I.FAST

Innovation Fostering in Accelerator Science and Technology

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Electro-optic Performance Report

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ABSTRACT

During the first 24 months of the I.FAST project, a novel electro-optic waveguide sensor has been developed that is suitable for high-bandwidth beam position measurements of the electric field of a passing relativistic particle bunch. Following optimisation of the electromagnetic design, a pair of such waveguide sensors were manufactured and incorporated into a prototype Electro-Optic Beam Position Monitor at Royal Holloway University of London. The prototype was first bench tested and then shipped to CERN for a series of beam tests at CERN's HiRadMat and CLEAR facilities, to assess the signal sensitivity and time response respectively. The results of the beam test campaign are documented here.

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

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Delivery Slip

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Executive summary

The objective of Task 10.7 has been the development of electro-optic waveguide sensors for ultra-fast intra-bunch beam diagnostics. Following the design and manufacture of novel sensors based on lithium niobate waveguides in association with UK photonics industry, a prototype Electro-Optic Beam Position Monitor (EO-BPM) for in-air beam tests has been produced and bench tested at Royal Holloway University of London (RHUL).

This deliverable documents the experimental characterisation study of the prototype EO-BPM at CERN's HiRadMat and CLEAR beam test facilities. At HiRadMat, a transverse scan was performed within a ±20mm range at 3GHz bandwidth to explore the beam position sensitivity. At CLEAR the time response of the electro-optic waveguide sensor was assessed by measuring electron bunches with <50ps longitudinal profiles at 1.5GHz repetition rate, recorded via a 33GHz optical probe. The results show the beam position sensitivity and measured time resolution are within the design requirements. An in-vacuum design has been developed for future beam tests.

1 Introduction

Objective: Within the context of WP10, Advanced Accelerator Technologies, Task 10.7 aims to develop novel electric-field sensors, based on electro-optic waveguides to address new challenges in fast time response (<50 ps) beam instrumentation for the HL-LHC or any future accelerator bunch-by-bunch diagnostic where rapid response is required. Among those potential applications are the detection of crabbed-bunch rotation or as a higher bandwidth alternative to standard Head-Tail instability monitors.

This advanced accelerator technology has been realized by utilizing the ultrafast time response of electro-optic crystals to the electric field of a passing relativistic bunch. As polarized laser light propagates through a birefringent crystal the refractive index is modified by the Pockels effect, effectively creating a phase retardation that is the optical analogue of the longitudinal charge profile. By combining multiple signals interferometrically, the light intensity is monitored by a fibre-coupled ultrafast photodetector. While early background studies have focused on the use of bulk crystals, the I.FAST project has enabled the important development of electro-optic waveguides, which have proven to significantly enhance the signal sensitivity.

The electromagnetic and mechanical design was developed at RHUL using Computer Simulation Technology (CST) simulations of the pick-up to optimise the electric field strength at the waveguide and assess the time response. Custom waveguides were produced in collaboration with the UK photonics industry and optically inspected in the *SuperFab* nanofabrication cleanroom facility at RHUL prior to assembly into the mechanical pickup, as shown in Figure 1.

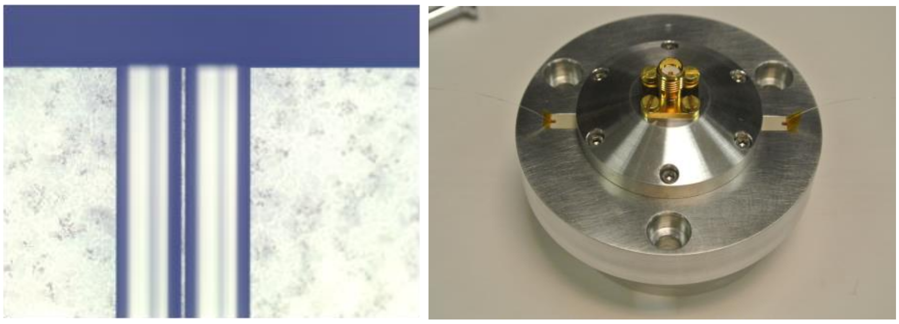

Figure 1 Left: Optical inspection of waveguide in RHUL clean room. Right: Compact fibre-coupled waveguide pick-up

Two opposing pick-ups were placed in a cylindrical coaxial line setup that enabled a fast electromagnetic signal to be sent to the pick-up mimicking the beam input. A fibre- coupled, narrow linewidth laser illuminated both pick-ups and the optical response was recorded as the signal was modulated. The light was conveyed via a splitter tree based on commercial bi-conic fused tapered couplers. The interferometric signals were detected by an array of fast (>10GHz) photodetectors and data were recorded using a vector network analyser to validate the frequency-response of each electro-optic pick-up. The completed prototype EO-BPM assembly is shown in Figure 2 during VNA bench tests at RHUL and at just prior to installation at CERN.

