ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU1I1

ELECTRO-OPTICAL BPM DEVELOPMENT FOR HIGH LUMINOSITY LHC

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

Abstract

An Electro-Optic Beam Position Monitor (EO-BPM) is being developed as a high-frequency (up to 10 GHz) diagnostic for crabbing and Head-Tail intra-bunch detection at the HL-LHC. Following an earlier prototype at the SPS that demonstrated single-pickup signals, an upgraded design of an interferometric EO-BPM has been beam-tested at the HiRadMat facility for validation and characterisation studies. In the new design, the fibre-coupled Mach-Zehnder interferometer arms are modulated by lithium niobate waveguides integrated in an upgraded opto-mechanical arrangement that has been developed to produce a highly magnified image field replica of the passing Coulomb field. A new detection technique that is directly sensitive to the interferometric optical difference signal from opposite EO buttons has been applied to measure single-shot bunches for the first time. A transverse resolution study over a ±20 mm range at 3 GHz bandwidth produced the first successful electro-optic bunch-by-bunch position measurement at the HiRadMat in-air extraction line. The results of this campaign show promise for an in-vacuum design that is in production for beam tests at the SPS during Run-3 of the LHC.

INTRODUCTION

The Electro-Optic Beam Position Monitor (EO-BPM) has been proposed as a high-frequency diagnostic for the High Luminosity Large Hadron Collider (HL-LHC), with an operational bandwidth that targets up to 6 – 10 GHz [1, 2]. Among the potential applications are the detection of crabbed-bunch rotation and as a higher bandwidth alternative to standard Head-Tail instability monitors [3].

A prototype of a single EO pickup with a lithium niobate (LN) crystal located 66.5 mm away from the beam was installed in the SPS in 2016, delivering the first EO acquisition of a proton-induced signal [4, 5]. The far location, the long bunch length, and the initial pickup design implied the detection of modulating fields below 1 kV/m, which represented a major challenge [6]. To enhance the signal strength, the prototype was replaced during the 2017 SPS run by a modified version that incorporated an electrode to concentrate the modulating field in the LN crystal, proving to be a good strategy [6, 7]. Since then, several improvements of the optical configuration and stability have been incorporated, transitioning towards a more compact and robust phase interferometer model [8, 9]. The culmination is the new opto-mechanical design tested at HiRadMat that, thanks to a refined electrode design, delivers a highly magnified image replica E_z of the propagating Coulomb field E_C within a LN waveguide volume. This hot-spot mechanism enhances the modulating field E_z parallel to n_e by a significant factor, reaching 190 kV/m for a nominal SPS bunch, according to CST numeric simulations [10].

In combination with the upgraded pickup, a new optical detection technique is proposed as shown in Fig. 1. A Common Interferometric Point (IP-C) is generated when two optical paths combine after going through LN waveguides embedded in EO buttons placed on opposite sides of the pipe. Additionally on each side, one path through the crystal pickup combined with a simple bypass generates left and right side interferometers (IP-L & IP-R). While previous experiments at the SPS were based on the latter, this paper presents results from the common mode for first time.

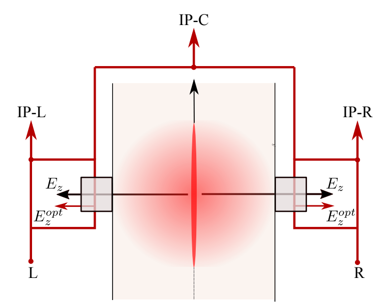


Figure 1: Triple interferometric layout of the EO-BPM.

The optical paths are linearly polarised in z at each LN waveguide, so E_z will activate the linear Pockels effect. This induces a time-profile optical modulation that is a replica of the passing bunch at IP-L & IP-R, and also at IP-C only when the beam is off-centre. Each interferometer has two output fibres from a 2×2 fused-coupler, so that each IP produces two opposite sign modulations: in-phase (+) and anti-phase (-). The IP-C detection allows us to correlate signal strength and transverse position using a single channel, and could also potentially deliver a straight intra-bunch measurement.

