BEAM MEASUREMENTS AT THE CERN SPS USING INTERFEROMETRIC ELECTO-OPTIC PICKUPS

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Abstract

Since 2016 a prototype electro-optic pickup has been installed on the SPS as part of the ongoing development of a high bandwidth electro-optic beam position monitor for the High Luminosity LHC. Following the success of initial beam signal observations with the prototype, improvements of the sensitivity and stability of the pickup have become the main focus of the project. A new concept has been developed which uses an interferometric technique to measure the image field of a passing bunch. One arm of an interferometer passes through an electro-optic lithium niobate crystal, embedded in a pickup, whereas the other arm bypasses. The recombination after the pickup results in an interference pattern that changes as a bunch passes by, due to the electro-optic response of the crystal to the image field. This technique enhances the sensitivity to the field and improves control of the working point. Results from high intensity beams at the SPS are presented. These include a comparison between two different interferometric configurations that were tested on different pickups with similar beam conditions. The stability is assessed by frequency scanning interferometry during beam operation.

INTRODUCTION TO CONCEPT

The High Luminosity Large Hadron Collider requires high-bandwidth diagnostics to monitor the crabbed rotation of the proton bunches and to detect rapid, high order bunch instabilities [1, 2]. The solution being developed in the HL-LHC-UK collaboration between Royal Holloway and CERN is an Electro-Optic Beam Position Monitor (EO-BPM), which in essence is an electrostatic BPM that incorporates high bandwidth lithium niobate crystals placed between electrodes in the core of the pickup. As the relativistic proton bunch passes by an electro-optic pickup, the electric field is concentrated by the electrode to interact with the polarised light traversing the crystal by the Pockels effect. The analogue of the longitudinal bunch profile convoluted with the average transverse offset along the proton bunch is imprinted in the phase modulation of light passing through the crystal. In the SPS prototype results presented here, the phase of the modulation of light in the output fibre is transformed into an intensity modulation by combining with an optical path through a second fibre that bypasses the crystal, enabling the rapid beam signal to be recorded by a remote fast photodetector [3].

This paper reviews various optical configurations that have been tested at the CERN SPS and presents new electromagnetic simulations based on an upgraded pickup design that is planned to be installed at the LHC for tests during Run-III.

EO-BPM OPTICAL CONFIGURATIONS

Crossed Polarisers

A variety of electro-optic layouts have been investigated in simulation and experiment, and for each configuration the strength of the optical modulation has been assessed. A standard Crossed Polarisers (CP) configuration was employed in the first EO-BPM prototype that was installed and tested in the CERN SPS in 2016 and 2017, which measured the first proton-induced EO signal from a single pickup [4–6]. This arrangement replicates an amplitude modulator where a linearly polarised laser beam is oriented at 45° as it approaches a vacuum-integrated LNB crystal within the pickup, and may be considered as split into two horizontal and vertical component paths through the crystal. Both components are phase-retarded by different amounts due to the crystal birefringence, changing the polarisation, typically to an elliptical state, and where the axes are modified by the passing beam and detected by an analyser oriented perpendicularly to the first one, at −45°.

Single Crystal Interferometer

Soon after the proof of concept delivered by the CP configuration, the optical layout evolved towards the more sensitive (×1.45) Single Crystal Interferometric (SCI) design shown in Fig. 1. In this case, the laser beam is linearly polarised along the entire optical path through the crystal and is typically parallel to the extraordinary refractive index n_e. The optical

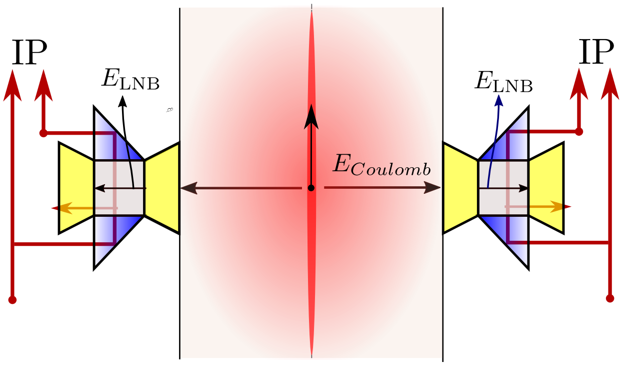

Figure 1: Single Crystal Interferometric layout.

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ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-WEAO04

modulation is produced at the Interaction Point (IP) by the phase difference between a crystal-modulated beam and a non-retarded path bypassing the pickup, which essentially creates an interferometer with the crystal in one arm (Figs. 2 and 3). A large, free-space arrangement was initially beam tested in September 2017, when the first interferometric single pickup signals were obtained [7]. An upgraded version with a fibre-coupled compact setup mounted on the upper flange of the EO-BPM prototype was tested in April 2018. These prototype tests at the CERN SPS have demonstrated the mechanical stability of a fibre-coupled interferometer during beam operation, and have confirmed the crucial advantage that the working point of the interferometer can be controlled by tuning the frequency of the laser [7].

