Detection of DC beams using electro-optical crystals and lasers (EO-DC-BPM)

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ABSTRACT

The transverse position of a particle beam is one of the most crucial observables in any accelerator. It is typically measured with detectors coupling to the beam's electromagnetic field with multiple antennas. The coupled signals are subtracted to reconstruct the beam position. Standard detectors, however, are insensitive to beams with no temporal structure, so-called DC beams, which are used at CERN to feed many experiments. These limitations can be overcome by replacing the antennas with electro-optical crystals encoding the beam's static field onto a laser beam. Beyond accelerators, the technology could suit applications in industry, energy, or medicine.

Keywords: detectors; front-end electronics; electro-optical systems; particle beam instrumentation.

1. INTRODUCTION

In most high-energy accelerators the beam is divided into distinct packets of particles called bunches which extends the beam's power spectrum up to high frequencies. Nonetheless, some physics experiments require DC or quasi-DC beams, e.g. the future Search for Hidden Particle (SHiP) at CERN [1]. Our project aims at developing a novel Beam Position Monitor (BPM) suitable for measurements of DC beams. Electro-optical (EO) crystals, intrinsically sensitive to DC electric fields, replace the coupling antennas of traditional BPMs, introducing attractive advantages:

- non-destructive coupling to the beam's DC field,
- precise and continuous field measurements,
- compatibility with the accelerator environment,
- optical-fibre-based signal transmission.

EO crystals change their refractive index when exposed to an electric field. If the change is proportional to the field's magnitude, this phenomenon is referred to as the Pockels effect and can be exploited to encode the incident field onto the polarization state of a laser beam traversing the crystal. Thanks to this property, EO crystals are widely used for electromagnetic field sensing [2] and are being investigated for high-frequency BPMs [3]. In the presence of a DC or quasi-DC electromagnetic field, free charge carriers of the crystal move to its boundaries creating a space charge region and an internal electric field. This phenomenon unavoidably affects the crystal's properties and its sensitivity to an external electric field, introducing a measurement error. This has limited the use of EO crystals to measurements above 20 Hz [4].

The EO-DC-BPM consists of four optical branches. Each branch is composed of two EO crystals: one inside the beam vacuum chamber sensing the beam's static field and the other outside to the beam-pipe modulated with an external signal to compensate the space charge effects induced on the in-vacuum crystal. Exploiting a time-varying modulation, the final measurement can be performed in the frequency domain.

The project is currently focused on experimentally proving the feasibility of this novel detection technique using a proof-of-principle test bench which is under construction. The particle beam has been replaced with a wire carrying a DC current and only two of the four optical branches are implemented. Fig. 1 demonstrates the principle of operation of the test bench.

The EO crystals, other optical components and the optimal test bench geometry have been selected based on the results obtained from a specially developed mathematical model. The design has been simulated using an electromagnetic field solver and will be validated with laboratory measurements once the test bench construction is complete.

2. STATE OF THE ART

The EO-DC-BPM aims to measure the transverse position of a DC particle beam confined in a vacuum chamber without affecting the beam's properties.

Literature describes different examples of electrostatic field measurements such as induction probes, oscillating parallel plate sensors or field mills [5]. However, they all

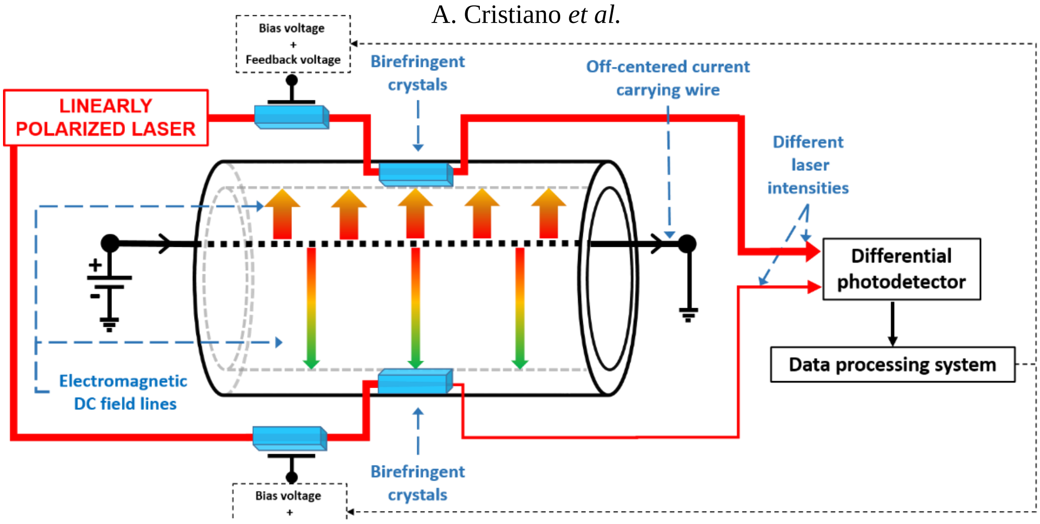

Fig. 1 Simplified schematic view of the designed test bench

disturb the electric field being measured due to the presence of metal. Furthermore, some of the commonly used sensors, such as induction probes, require frequent re-zeroing, rendering measurements over a long time impossible.