In summer 2021, the first interferometric EO-BPM system based on this promising fibre-coupled waveguide model was propitiously installed and tested at the HiRadMat facility. The proton bunch parameters for this SPS extraction line towards a target were similar to those for the nominal LHC bunch, typically ~ $1.15 \cdot 10^{11}$ protons and 4σ ~ 1 ns long Gaussian bunches. In-air characterisation tests of the transverse resolution were performed for single-shots and the results are presented in this paper. The ultimate goal of this campaign was to validate the common-mode detection technique and the new waveguide-based EO-BPM design under realistic beam conditions.

* alberto.arteche@rhul.ac.uk
† stephen.gibson@rhul.ac.uk

11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU1I1

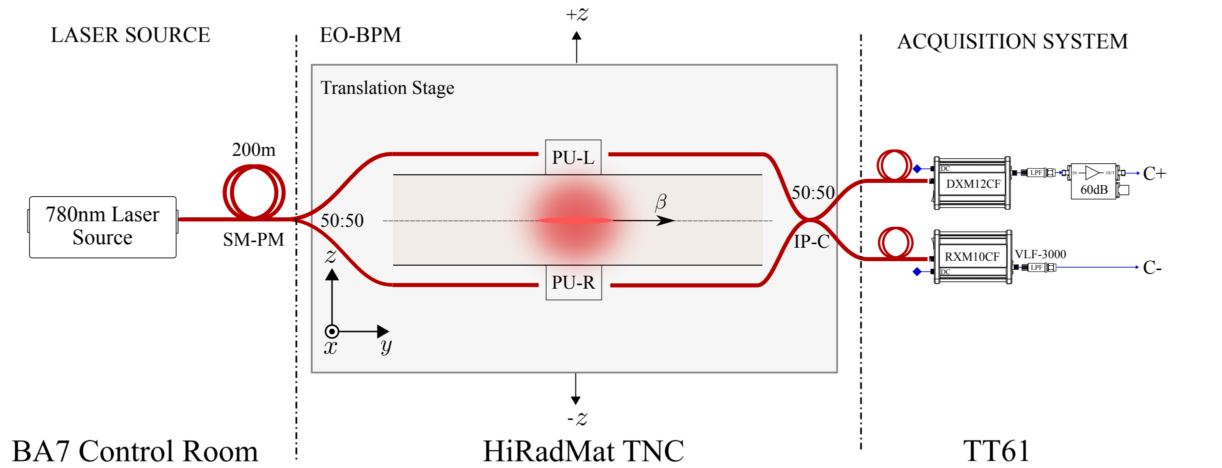


Figure 2: Simplified experimental setup showing locations of the laser source, the common mode Mach-Zehnder interferometer that generates an optical different signal, and the two detectors at the in-phase and anti-phase fibre-coupled outputs.

TRANSVERSE BEAM RESOLUTION TEST

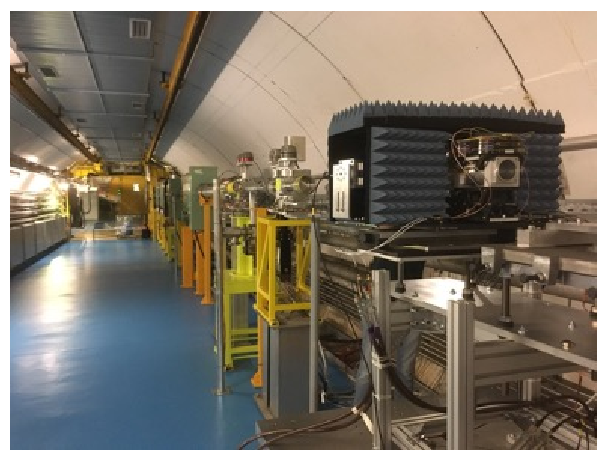
Experimental Setup at HiRadMat

The experimental hardware was implemented in three different locations that were fully fibre-connected as shown in Fig. 2. At the surface level in the BA7 control room, a CW Optical Beam (OB) emerging from a narrow linewidth 780 nm laser source is carried over 200 m of Single Mode Polarisation Maintaining fibre (SM-PM) to the TNC tunnel, where the light is evenly split to feed the EO-BPM installed in a free-space section along the HiRadMat beamline. As explained earlier, both arms go in parallel across the crystal waveguides and are combined at IP-C, trying to keep the distance equal to reduce the interferometric length.