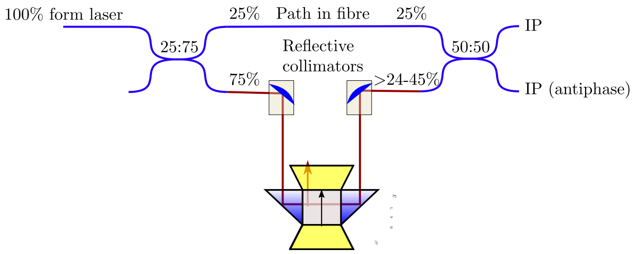

Figure 2: Optical layout for the fibre-coupled, single crystal interferometer (SCI) setup.

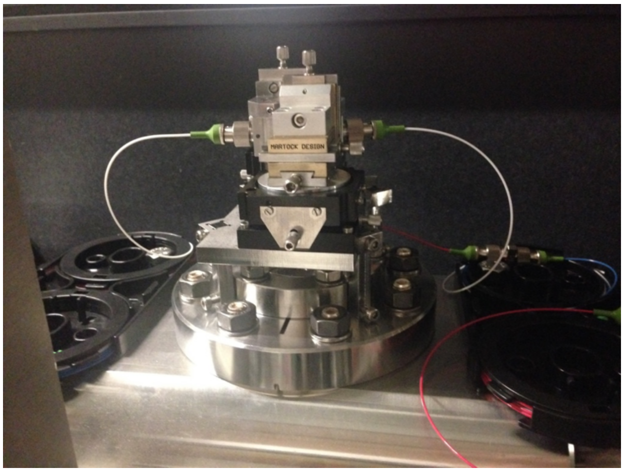

Figure 3: A compact, flange-mounted, fibre-coupled interferometric EO-pickup installed at the CERN SPS.

Double Crystal Interferometer

For the HL-LHC design, a Double Crystal Interferometric (DCI) solution has been proposed, which replicates a Mach-Zehnder layout in which an second, equally long L_y LNB crystal is now placed in the unmodulated arm of the SCI configuration, in the manner shown in Fig. 4. In this way, the two arms of the interferometer go through different crystals located in opposing pickups; thereby both optical paths are phase-retarded by the same extent as the particle beam moves transversely but with opposite signs, doubling the effect with respect to the SCI method (×2) [8]. Moreover, the interferometric combination of signals from opposing pickups is such that the longitudinal bunch profile (the sum signal) is optically cancelled, while preserving the difference signal.

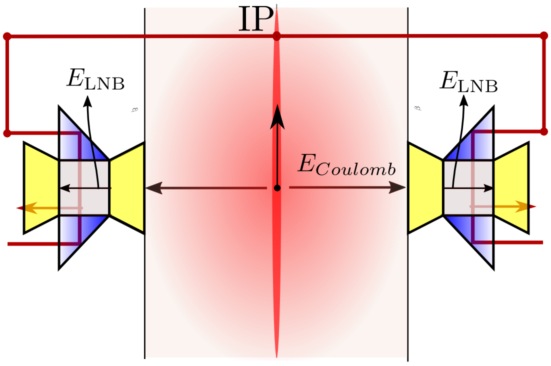

Figure 4: Double Crystal Interferometric layout.

BEAM TEST RESULTS

SPS Prototype Design

After the initial SCI tests described in the preceding section, further measurements that were taken in November 2018 are now presented. The detection system was upgraded, which allowed us to obtain a significantly enhanced signal at higher bandwidth from the top compact setup and also the first simultaneous detection from opposing pickups on the horizontal plane of a passing beam.

The optical modulation carried by the single mode fibres was transformed into an electric signal by a > 10 GHz, < 30 ps rise time ALPHALAS UPD-30-VSG-P photodetector and then AC decoupled before amplification. The fast changing signal induced by the proton beam was readout by an 0.01 − 2 GHz wideband, low noise amplifier chain with 62 dB total gain, and 8-bit oscilloscope.

Stability Assessment

In the absence of a modulating field, the SCI phase offset ϕ_0 exhibited by an optical beam of wavelength $\lambda = \nu / c$ across a LNB sample of length L_y is

$$\phi_0 = \frac{2\pi\nu}{c} n_e L_y \,, \tag{1}$$

where ν is the laser frequency and c is the speed of light. The 780 nm New Focus TLB-6800 laser source allowed us to perform sensitivity frequency scans by shifting very finely the wavelength. Figure 5 shows the interference fringes generated by the top fibre-coupled compact system as the frequency is cyclically scanned over a short range.

