HIGH FREQUENCY ELECTRO-OPTIC BEAM POSITION MONITORS FOR INTRA-BUNCH DIAGNOSTICS AT THE LHC

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Abstract

At the HL-LHC, proton bunches will be rotated by crab-cavities close to the interaction regions to maximize the luminosity. A method to rapidly monitor the transverse position of particles within each 1 ns bunch is required. A novel, compact beam diagnostic to measure the bunch rotation is under development, based on electro-optic crystals, which have sufficient time resolution (< 50ps) to monitor intra-bunch perturbations. The electro-optic beam position monitor uses two pairs of crystals, mounted on opposite sides of the beam pipe, whose birefringence is modified by the electric field of the passing charged particle beam. The change of birefringence depends on the electric field which itself depends on the beam position, and is measured using polarized laser beams. The electro-optic response of the crystal to the passing bunch has been simulated for HL-LHC bunch scenarios. An electro-optical test stand including a high voltage modulator has been developed to characterize $LiTaO_3$ and $LiNiO_3$ crystals. Tests to validate the different optical configurations will be reviewed. The opto-mechanical design of an electro-optic prototype that will be installed in the CERN SPS will be presented.

MOTIVATION

HL-LHC Crab-Cavity Bunch Rotation

An ambitious High Luminosity upgrade of the Large Hadron Collider will increase the luminosity by a factor of ten. The proton bunches will be rotated by crab-cavities placed before and after the interaction regions, so that the bunches collide head-on to reduce the overlap area and maximize the luminosity. Optimising the performance of the crab-cavities at the HL-LHC requires new instrumentation that can perform intra-bunch measurements of the transverse position of particles within a 1 ns bunch. Conventional electrostatic stripline BPMs are fundamentally limited to a few GHz bandwidth and take up valuable space close to the interaction region. A novel, compact beam diagnostic to measure the bunch rotation is under development, based on electro-optic crystals, which have sufficient time resolution (<50 ps) to monitor intra-bunch perturbations.

Head-tail Instability Monitors

A high-frequency monitor is also necessary to detect intra-bunch instabilities on a turn by turn basis. At the SPS and LHC, *head-tail* (HT) monitors are the main instruments to visualise and study beam instabilities as they occur [1]. The present HT monitors are based on stripline beam position monitors and fast sampling oscilloscopes [2]. Recent measurements reveal low order modes as shown in Figure 1. However the HT monitors only offer a bandwidth up to few GHz limited by the pick-up, cables and acquisition system. Novel pick-ups based on electro-optical crystals and laser pulses [3, 4] have already demonstrated response times in the picosecond range [5], making this technique a promising candidate to achieve higher resolutions to improve the HT monitors capacity to solve bunch shapes and instabilities.

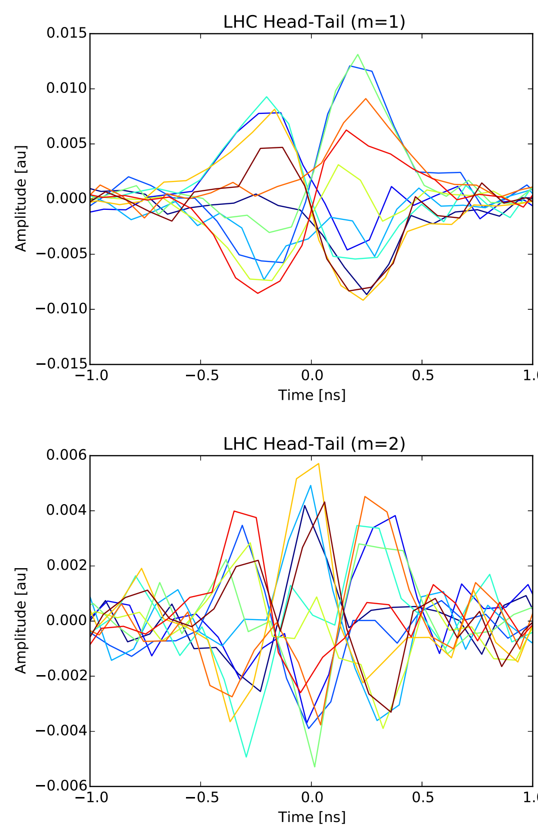

Figure 1: Mode 1 and 2 bunch instabilities recorded with a stripline BPM HT monitor in August 2015 at the LHC.