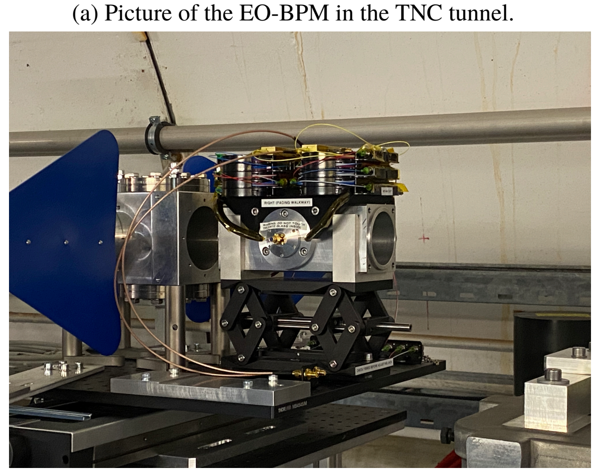
The optical signal was split and then conveyed by 20 m of SM fibre to the acquisition system placed located in the adjacent TT61 tunnel, where two different detection systems measured simultaneously the in-phase (C+) and anti-phase (C-) signals. The split signals permitted us to check the opposite sign modulation and therefore confirm the interferometric nature of the beam signal.

The diagram reveals that C+ was readout by a Thorlabs DXM12CF receiver lacking any pre-amplification connected to a 1 GHz 60 dB amplifier, whereas the photodetector Thorlabs RXM10CF required no further amplification. A 3 GHz Low Pass Filter (LPF) limited the outcome bandwidth of both detectors. The DC optical power reaching the detectors never exceeded 4 mW and the optical modulations were in the order of 1 – 2 mW.

The two EO pickups were installed on opposite sides of a 61 mm diameter pipe in the horizontal plane. As it was an in-air test, the system was assembled on a pipe section resting on a stepping-motor translation stage that allowed transverse movement with respect to the proton beam within a ±20 mm range. Positive offsets ($+z$) indicate the proton beam approaches the right pickup and negative values otherwise. Figure 3 shows the EO-BPM body on the translation stage installed in the HiRadMat beamline.



(a) Picture of the EO-BPM in the TNC tunnel.



(b) Close-up picture of the EO-BPM.

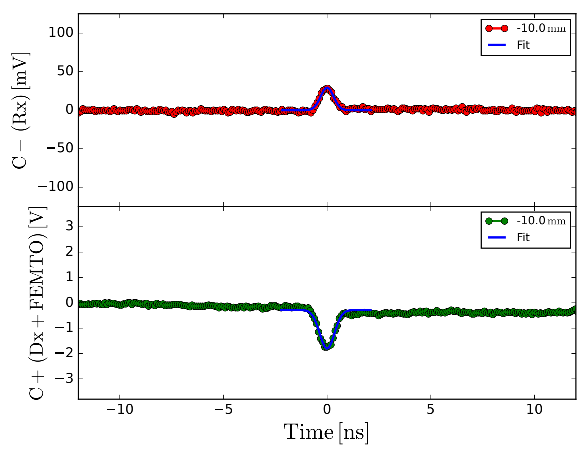
Figure 3: Pictures of the EO-BPM system installed in a free-space section of the HiRadMat beamline in the TNC tunnel.

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU1I1

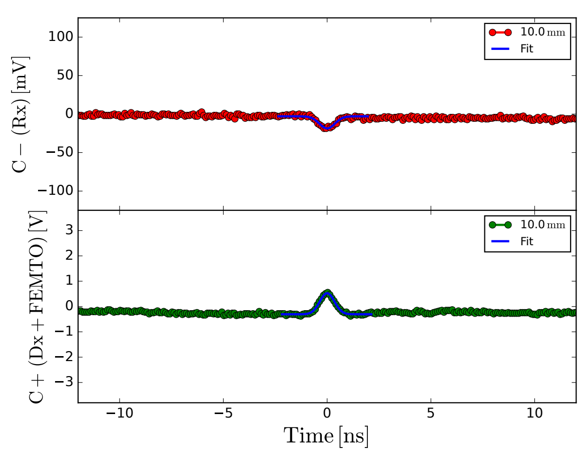
The stability of the interferometric working point was assessed by a wavelength lock-in system based on an in-house etalon. To prevent the laser frequency from drifting, this system provided with a feedback for the laser piezo to compensate accordingly. This is also one of the relevant new features that were integrated in the system with respect to the previous experiments at the SPS. In addition, optical probes were installed to detect possible back reflections and malfunctioning.