This pattern characterises the performance of the system since the working point is found when ϕ_0 is such that the intensity modulation is at the centre of the fringe amplitude. This is the most sensitive point whereas the fringe maxima and minima correspond to points of almost zero response to the modulating field. In addition, a wavemeter was integrated in the acquisition system to monitor the laser wavelength while the frequency scans were performed.

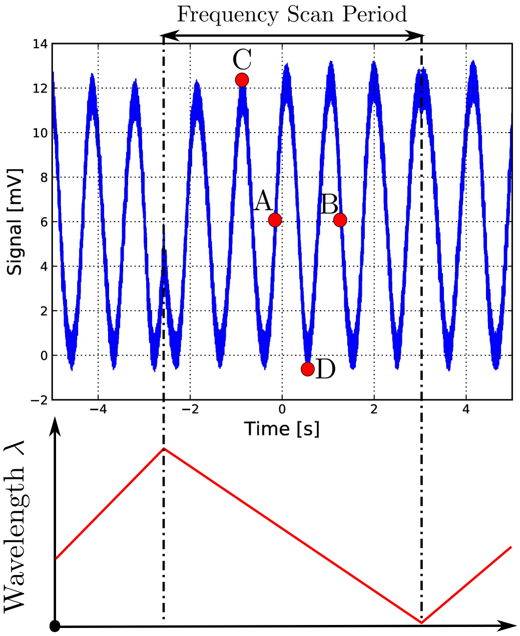

Figure 5: Interferometer intensity modulation as the frequency is scanned. Points A and B are sensitive working points that produce modulations of opposite sign; points C and D are non-sensitive points that produce no optical modulation.

According to Equation 1, the offset ϕ_0 depends on the laser frequency ν and should remain constant in absence of a modulating field (n_e = cte). However, the crystal length L_y may be subject to minimal changes that could potentially lead to an offset shifting, and therefore a sensitivity drift.

Beam Test Results

Figure 6 shows a set of interferometric signals delivered by the fibre-coupled compact setup installed on the top pickup. The acquisition was obtained under AWAKE beam conditions, similar to the LHC nominal bunch, averaging less than 80 sweeps with the new amplification system described previously.

This study was performed at relevant points along the interferometric fringes shown in Fig. 5 to study the sensitivity response. The positive and negative signals correspond to opposite optical modulations, in ascendant and descendent points of the interferometric fringe, as the working points A and B shown in Fig. 5. In contrast, the absence of signal in the middle graph corresponds to data taken at the fringe maximum or minimum (point C or D in Fig. 5), and therefore does not show any response at all as the beam passes.

DESIGN FOR LHC

Although the key concept for the EO interferometric detection has been demonstrated, a significant upgrade is planned for the Hi-Lumi LHC design. In particular, the geometry formed by the LNB sample, the electrodes, and the ceramic insulator has been further optimised to increase significantly the modulating field inside the crystal. Electromagnetic simulations were carried out in CST particle studio to determine the most efficient geometry while keeping both the thermal load in the ceramic piece and the impedance minimal [9].

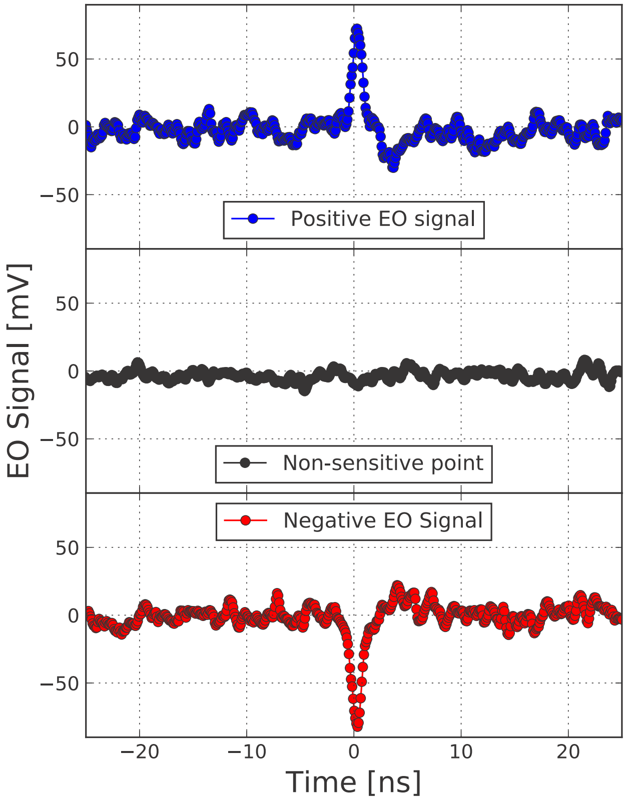

Figure 6: Enhanced EO signal at different working points.