EO-BPM Project Aims

The above considerations have stimulated a collaboration between the CERN Beam Instrumentation group and Royal Holloway, University of London (RHUL) to develop novel beam diagnostics based on electro-optical crystals, which have sufficient time resolution to monitor intra-bunch perturbations. The aim is to develop a prototype electro-optic Beam Position Monitor (EO-BPM) that will be initially tested to monitor intra-bunch instabilities in the CERN SPS. Success would validate their use as a future diagnostic tool for the HL-LHC to monitor crab rotation of the bunches.

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EO-BPM CONCEPT AND DESIGN

Electro-Optic Beam Position Monitor Concept

The concept of using electro-optic crystals to monitor beam position has been previously proposed [3–7]. The general technique is to exploit the Pockels electro-optic effect, which has a linear dependence on the applied electric field. An electro-optic beam position monitor (EO-BPM) is essentially a conventional button-BPM, in which the pick-ups have been replaced with electro-optic crystals. Each axis of the EO-BPM uses a pair of crystals, mounted on opposite sides of the beam pipe, whose birefringence is modified by the electric field of the passing charged particle bunch. The change of birefringence depends on the electric field which itself depends on the bunch position, and can be measured using polarized laser beams.

Design and Optical Configuration

In designing the EO-BPM for the SPS/LHC, several configurations of the crystal type, cut, the light propagation direction, polarizer/analyser orientation and electric field were considered. The challenge is to tune these parameters to ensure the best time and positional resolution is achieved for the LHC bunch. Two configurations were selected for experimental investigation as shown in Figure 2. Both options are fibre-coupled so that the laser and detection system can be housed in a remote counting room, 160 m from the accelerator tunnel.

(a) Polarizer-analyser per pick-up Light from a laser in the counting room is conveyed via optical fibre to a vacuum feedthrough in the BPM flange, where the divergent beam is collimated by a GRIN lens. The light passes through a polarizer, reflects into an electro-optic crystal and emerges through an analyser, before being coupled back into fibre and the signal is recorded by a remote photodetector. As the particle beam passes, the electric field across the crystal induces a rotation in the polarization, which creates an intensity change at the detector. The light travels parallel to the particle beam to aid phase matching with the electric field of the relativistic bunch. The pick-ups are independently read-out and the difference and sum signals are determined by electronic signal processing, like a conventional BPM. This layout has the advantage of a simple robust design, however, the full signal due to the charge of the passing bunch must be covered by operational range of the photodetector.

(b) Interferometric design An alternative arrangement proposed here is based on a fibre-coupled interferometer that uses electro-optic phase modulation to monitor the bunch position. Coherent light is exploited to optically suppress the common mode signal, such that the detector directly measures the difference signal between the two pick-ups. The potential advantage of this layout is to improve the positional resolution by using the full dynamic range of the detector to record the optically generated difference signal. A free-space interferometric design was originally considered in earlier studies, but was ruled out due to the thermal stability and alignment requirements across the mechanical BPM body [8]. However, the stability tolerance may be improved by using short and equal lengths of optical fibre between the fibre-splitters and BPM, with similar routing, such that common thermal fluctuations cancel in the difference signal. The fibres should also be of equal length, so that the arrival time of the light at both pick-up is synchronized to interact with the same time-slice of the charged particle field.

