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ENHANCED BUNCH MONITORING BY INTERFEROMETRIC ELECTRO-OPTIC METHODS

S. M. Gibson*, A. Arteche, S. E. Bashforth, A. Bosco,
JAI at Royal Holloway, University of London, UK
M. Krupa, T. Lefèvre, CERN, Geneva, Switzerland

Abstract

A prototype Electro-Optic Beam Position Monitor has been installed for tests in the CERN SPS to develop the concept for high-bandwidth (6-12 GHz) monitoring of crabbed-bunch rotation and intra-bunch instabilities at the High Luminosity LHC. The technique relies on the ultrafast response of birefringent $MgO:LiNO_3$ crystals to optically measure the intra-bunch transverse displacement of a passing relativistic bunch. This paper reports on recent developments, including a new interferometric electro-optic pick-up that was installed in the CERN SPS in September 2017; in first beam tests with nominal bunch charge, a corresponding interferometric signal has been observed. The interferometric arrangement has the advantages of being sensitive to the strongest polarization coefficient of the crystal, and the phase offset of the interferometer is controllable by frequency scanning of the laser, which enables rapid optimisation of the working point. Novel concepts and bench tests for enhancements to the pick-up design are reviewed, together with prospects for sensitivity during the first crab-cavity beam tests at the CERN SPS in 2018.

INTRODUCTION

Motivated by the need to monitor bunch rotation induced by crab-cavities at the High Luminosity LHC [1], an Electro-Optic Beam Position Monitor (EO-BPM) is being developed to measure the transverse shape of a proton bunch in a single pass [2]. The aim is to determine the mean transverse displacement along a $4\sigma \sim 1$ ns, nominal 1.15×10^{11} proton bunch, to detect the intra-bunch perturbations before and after the bunch crabbing and track the evolution of any residual instabilities in subsequent turns. The technique relies on the high bandwidth electro-optic (EO) response of MgO doped lithium niobate crystals, that essentially replace the electrodes in a capacitive button BPM. The phase and/or polarization state of light transmitted through each crystal is altered by the electric field of the passing proton bunch. By illuminating and reading out the EO-crystals via single mode fibres, the beam signal is conveyed optically to a fast photodetector in the rack room, thus dispensing with the bandwidth limiting hybrid electronics associated with electrostatic BPMs in the accelerator tunnel. The technique targets operational bandwidths of 6 – 12 GHz to access higher order modes of intra-bunch perturbation.

Project Status

A prototype EO-BPM was installed in the 4$^{\text{th}}$ sextant of the CERN Super Proton Synchrotron (SPS), as described in earlier studies [3, 4], and was placed adjacent to the existing Head Tail monitor [5]. First beam signals from the EO pick-ups of the proton bunch were observed in December 2016 using a *robust* configuration of the remote controlled analyzer optics [6, 7]. In 2017, an improved design of the pick-up demonstrated sensitivity to transverse displacement of the bunch via measurements of the vertical and horizontal SPS tunes [6]. In addition, coasting beam measurements have since demonstrated that a single pick-up signal is well correlated with deliberately induced lateral offsets of the beam position during dedicated tests at the SPS [7].

This paper reports on the design and implementation of a free-space interferometric pick-up that was installed in Sept. 2017 and a subsequent compact, fibre-interferometric design that was installed in Feb. 2018 in the vertical plane. The concepts of these new designs are presented, alongside electromagnetic simulations and analytic estimates of the expected signal enhancement based on prior beam and bench test results. The first beam signals from the interferometer are reported, together with prospects for sensitivity during beam tests in 2018, following the recent installation of a prototype crab-cavity in the SPS.

INTERFEROMETRIC EO CONCEPTS

Previous EO-BPM results [6, 7] were obtained from a *robust* optical configuration of the EO pick-up in which light incident on the xz face of the z-cut $MgO:LiNO_3$ crystal was linearly polarized at 45° to the x and z-directions. When the electric field $E_a(t)$ from the passing relativistic bunch is in the z-direction, the resulting electro-optic retardation is

$$\Gamma(t) = \frac{2\pi}{\lambda}(n_e - n_o)l + \frac{\pi}{\lambda}(n_e^3 r_{33} - n_o^3 r_{13})lE_{az}(t)$$

where n_e and n_o are the extraordinary and ordinary refractive indices of a crystal of length l in the propagation direction, with linear electro-optic coefficients, r_{33} and r_{13}. The first term is the static natural birefringence of the crystal, while the second term is the electro-optically induced birefringence and is proportional to the electric field. Note that the constant of proportionality depends on the difference between the cube of the refractive indices multiplied by their corresponding EO-coefficients. The retardation results in a polarization change of light emerging from the crystal which is converted to an intensity modulation after an analyser.