A simpler mechanical design of the EO button has been proposed as shown in Figs. 7 and 8, in which the shape of the electrodes had been optimised to channel the propagating Coulomb field into the crystal, with reduced crystal of dimensions of $(L_x, L_y, L_z) = (1.0\,\mathrm{mm}, 9.0\,\mathrm{mm}, 0.3\,\mathrm{mm})$. In this configuration, the innermost electrode surrounded by the alumina insulator is brazed on a vacuum flange, such that the crystal and the fibre coupling optics can be placed outside of the vacuum.

With this new design, CST simulations (see Fig. 9) indicate that the modulating image field delivered into the crystal would reach up to 80 kV/m for a $L_z = 300\,\mu\mathrm{m}$ thick crystal, which is an increase factor of ~28 compared to the SPS EO prototype, with a direct improvement on the signal-to-noise. This improvement in field strength brings the calculated optical phase modulation to levels that are similar to the fraction of transfer function achieved in a commercial electro-optic modulator. In addition, the detection system will be upgraded so the saturation power can be increased 20 times from approximately 1 mW as up to 20 mW, making the total factor about ~560.

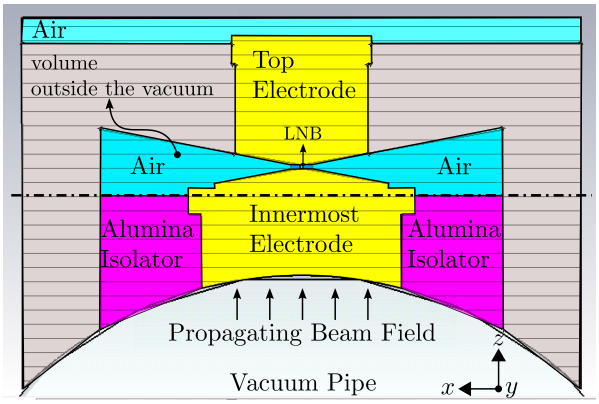

Figure 7: Transverse view of the CST simulation.

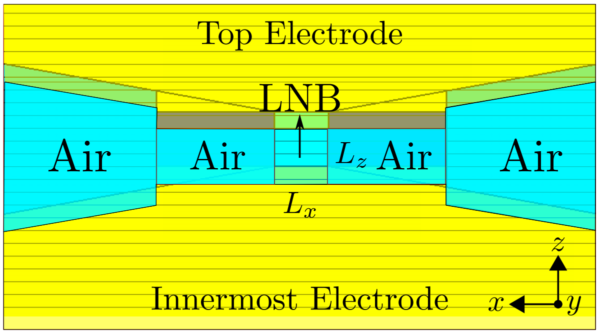

Figure 8: Zoomed view section of the CST simulation.

Furthermore, the configuration of the EO-BPM for HL-LHC will be upgraded according to the DCI layout shown in Fig. 4. This strategy adds an extra factor 2 with respect to the SCI results presented in this paper, giving an overall improvement factor above 1000.

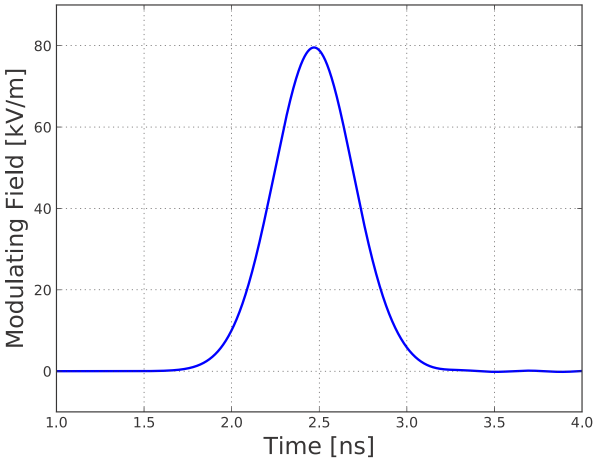

Figure 9: Modulating field time-profile inside the crystal according to the CST simulation for a $L_y = 300\,\mu\text{m}$ thick crystal.

CONCLUSION

The studies performed in the EO pickup prototypes installed in the CERN SPS during the 2017 and 2018 runs demonstrated the working principle of the beam detection by interferometric EO means for first time. Furthermore, the crucial mechanical stability was successfully tested and very importantly, the wavelength tunability proved to be an efficient way to prevent the system from sensitivity drifts caused by interferometric length variations.

The studies towards an LHC design are progressing well with significant improvements in sensitivity expected using a new design of the EO button, a more sensitive detection system and higher optical power.

The next phase of the project aims at implementing this new design as a full EO-BPM demonstrator, foreseen to be tested in the LHC during Run-III.

ACKNOWLEDGEMENTS

Work supported by UK STFC grants ST/N001583/1, ST/P00203X/1, Royal Holloway Univ. of London & CERN.

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