Beam Test Results

We present two different sets of single-shot proton bunch measurements, taken parasitically throughout a multi-experiment data-taking campaign at HiRadMat. As those sets were acquired on different dates, the beam intensity was slightly different for each one, particularly, at almost nominal SPS bunch charge ($\sim 1.02 \times 10^{11}$) and at lower charge ($\sim 7 \times 10^{10}$).



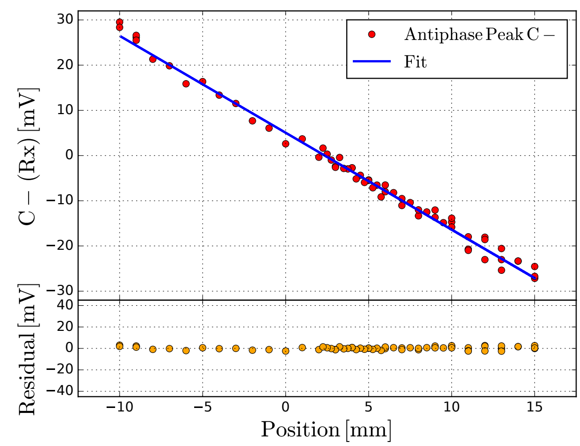
(a) $z = -10.0$ mm



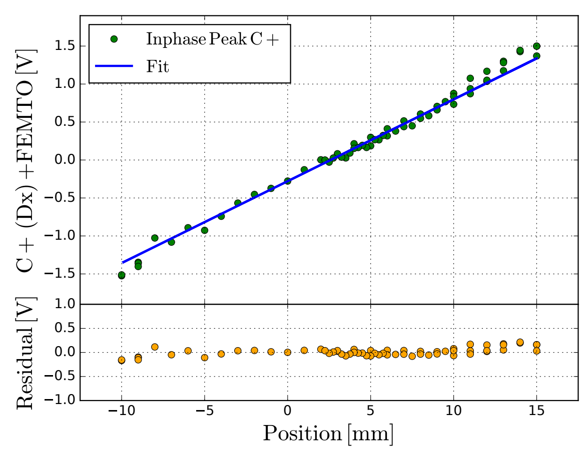
(b) $z = +10.0$ mm

Figure 4: Collection of common mode signals that correspond to in-phase C+ (green) and anti-phase C- (red) optical modulations induced by passing SPS-like proton beams obtained in the HiRadMat extraction line.

Figure 4 is a representative collection of the time-profile single-shot measurements. For each passing beam, a pair of in-phase C+ (green) and anti-phase C- (red) optical modulations were acquired. Despite being a highly radiation environment where most of the electronic equipment exhibited a great deal of distorting noise, the common mode channels C+ & C- delivered a reasonably clean and good quality signal, especially in the pre-amplified channel C-.



(a) Pre-amplified channel C-; +107.8 mV/mm



(b) Amplified channel C+; −2.1 mV/mm

Figure 5: Peak signal modulation against translation stage position z for a set of low intensity single-shot measurements.

Those traces were taken at different transverse positions z by moving remotely the translation stage. Given the diagram depicted in Fig. 2, a larger signal should be expected out of C+ as it includes a 60 dB amplification, i.e. a factor 1000 after the receiver, whereas C- is the signal directly from the pre-amplified detector. Also, the interferometric signals exhibited opposite signs, as foreseen. The acquisition bandwidth was limited by the 1 GHz output of the amplifier in C+, and the LPF at 3 GHz in the pre-amplified channel C-. By implementing an automated feedback to the laser to control the working point on the transfer function, we assured all the