If instead the light incident on the crystal xz-face is linearly polarized in the z-direction, then the light remains linearly polarized as it propagates along the crystal and simply experiences a phase shift:

$$\phi(t) = \frac{2\pi}{\lambda}n_e l + \frac{\pi}{\lambda}n_e^3 r_{33} l E_{az}(t)$$

* stephen.gibson@rhul.ac.uk

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On interfering with light that bypasses the crystal the resulting phase modulation is enhanced compared to the *robust* case by a factor of $\frac{n_e^3 r_{33}}{n_e^3 r_{33} - n_o^3 r_{13}}$ for the same applied electric field. To benefit from this enhancement the SPS prototype was modified in Sept. 2017 by placing two polarizing beam splitters in front of one EO-pickup, as depicted in Fig. 1, such that light traversing the crystal was horizontally polarized, in the z-direction, while vertical polarization bypassed the crystal. The combined beams were analysed and the intensity modulation was recorded by a fast photodetector.

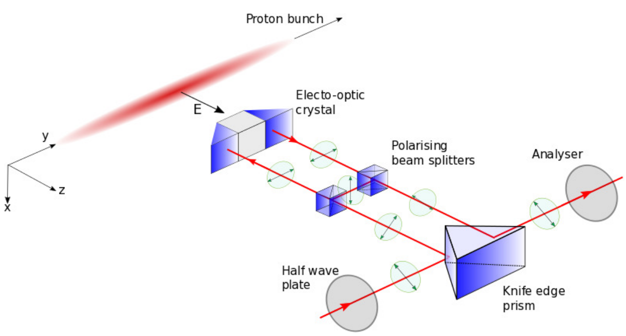

Figure 1: Free-space interferometer optical concept.

Alternatively a pair of fibre-splitters can be used to create an interferometer around one crystal as shown in Fig. 2. Note the simple arrangement presented here is for one pick-up only, however, in principle the concept is extendable to an interferometer that has crystals on opposite sides of the beam pipe in each arm of the interferometer, as proposed previously [2], to measure directly the difference signal between the two opposing pickups.

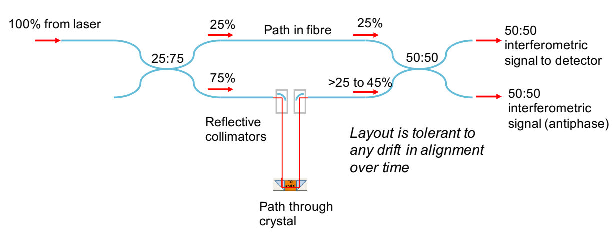

Figure 2: Compact fibre interferometer concept.

A third interferometric concept is to house two parallel crystals in one pickup, with the second crystal inverted so the sign of the electro-optic response is reversed to create a push-pull Mach-Zehnder interferometer. Similar to an electro-optic modulator, such a design doubles the effective phase modulation signal for a given length of crystal. A pick-up of this type has been manufactured and is intended for future beam tests at the CERN CLEAR facility.

MECHANICAL DESIGN

Free-space Interferometer Design

The original *robust* layout of the optical breadboard adjacent to one EO pick-up is shown in Fig. 3, including remote controlled optics to reconfigure and analyse the polarization states and optimise the fibre-coupling. The layout was modified as shown in the photographs to create the free-space interferometer concept sketched in Fig. 1.

