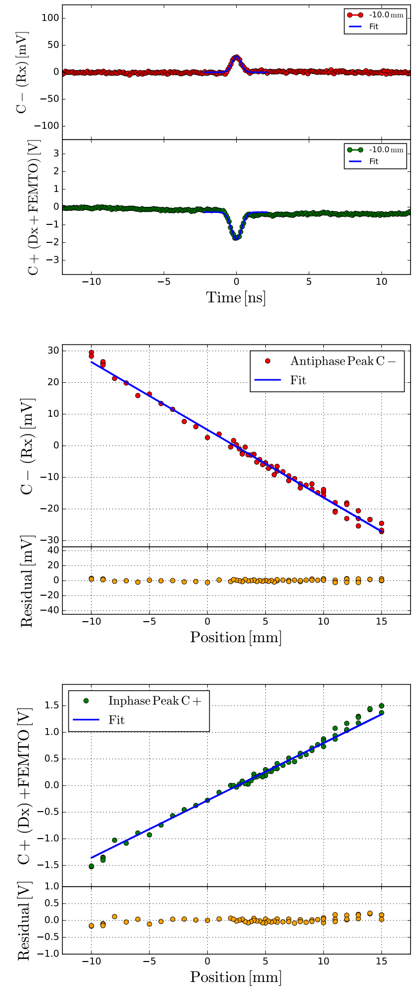

Figure 4: Transient single-shot bunch signals and position reconstruction, for both anti-phase outputs of the electro-optic BPM interferometer at HiRadMat.

In-Vacuum Design

Following the promising in-air beam tests, new pick-ups have been incorporated into an in-vacuum design for beam tests at the CERN SPS, as in Fig. 5, as a demonstrator for the HL-LHC.

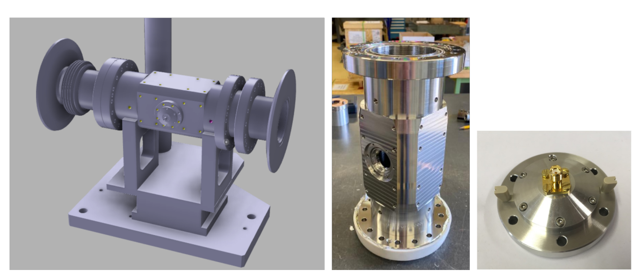

Figure 5: Design and manufacture of in-vacuum EO-BPM demonstrator for beam tests at the CERN SPS.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL160

OPTICAL TIME-STRETCH TECHNIQUE

Optical time-stretch techniques developed for electron bunch diagnostics include: spectral decoding, spatial encoding, temporal decoding and spectral up-conversion [12], which rely on ultra-short laser pulses (fs) stretched to ps. The scheme proposed here instead aims to time-stretch the optical pulse from an EO-BPM by a factor ≈10, so that 1 ns bunch signals can be recorded over ≈10 ns. This reduces the bandwidth requirements on the photodetector, amplifier chain and digitizer. The technique investigated is based on Free-space Angular-Chirp-Enhanced Delay (FACED), as proposed for fast biological imaging [13], whereby an angular chirp produces a range of virtual sources with differing delays for an optical pulse, when reflected successively between two non-parallel mirrors, as modelled in Fig. 6.

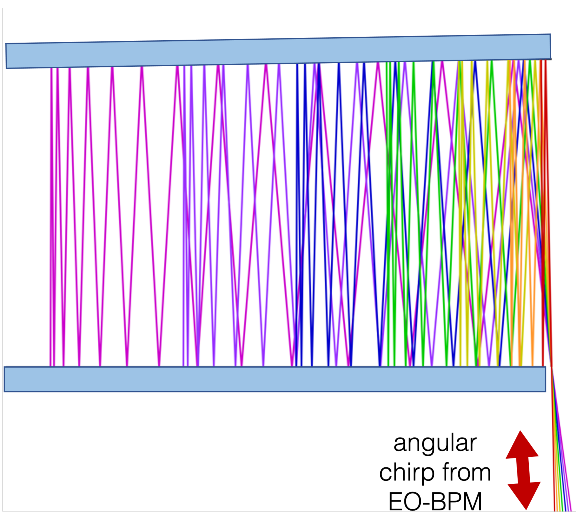

Figure 6: In a FACED setup the path length between two non-parallel mirrors differs according to incident angle.

A FACED experimental setup was tested using a CW laser and an EO phase modulator in a fibre-coupled Mach-Zehnder interferometer to generate optical pulses, as in Fig.7. Small changes in the incident angle of the collimated light sent into the FACED device result in further reflections that sequentially extend the path length. The delay was analysed by comparing the photodetector signals with trigger pulses

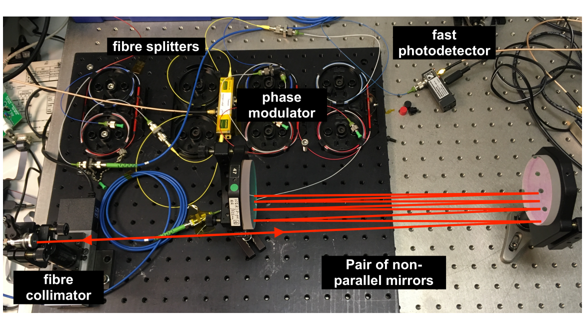

Figure 7: Simple experimental setup of FACED technique to test delay of EO modulated pulse.

as in Fig. 8 and is plotted in Fig. 9 with a measured delay of the optical pulse by up to 12 ns in the arrival time at the fibre-coupled fast photodetector.