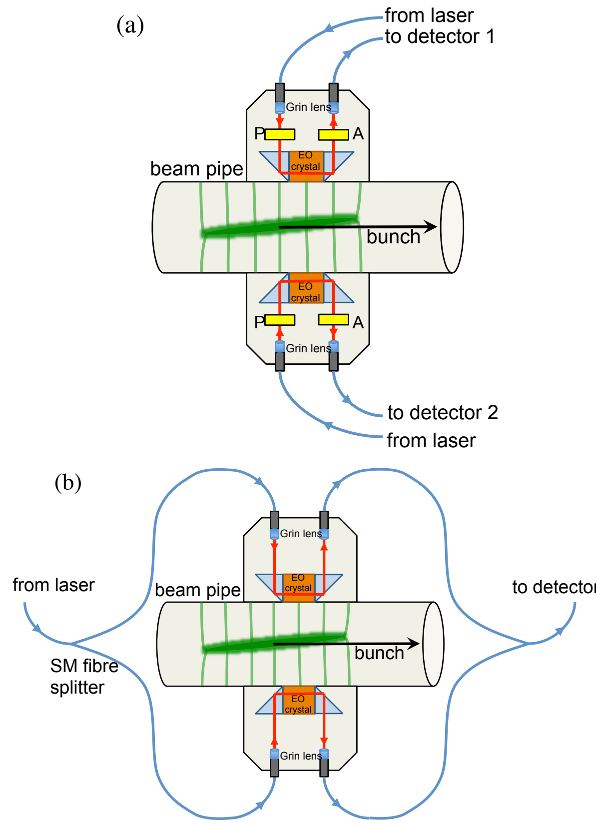

Figure 2: Two optical configurations are investigated for a fibre-coupled electro-optic beam position monitor: (a) a polarizer-analyser per pick-up; (b) a phase-modulated interferometric design.

Detection and Acquisition Scheme

The signals generated by the two configurations have been simulated, as detailed in the next section. In both cases, Metal-Semiconductor-Metal (MSM) photodetectors are envisaged, owing to their <30 ps rise time and the polarity independent biasing facility [8]. One option is to directly acquire the MSM signal with a high speed digitizer. At the required analogue bandwidth of 6-12 GHz, however, the effective number of bits is at best ∼6, which limits the transverse positional resolution, especially in the P-A configuration. A related development is the multiband-instability-monitor (MIM) [9] that uses frequency domain analogue pre-processing to achieve higher resolutions than direct sampling. The MIM would benefit from the additional frequency range that the eo-pick-up has over traditional striplines [10].

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SIMULATION OF EO-BPM SIGNALS FOR LHC BUNCH PARAMETERS

A computer model has been developed to study the optical response of the electro-optic pick-up to a transversely perturbed relativistic bunch. The input parameters to the simulations are summarised in Table 1 and the simulations involve three main steps:

1. The time profile of the transverse electric field generated at the radial position of each eo-crystal is calculated for the relativistic perturbed bunch.

2. The electro-optic response to the electric field is calculated using the crystal parameters and wavelength, for each optical configuration.

3. A simple difference signal is calculated for the polarizer-analyser setup, or the interference signal is calculated.

A transverse offset is first applied along the particle bunch according to the shape of the instability mode as in Figure 3a. The contributions from slices of the relativistic Gaussian charge distribution are then summed to calcualte the electric field at each pick-up, as in Figures 3b and 3c. The difference signals generated in a model of the crystal response for the polariser-analyzer and interferometric configurations are plotted in Figures 3d and 3e respectively.

Both optical configurations are sensitive to the instability modes. In the P-A setup, however, the photodetector must capture the full Gaussian signal of the passing bunch charge distribution, whereas the interferometer is directly sensitive to the difference signal. For the maximum crystal length of 20 mm taken in these simulations, this results in some non-linearity at large amplitudes (see e.g. mode-0) in the P-A setup, because the polarization change exceeds the linear region of the sinusoidal intensity variation. This non-linearity can be reduced by selecting a shorter crystal, albeit with a corresponding reduction in the sensitivity. In contrast, the interferometer signal exhibits no non-linearity at these amplitudes, because it is sensitive to the phase difference between the two crystals.