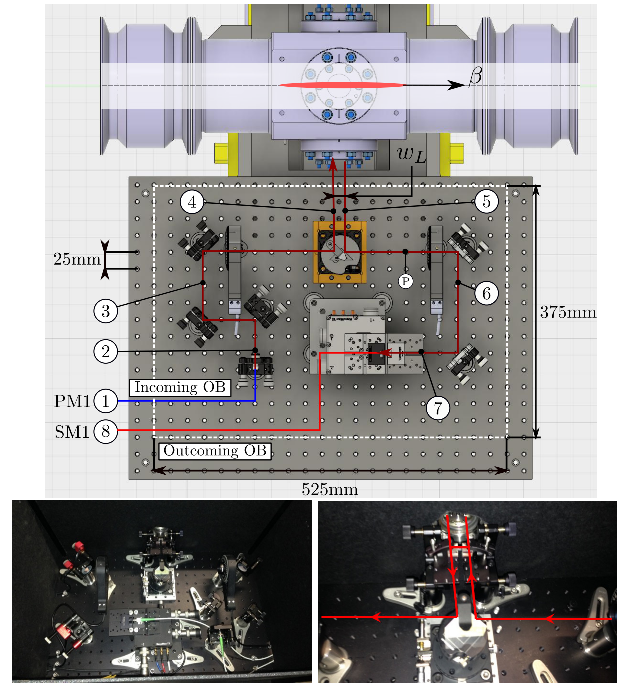

Figure 3: *Robust* optical layout of EO prototype at SPS [7] and modification with beam-splitters to generate a free-space interferometer around the EO-crystal.

Compact Interferometer Design

The concept in Fig. 2 was realised by a compact mechanical design in Fig. 4 that fits the fibre-coupled optical beam delivery system entirely within the outer dimension of a standard LHC BPM flange of diameter 114 mm. A custom sup-

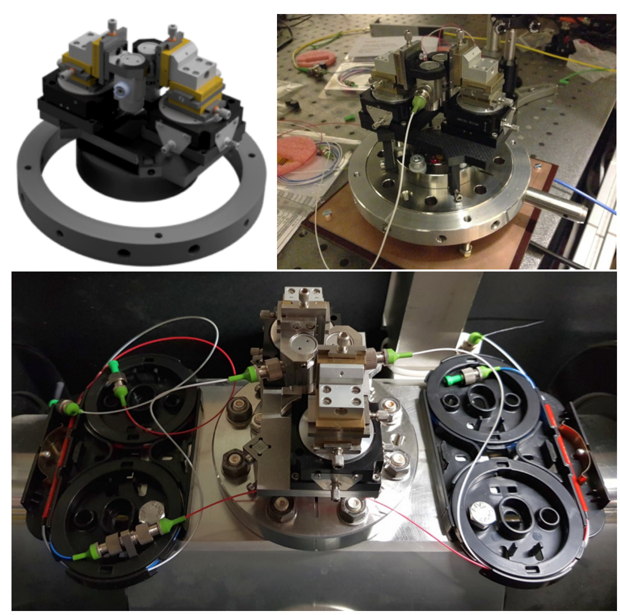

Figure 4: Mechanical design of compact interferometric EO pick-up with fibre-coupled optics, mounted for bench tests, and installed on the top flange of the EO-BPM in the SPS.

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port attached to the 70 mm diameter viewport flange holds two reflective fibre collimators, independently mounted on miniature translation and rotation stages to provide 6 degrees of manual adjustment in X,Y, Z, tip, tilt, and polarization axis, for each collimator. Alignment of the optics in the accelerator tunnel was quickly achieved and interferometric fringes were observed with good visibility during installation in Feb. 2018.

BENCH TEST AND BEAM RESULTS

The EO pick-up signal was validated by test bench measurements in which a voltage modulation was applied directly to the electrode, or the pick-up was in an electric field generated by a coaxial line. The EO signals from the test bench in Fig. 5 and from earlier beam tests were all found to be in good agreement with the prediction from electromagnetic simulations and analytic model [7].

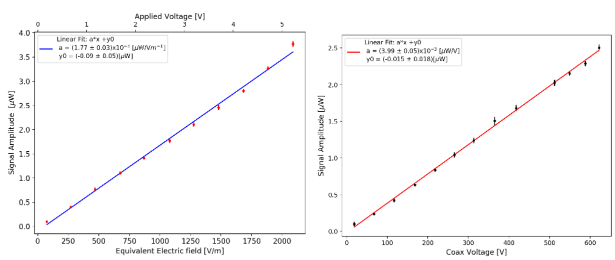

Figure 5: Linearity of EO signal amplitude due to voltage pulses applied directly to the electrode and via a coaxial line.

Free-space Interferometer Signal

First interferometric EO signal was observed in Sept. 2017 as in Fig. 6, which shows the multi-turn averaged response to a train of 16 bunches in the SPS. The sign and strength of the optical signal depends on the interferometer phase $\phi = \frac{2\pi}{c}\nu n_z' l$, hence by changing the laser frequency, ν, the working point is set to optimise the beam signal obtained. The single EO pick-up that was first tested interferometrically was the initial *variant 0* design with only a small 5 mm length crystal and no electrode [7], nonetheless a reasonable signal amplitude in response to the longitudinal bunch profile was observed in tests with the free-space interferometric setup.