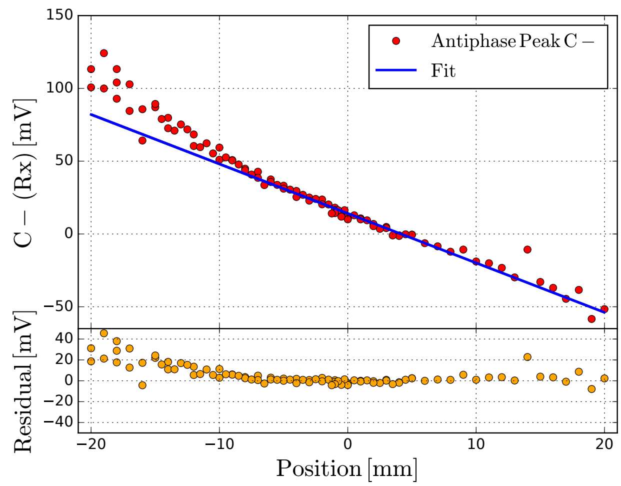
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU1I1

points were obtained at the same conditions of sensitivity so the peak strength variation was driven almost uniquely by the proton bunch parameters.

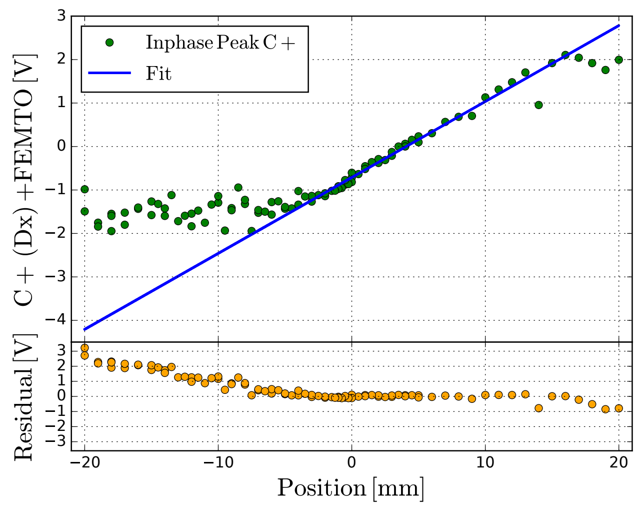
Figures 5 and 6 show the trace peak value extracted from the fit versus the translation stage position z for the low and nominal beam intensities, respectively. The in-phase C+ is represented in green whereas the anti-phase C- is in red. Due to the opposite sign nature, the pre-amplified modulation C- translates into a negative slope whereas the amplified C+ modulation is positive. Ideally, if the pickups were equally responsive, no signal should be expected at $z = 0$. However, one can observe that the distribution of points does not cross the centre, but there is an off-centre offset that implies an non-symmetric response between the prototype pickups. The sign of the offset implies a less than optimal performance of the right pickup, as expected due to small imperfections that were identified during assembly at RHUL prior to shipping to CERN. It is important to note that the 60 dB amplifier had a maximum output voltage of $|V| \sim 2$ V, which is why the cloud of points saturates in Fig. 6 for C+ due to a high beam signal at large displacements compared to the smaller range for the same channel in the low intensity set.

A straight line fit to the data in the non-saturating region was performed for each signal, as indicated by the blue lines in Figs. 5 and 6, which also show the residual difference between the experimental peak value and fitted blue line is shown by lower plots. The measured gradients for the nominal and low intensity data sets, and for each amplifier type are summarised in Table 1. The standard deviation of the residual σ_{residual} was used to estimate an upper limit on the transverse linearity over the full range of the fit, as included in Table 1. The results demonstrate that this direct optical difference signal exhibits good linearity over a wide translation range. The sub-millimetric linearity represents an upper limit on the resolving capability of the EO pickup which is expected fundamentally to be much better, given that the residuals shown here are uncorrected for the effects of bunch charge variations from the HiRadMat single-shot extraction line, laser optical power fluctuations, and include amplifier noise of the prototype acquisition system. These results demonstrate the first single-shot, bunch-by-bunch translation measurements, taken over many hours and on different days, and show there is room for improvement in future, particularly in the detection system.