The P-A setup measures both pick-ups independently, so it is possible to compute a difference over sum normalization. The interferometer setup can be improved by adding a fur-

Table 1: Input Parameters to the EO-BPM Simulation

LHC bunch intensity	1.15×10^{11}	protons per bunch
Bunch length 4σ	1.0	ns
SPS beam energy	450	GeV
Instability modes	0, 1, 2 & 6	
Instability amplitude	0 to 2.5	mm
Pick-up radius	40	mm
Laser wavelength	632.8	nm
Crystal type	$LiNiO_3$	[also $LiTaO_3$]
Crystal length	1, 5, 10, **20**	mm

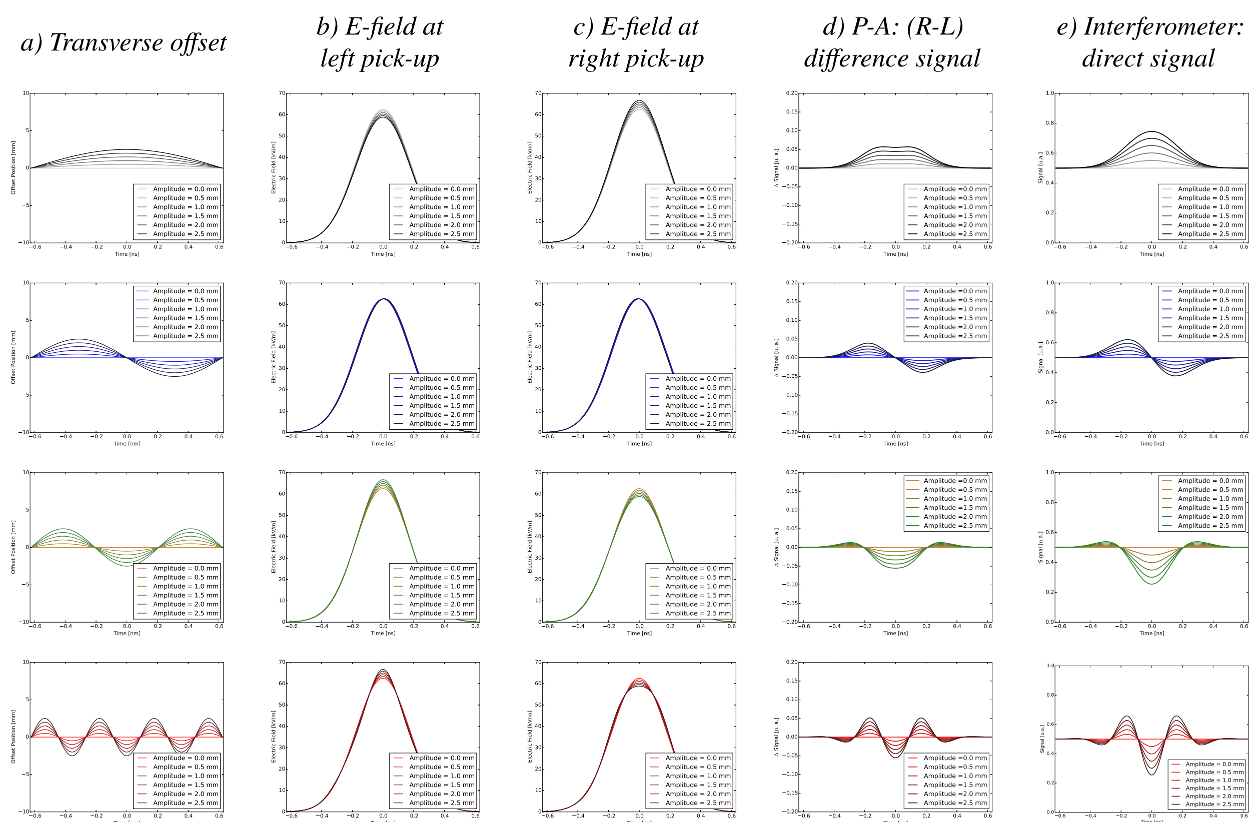

Figure 3: Simulation of EO-BPM response to bunch instability modes 0, 1, 2, and 6.