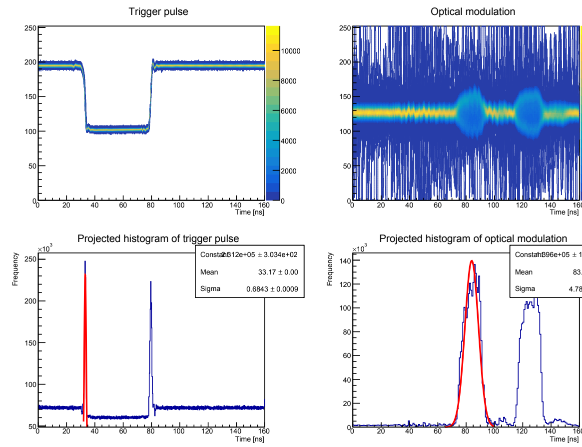

Figure 8: Analysis of the time delay of two optical pulses after passing through the FACED device, relative to the trigger signal that drives the optical modulator.

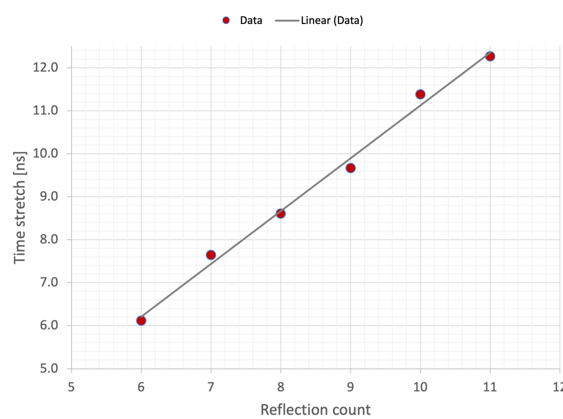

Figure 9: Measured effective time-stretch for an optical pulse versus the number of reflections in a FACED setup.

CONCLUSION

Two successful beam test campaigns of electro-optic waveguide pickups have been performed at HiRadMat and CLEAR, demonstrating the first single-shot measurements of each passing bunch, and promising time resolution of the pick-up. The translation of an EO-BPM across the HiRadMat extraction line gives the first bunch by bunch position measurements. An in-vacuum EO-BPM demonstrator is in production for further beam tests at the SPS. An optical time-stretch method is under investigation for a novel acquisition scheme of fast optical signals.

ACKNOWLEDGEMENTS

Funded by UKRI ST/N001583/1 and ST/P00203X/1, Royal Holloway University of London, CERN and EU Horizon 2020 GA No 101004730. We gratefully acknowledge assistance from P. Simon, N. Charitonidis & the HiRadMat team, and A. Schloegelhofer, C. Pakuza & the CLEAR team.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL160

REFERENCES

[1] S. M. Gibson *et al.*, "High Frequency Electro-Optic Beam Position Monitors for Intra-Bunch Diagnostics at the LHC", in *Proc. IBIC'15*, Melbourne, Australia, Sep. 2015, pp. 606–610. doi:10.18429/JACoW-IBIC2015-WEDLA02

[2] G. Apollinari et al., "High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report V. 0.1", CERN-2017-007-M, Yellow Report., 2017. doi:10.23731/CYRM-2017-004

[3] T. E. Levens, K. Lasocha, and T. Lefèvre, "Recent Developments for Instability Monitoring at the LHC", in *Proc. IBIC'16*, Barcelona, Spain, Sep. 2016, pp. 852–855. doi:10.18429/JACoW-IBIC2016-THAL02

[4] A. Arteche *et al.*, "Development of a Prototype Electro-Optic Beam Position Monitor at the CERN SPS", in *Proc. IBIC'16*, Barcelona, Spain, Sep. 2016, pp. 634–637. doi:10.18429/JACoW-IBIC2016-WEPG09

[5] A. Arteche *et al.*, "First Beam Tests at the CERN SPS of an Electro-Optic Beam Position Monitor for the HL-LHC", in *Proc. IBIC'17*, Grand Rapids, MI, USA, Aug. 2017, pp. 270–273. doi:10.18429/JACoW-IBIC2017-TUPCF23

[6] A. Arteche, "Studies of a prototype of an electro-optic beam position monitor at the CERN Super Proton Synchrotron", Ph.D. thesis, Royal Holloway, University of London, CERN-THESIS-2018-316. http://cds.cern.ch/record/2653351

[7] S. M. Gibson *et al.*, "Enhanced Bunch Monitoring by Interferometric Electro-Optic Methods", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2353–2356. doi:10.18429/JACoW-IPAC2018-WEPAL073

[8] A. Arteche *et al.*, "Characterisation of Electro-Optic Pickups for High Bandwidth Diagnostics at the High Luminosity LHC", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2690–2693. doi:10.18429/JACoW-IPAC2019-WEPGW088

[9] A. Arteche *et al.*, "Beam Measurements at the CERN SPS Using Interferometric Electro-Optic Pickups", in *Proc. IBIC'19*, Malmö, Sweden, Sep. 2019, pp. 457–460. doi:10.18429/JACoW-IBIC2019-WEAO04

[10] A. Arteche, S. M. Gibson, T. Lefèvre, and T. E. Levens, "Electro-Optical BPM Development for High Luminosity LHC", in *Proc. IBIC'22*, Kraków, Poland, Sep. 2022, pp. 181–185. doi:10.18429/JACoW-IBIC2022-TU1I1

[11] A. Arteche *et al.*, Journal paper in preparation.

[12] A. Gillespie, "Bunch Length Diagnostics: Current Status & Future Directions" *Proc. of 2018 CERN-Accelerator-School on Beam Instrumentation, Tuusula, Finland*. doi:10.48550/arXiv.2005.05715

[13] Wu, JL., Xu, YQ., Xu, JJ. et al. "Ultrafast laser-scanning time-stretch imaging at visible wavelengths". *Light Sci Appl 6, e16196 (2017)*. doi:10.1038/lsa.2016.196