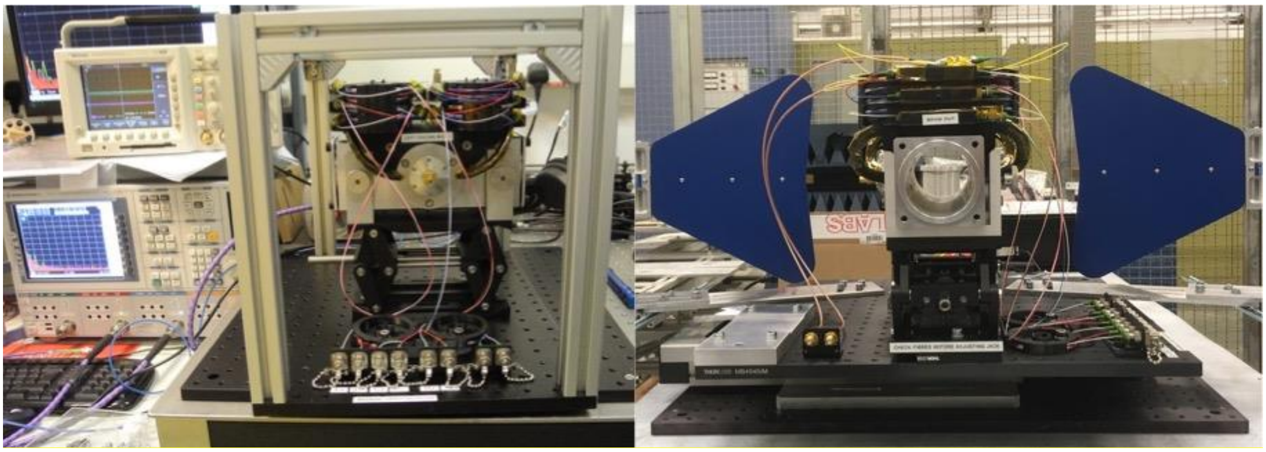

Figure 2 Left: the prototype waveguide EO-BPM delivered for VNA bench tests at RHUL. Right: ready for installation at CERN.

The scope of this deliverable is to report on the performance as evaluated during the beam test campaign of the prototype electro-optic beam position monitor at CERN's HiRadMat and CLEAR test facilities, described in the next sections.

2 Position Sensitivity Beam Tests at HiRadMat

2.1 Experimental setup

In July 2021 a prototype EO-BPM based on the fibre-coupled waveguide design was shipped to CERN and installed and tested at the HiRadMat facility. As an extraction line from the CERN Super Proton Synchrotron the proton beam parameters at HiRadMat were similar to the nominal LHC bunch parameters of $1.15 \cdot 10^{11}$ protons per bunch and $4\sigma \sim 1$ ns long bunches. In-air characterisation beam tests were performed for single-shots and for bunch trains. The aim was to validate the waveguide EO-BPM design under realistic beam condition and study the sensitivity to transverse position.

The relevant experimental hardware was installed in three locations shown in Figure 3: (a) the laser light source at the surface level in the BA7 HiRadMat control room, which is about 200m away from the second point (b), the TNC tunnel, where the EO-BPM was installed along the HiRadMat beamline; finally, the third point (c) is for the acquisition system placed in the adjacent shielded TT61 tunnel 20 m away from the EO-BPM installation.

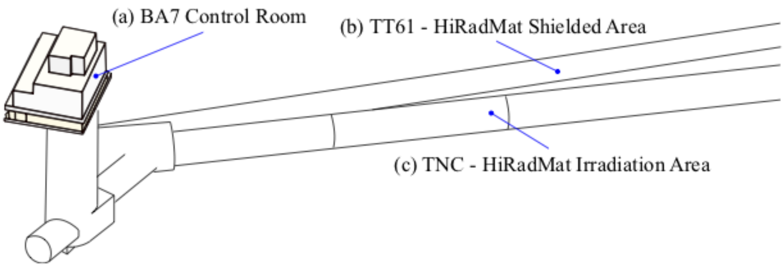

Figure 3: Experimental overview of HiRadMat facility

Light was conveyed between these three locations by optical fibre, as shown in Figure 4. A narrow linewidth 780nm laser-amplifier source was connected via 200m of Single Mode Polarisation Maintaining fibre (SM-PM) to the TNC tunnel, where the light is evenly split to illuminate both arms of the in-fibre Mach-Zehnder interferometer that is formed by two electro-optic waveguides located on opposite sides of the beamline. The interferometric optical difference signal is generated at the fibre-combiner and read-out for both in-phase and anti-phase. The split signals permit a check of opposite sign modulation and therefore confirm the interferometric nature of the beam signal.