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ther fibre-splitter after each crystal, before the combiner, to enable the phase modulation of each crystal to be measured independently, as well as the optically generated difference signal. Both configurations will be evaluated experimentally as described in the next sections.

CRYSTAL CHARACTERISATION EXPERIMENTAL RESULTS

Electro-Optic Theory and Crystal Choice

The eo-crystals investigated are $LiNbO_3$ and $LiTaO_3$, which are uniaxial crystals with excellent electro-optic coefficients and are related to Al_2O_3, known to be fairly radiation tolerant[1]. In a z-cut $LiNbO_3$ [or $LiTaO_3$] crystal, with light propagating in the x-direction the principle refractive indices under an applied electric field along z are

$$n'_y = n_o - \frac{1}{2} n_o^3 r_{13} E_{az} \quad (1)$$

$$n'_z = n_e - \frac{1}{2} n_e^3 r_{33} E_{az}, \quad (2)$$

where the ordinary and extraordinary refractive indices are $n_o = 2.29[2.19]$ and $n_e = 2.21[2.18]$ (at 633 nm), and the dieletric tensor elements are $r_{33} = 30.9[30.5]$ pm/V and $r_{13} = 9.6[8.4]$ pm/V. The eo-crystal response is characterised by the half-wave voltage,

$$V_\pi = \frac{\lambda}{r_{33} n_e^3 - r_{13} n_0^3} \frac{d}{L}, \quad (3)$$

where the wavelength λ, crystal height d and length L, are free parameters to be selected. $LiTaO_3$ is less prevalent than $LiNiO_3$, but has a slightly better V_π for equivalent crystal dimensions and is more robust, with a higher density, melting point and damage threshold.

Experimental Validation

Samples of $LiNbO_3$ and $LiTaO_3$ crystals have been characterized with a high voltage (HV) modulator and optical test stand at Royal Holloway, as shown in Figure 4. The setup allows linearly polarized light to be directed onto the crystal face, while HV is applied across the crystal, and the throughput light intensity is recorded after an analyser. The polarizer and analyser have their orientations controlled by automated rotation stages, enabling the polarization state at any voltage to be assessed.

Tests were initially conducted at $\lambda = 532$ nm, to reproduce earlier tests at CERN [7], in which the wavelength was selected from considerations of the sensitivity and dispersion. An intensity modulation with HV was achievable, however, it was found that the photorefractive effect dominates at this wavelength, even when a MgO doped $LiNiO_3$ was used. To avoid this region, tests were performed with a HeNe laser, $\lambda = 632.8$ nm, at which the refractive index still implies a good sensitivity. An example HV scan at 632.8 nm is shown in Figure 5 and the fitted $V_\pi = 1410 \pm 19$ V is in good agreement with the predicted value of $V_\pi = 1398.2$ V.

[1] the radiation tolerance of the selected crystal will be assessed.