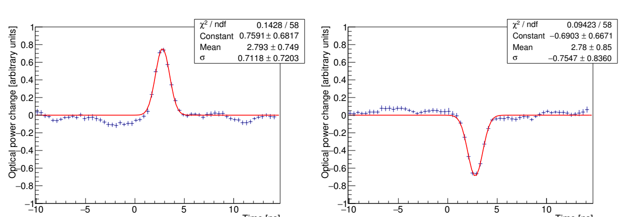

Figure 6: Response of the free-space EO interferometer to an average SPS bunch when the laser frequency was set at positive and negative working points.

Compact Interferometer Signal

An enhanced signal was observed in first beam tests of the compact interferometric setup in response to bunch trains for LHC scrubbing prior to acceleration in the SPS in April 2018. The pick-up was a *variant 1* design, with a 9 mm length crystal and electrode whereby a factor 8 improvement is predicted in simulation [7]. Fig 7 shows the averaged longitudinal bunch profile measured by the single EO pickup, for a sequence of laser frequencies, demonstrating the expected sinusoidal variation in signal amplitude as the working point is stepped through 2π in interferometer phase. The time resolution was limited by the amplifier bandwidth.

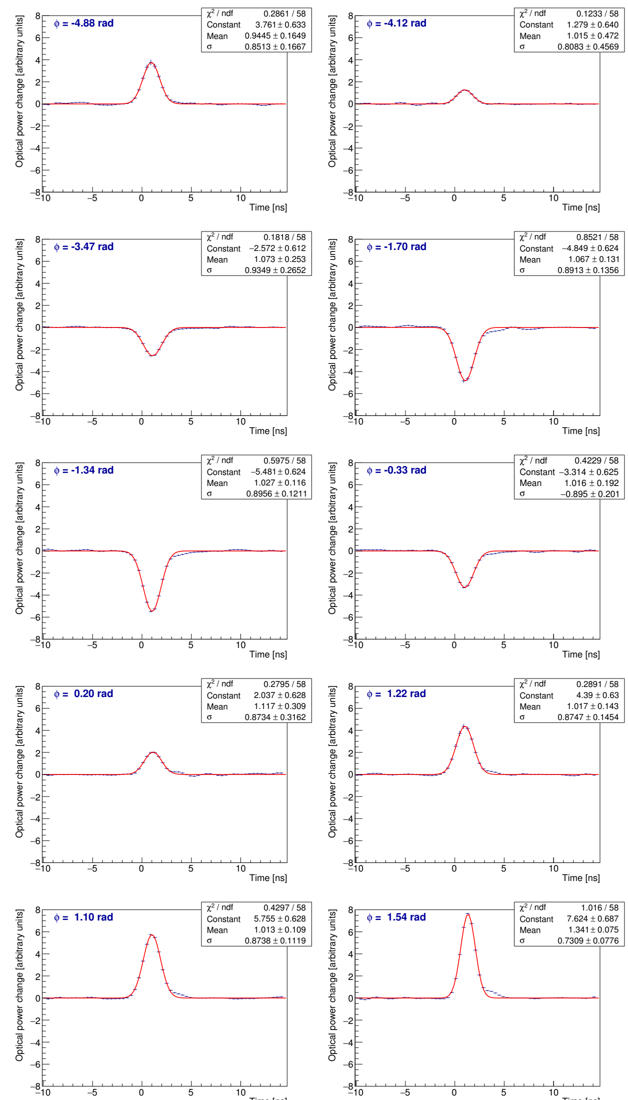

Figure 7: Optical response of the compact interferometer to an average SPS bunch as the laser frequency is scanned.

CONCLUSION AND OUTLOOK

A new design of electro-optic pick-up based on interferometry has observed first signal in response to nominal bunches in the SPS. The sensitivity of the flange mounted, compact setup is enhanced compared to earlier studies and demonstrates the expected variation with interferometer phase. In future an improved low noise, high bandwidth photodetector and amplifier will be tested at the SPS and a dual crystal interferometer will be characterised with short electron bunches at CERN's CLEAR facility to assess the timing resolution.

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