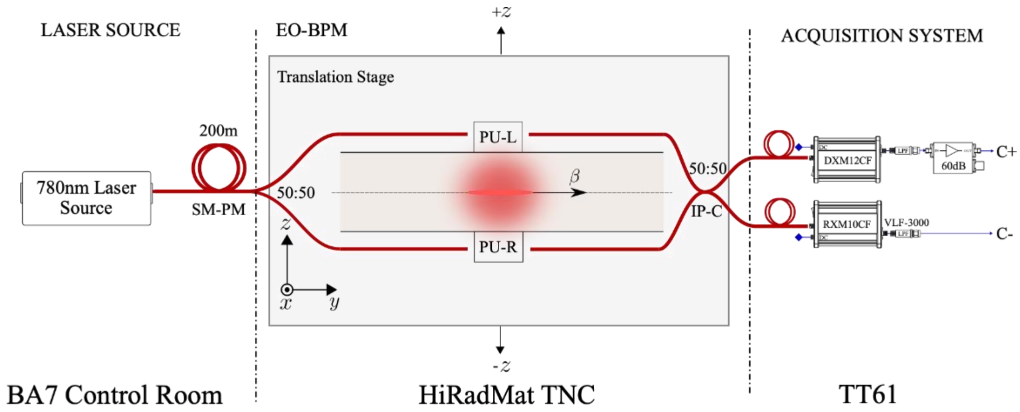

Figure 4: A simplified experimental setup showing locations of the laser source, the Mach-Zehnder interferometer that generates an optical different signal, and the two detectors at the in-phase and anti-phase fibre-coupled outputs.

The two electro-optic pick-ups were installed in the horizontal plane, on opposite sides of a 61mm diameter pipe that rested on a translation stage. The setup enabled precise transverse movement with respect to the extracted proton beam within a ±20 mm range. Positive offsets (+z) indicate the proton beam approaches the right pickup and negative values otherwise. Figure 5 shows the EO-BPM body on the translation stage installed in the HiRadMat beamline. Further details on the experimental setup and data acquisition system are described in [1].

Figure 5: The waveguide EO-BPM installed in the HiRadMat (TNC) facility at CERN for beam tests with single-shot bunch trains.

2.2 Transverse position tests

The left plot in Figure 6 represents the time-profile resulting from a single proton bunch extracted from the SPS on passing through the EO-BPM, while the translation stage was set to the -10mm position. As the bunch passed, a pair of in-phase C+ (green) and anti-phase C- (red) optical modulations were acquired. Despite being installed in a high radiation environment where most of the electronic equipment exhibited a great deal of distorting noise, the optical channels C+ & C- delivered a reasonably clean and good quality signals, especially in the pre-amplified channel C-. The amplitude of the signal peak was extracted via a fit to the data.

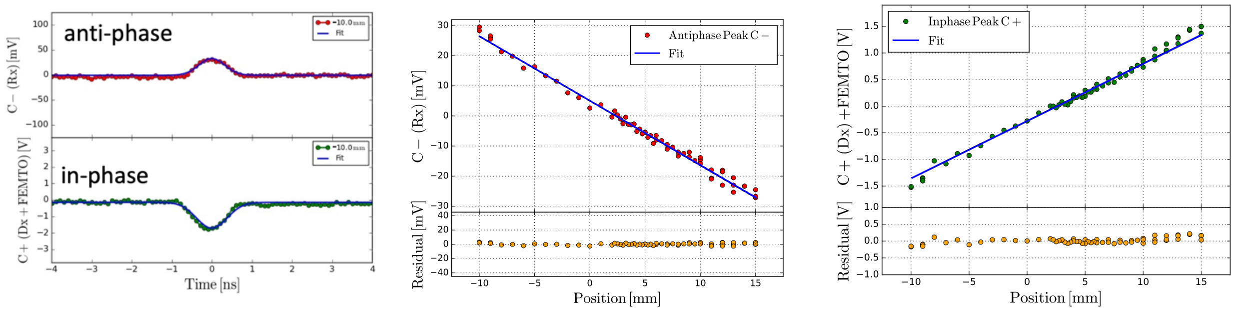

Figure 6 Left: Typical single-shot signals of waveguide pick-up. Middle and Right: Beam position scan by moving EO-BPM on stage for a set of low intensity single-shot measurements.

The middle and right plots in Figure 6 each show the same series of single-shot measurements as the translation stage was moved sequentially across the extracted particle beam. The intensity of ~7x 10^{10} protons per bunch for these measurements was lower than the nominal bunch intensity. 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, which was expected from bench tests of the individual pick-ups at RHUL.