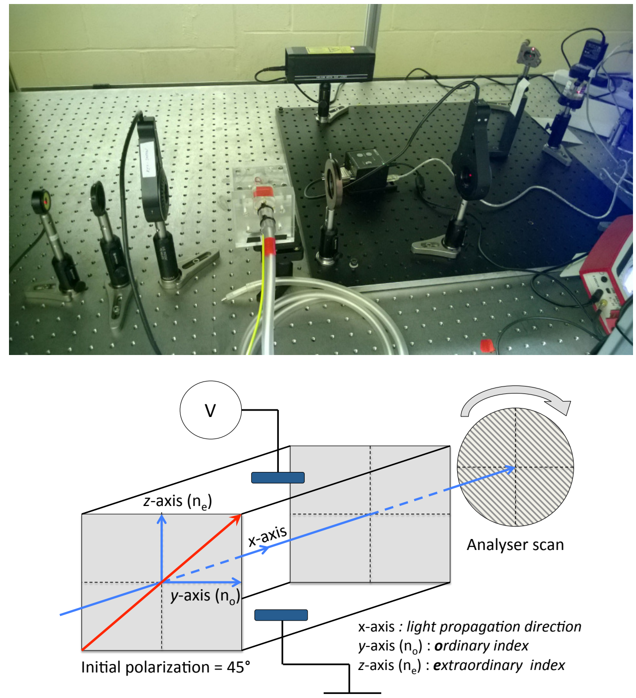

Figure 4: Crystal characterisation test stand and configuration of the e-o crystal. Linearly polarised light incident at 45° on the crystal is rotated when high-voltage is applied.

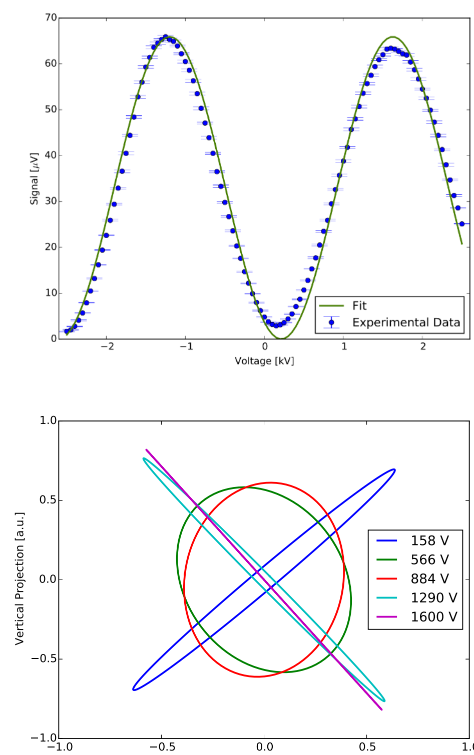

Figure 5: HV scan of a z=5 mm, x=10 mm, MgO:$LiNiO_3$ crystal. The polarization state at key voltages is analysed.

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A PROTOTYPE EO-BPM FOR CERN SPS

A beam test of a prototype EO-BPM is planned in the CERN SPS, with the dual aim of validating the electro-optic pick-up with the LHC bunch parameters and monitoring SPS bunch instabilities. Space has been reserved for the EO-BPM prototype at SPS point 4, close to the existing head-tail monitor stripline BPM, so it can be used for cross-checks. The opto-mechanical layout of the EO-BPM has been designed [11] and is shown in Figure 6.

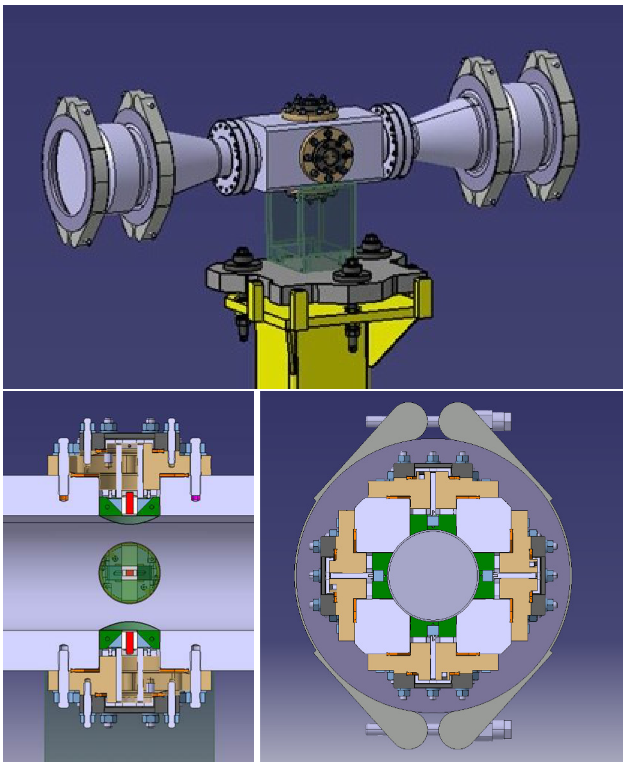

Figure 6: Preliminary opto-mechanical design of a prototype EO-BPM, planned for installation the SPS at CERN.