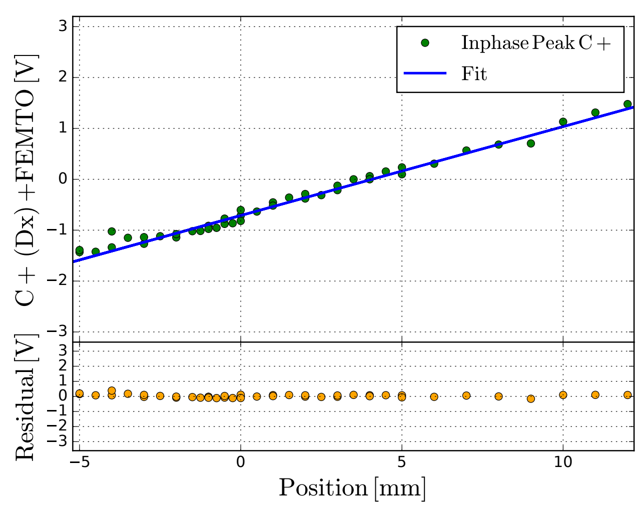
Due to the entirely optical nature of signal generation process, this technology has great potential as a diagnostic tool for high-radiation target beamlines, such as HiRadMat, where back-scattering effects can adversely impact conventional electronics. Even in this system due to the relatively close location of the acquisition system in the adjacent accelerator tunnel, the amplified channel C- exhibited electronic distortion in the time-profile baseline. In a future system design, the acquisition system is sufficiently separated from the beamline or target by a longer length of optical fibre to ensure a clean good-quality signal.



(a) Pre-amplified channel C-; −3.4 mV/mm



(b) Amplified channel C+; +174.7 mV/mm



(c) Zoomed-in amplified channel C+

Figure 6: Peak signal modulation against translation stage position z for a set of nominal intensity single-shot measurements.

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TU1I1

Table 1: Gradient, Standard Deviation of the Residuals and the Linearity Calculated for Each Beam Intensity Case and Channel

Single-shot Set case	Bunch Intensity	Gradient [mV/mm]	σ_{residual} [mV]	Linearity [µm]
Low-Intensity amplified C+	~ 7×10^{10}	107.8	49.2	460
Low-Intensity pre-amplified C-	~ 7×10^{10}	-2.1	1.1	520
High-Intensity amplified C+	~ 1.02×10^{11}	174.7	75.1	430
High-Intensity pre-amplified C-	~ 1.02×10^{11}	-3.4	2.2	650

CONCLUSION

The characterisation studies performed during the HiRadMat campaign that are reported here represent a major milestone in the development of the Electro-Optic Beam Position Monitor. For first time, complete sets of passing single bunches were successfully acquired combining interferometric optical modulations from opposite EO pickups. This approach achieved the first EO transverse beam position measurement. These results confirm that the new EO waveguide design has improved by two orders of magnitude the measured field with respect to the previous design, as predicted by electromagnetic CST simulations. Moreover, the anti-phase channel C- delivered a 3 GHz time-profile traces, achieving a bandwidth comparable with state-of-the-art electromagnetic head-tail monitor alternatives.

This in-air EO-BPM prototype system demonstrates sub-millimetric linearity over a wide translation range at the first attempt. In future, the optical power could be increased, the assembly process improved, and the acquisition system optimised to help approach the fundamental resolution expected from the pickup, and obtain a more symmetric response.

An in-vacuum EO-BPM design is currently in production and is planned to be installed in the SPS and tested during Run-3 of the LHC. This will enable further validation of the EO-BPM concept in an operational accelerator environment, and as a demonstrator ahead of implementation of multiple EO-BPMs for the HL-LHC era.

ACKNOWLEDGEMENTS

Work supported by UK STFC grants ST/N001583/1, ST/P00203X/1, Royal Holloway University of London & CERN. This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730. We would like to gratefully acknowledge the very useful assistance provided by Pascal Simon and the HiRadMat team.

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. Lefevre, "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, 2018.

[7] S. M. Gibson, A. Arteche, A. Bosco, S. E. Bashforth, M. Krupa and T. Lefevre, "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, S. E. Bashforth, A. Bosco, S. M. Gibson, M. Krupa, and T. Lefèvre, "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] Computer Simulation Technology, https://www.cst.com/