An estimate on the upper limit on the transverse linearity over the full range of the fit was calculated for various bunch intensities [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.

3 Time Resolution Beam Tests at CLEAR

3.1 EXPERIMENTAL SETUP

In July 2022, the prototype EO-BPM was installed in the CLEAR beamline at CERN for additional beam tests to check the time resolution to short electron bunches. The setup for the EO-BPM was similar to that for the HiRadMat, except that only a single interferometric channel (C+) was measured, connected to a 33 GHz optical probe and corresponding Keysight UXR 33 GHz oscilloscope. This oscilloscope allowed the simultaneous detector of the working point of the electro-optic transfer function as well as the optical modulation. The EO-BPM was installed in the in-air section of the beamline on a translation stage to perform transverse beam measurements, as in Figure 7

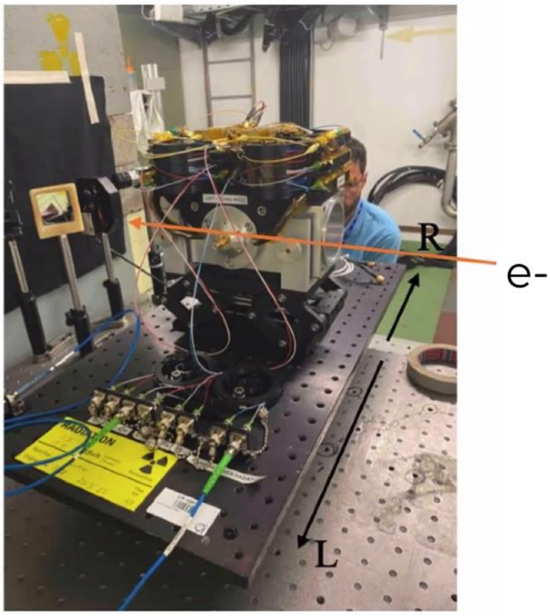

Figure 7: EO-BPM installed in in-air beamline of the CLEAR beam test facility

3.2 BUNCH TRAIN TESTS

Initial measurements of a train of 5 electron bunch pulses spaced by 666ps (1.5GHz) were observable at a photodetector, where the pulse width was limited by the bandwidth of the photodetection system, as shown in Figure 8. With an upgraded detector, the pulse width indicates the time resolution of the electro-optical waveguide sensor is within the <50ps specification required for the HL-LHC measurement of 1ns. These preliminary results together with an analysis of the HiRadMat data were presented in an invited talk at the International Beam Instrumentation Conference in Kraków, Poland in September 2022 [1].

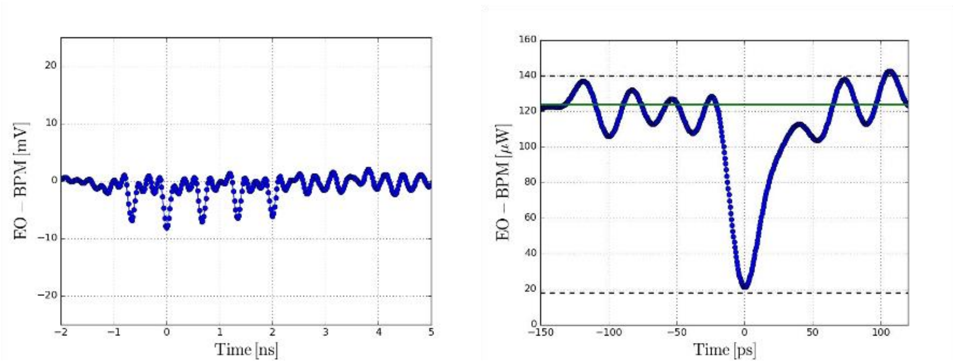

Figure 8: Left: Measured train of 5 electron bunches at CLEAR. Right: a single-shot, single pulse measurement at CLEAR.

4 Conclusion and outlook

The characterisation studies performed during the HiRadMat campaign that are reported here represent a major milestone in the development of an 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 bunch-by-bunch position measurements.

These results confirm that the new EO waveguide design enabled by the I.FAST programme, has significantly improved the measured field with respect to the earlier 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.

Furthermore, the measurement of <50ps electron bunches at CLEAR indicate a time resolution of the electro-optic is within the required specification to measure the intra-bunch profile of 1ns bunches at LHC or other hadron accelerators. 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.

5 Acknowledgements

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References

[1] Arteche, A., Gibson, S. M., Lefèvre, T., Levens, T., "Electro-optical BPM development for High Luminosity LHC", TU1I1, *11th International Beam Instrumentation Conference proceedings* 181-185, Sept 2022, Krakow, Poland. Jacow Publishing. doi:10.18429/JACoW-IBIC2022-TU1I1

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