The design is based on a CERN standard BPM body that is compatible with the LHC aperture. A taper brings the SPS aperture to the 80 mm diameter, which ensures the pick-ups are tested at the appropriate radius. The two configuration concepts described earlier will be tested in orthogonal planes.

In these first tests it is planned that the opposing pair of pick-ups in the horizontal plane will be illuminated and read-out via an anti-reflection coated viewport to offer maximum flexibility for possible reconfiguration. In the design, incoming linearly polarized light is reflected from a 45° prism towards the eo-crystal, highlighted in red, and the outgoing beam is then reflected by a second prism. In the vertical plane, a pair of fibre-coupled pick-ups is envisaged, with the aim of checking the compact fibre optic configuration and evaluating the sensitivity of the interferometric method. It is expected that the BPM body will be installed in the Christmas shutdown and SPS beam tests with the EO-BPM prototype will commence in 2016.

CONCLUSIONS AND FUTURE

An Electro-Optic Beam Position Monitor is under development, aimed at high-frequency bunch instability monitoring at the CERN SPS and intra-bunch diagnostics at the HL-LHC. The electro-optical response has been simulated and indicates good sensitivity to high order bunch instability modes for electro-optic crystal lengths of 10 to 20 mm. The e-o crystal response has been validated in laser laboratory bench tests, using the polarizer-analyser configuration. An interferometric setup has been proposed with the potential for enhanced sensitivity. The opto-mechanical layout of an EO-BPM has been designed, in preparation for installation of a prototype in the CERN SPS in early 2016.

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REFERENCES

[1] B. Salvant et al, "Transverse Mode-coupling Instability in the CERN SPS/ Comparing HEADTAIL simulations with Beam Measurement", Proceedings of Hadron Beam conference, Nashville, Tennessee, USA, 2008, 45.

[2] R. Jones et al, "Recent advances in the Measurement of Chromaticity via Head-tail Phase shift analysis", Proceedings of DIPAC, Mainz, Germany, 2003, 107.

[3] M.A. Brubaker et al, "Electro-Optic Beam Position and Pulsed Power Monitors for the Second Axis of DARHT", Proceedings of PAC, Chicago, USA 2001, 534.

[4] Adam Joseph Iverson, "Electro-optic Pockels cell voltage sensors for accelerator diagnostics", Masters thesis in Electrical Engineering, Montana State University, 2004.

[5] Y. Okayasu et al, "The First Electron Bunch Measurement by Means of Organic EO Crystals", Proceedings of IBIC, Tsukuba, Japan, 2012.

[6] D.H. Dowell et al., "An Electro-Optic Beam Position Monitor with Sub-Picosecond Resolution", Workshop on Laser Issues for Electron RF Photoinjectors, SLAC, October, 2002.

[7] J. Doherty and R.J. Steinhagen, "The Electro-Optic Beam Position Monitor", CERN student report, October 2013.

[8] R. J. Steinhagen et al, "Application of metal-semiconductor-metal (MSM) photodetectors for transverse and longitudinal intra-bunch beam diagnostics", MOP20, Proceedings of IBIC2013, Oxford, UK.

[9] R. J. Steinhagen et al, "A multiband-instability-monitor for high-frequency intra-bunch beam diagnostics", MOP20, Proceedings of IBIC2013, Oxford, UK.

[10] R. Jones, "Challenges in beam instrumentation and diagnostics for large ring colliders - based on the LHC experience" SUT1B2, Proceedings of HF2014, Beijing, China.

[11] P.-Y. Darmedru "Conception mécanique d'un instrument de mesure de position d'un faisceau de particules", CERN EN report, Groupe 2A04, 2015.

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