Other methods to evaluate the transverse position of a DC beam exist such as screen-based BPMs [6]. These sensors can be installed inside the accelerator vacuum to observe not only the transverse position of a DC beam but also its shape by measuring the radiation scattered from thin screens placed in the beam path. However, the screen-beam interaction, especially in ring accelerators using low energy particles, can change the beam's parameters in an unacceptable manner. Moreover, screens cannot be used with high intensity beams due to the significant power stored in the beam, which would result in permanent damage to the screen itself.

Indirect measurements of DC beams are also possible, such as sensing the electromagnetic transverse Schottky spectrum [7]. Since the beam consists of a finite number of charged particles, there will always be some statistical fluctuations. By looking at such fluctuations with a sensitive spectrum analyser, one can detect several beam parameters including the transverse position. However, the measurement times are long, which typically restricts the use to circular machines where there is little change in the beam characteristics during this time.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Although some techniques to observe the transverse position of a DC particle beam exist, there is no universal, direct, non-destructive measurement method for high-energy, high-intensity beams. The EO-DC-BPM aims to fill this gap and become a reference technology for all particle accelerator facilities using DC or quasi-DC beams.

The novel approach for compensating the space-charge extends the applicability of EO-crystal-based measurements to frequencies below 20 Hz. Additionally, the developed technology is inherently insensitive to the beam energy and therefore can be readily adapted to any physics, medical or industrial facility.

Beyond particle accelerators, precise measurements of static electric fields are required in many applications, from process control on industrial machinery, to weather forecasting, to safety on high voltage power lines. Since EO crystals are suitable for operation in harsh environments, including in liquids or vacuum-sealed equipment, they are well adapted for installation in industrial settings e.g. high-power, oil-cooled transformers. Moreover, using optical fibres instead of copper cables for signal transmissions will allow solutions based on this technology to be used for distributed sensor networks with a central measurement point, e.g. monitoring high-power transmission lines.

4. PROJECT RESULTS

A detailed mathematical model of the optical chain, shown in Fig. 2, was developed in MATLAB to demonstrate the feasibility of the proposed technique and to guide the choice of the test bench components. Two lithium niobate ($LiNbO_3$) crystals are arranged in a crossed-polarizer configuration. Each serves a different role: one is used to set the working point (bias) of the system, the other senses the particle beam. As a linearly polarized laser beam traverses the chain, its polarization state changes due to the field incident on the crystals.

Fig. 3 shows the system's transfer function obtained by sweeping the bias electric field in the first crystal while measuring the relative output light intensity. No electric field is applied to the second crystal which is equivalent to the lack of a particle beam. The bias electric field can be used not only to set a static working point but also to sweep it over a given range using a periodic modulation. An example of this is presented in Fig. 4: as the bias electric field is modulated, so is the output light intensity is modulated at twice the applied modulation frequency.

The DC component of the bias electric field is chosen to intentionally exploit the symmetry of the transfer function and to obtain an output signal containing only even harmonics of the modulation frequency. Fig. 5 compares the spectral power of the modulation signal and the resulting output light intensity.

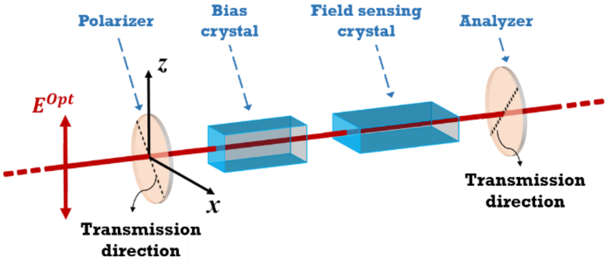

Fig. 2 Modelled optical chain

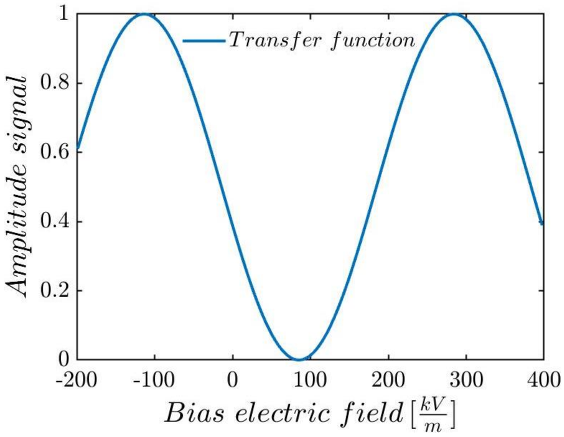

Fig. 3 Transfer function of the modelled optical chain

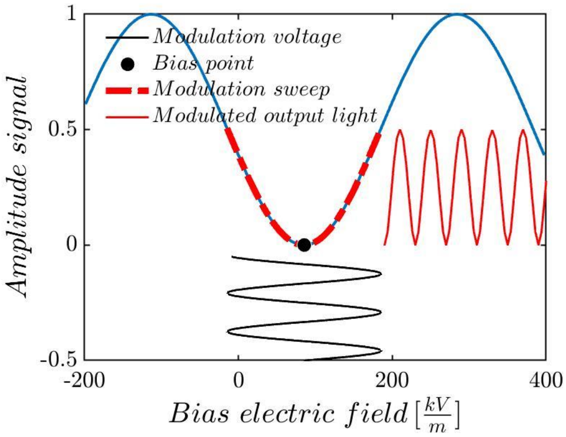

Fig. 4 Modulation of the bias field

Any electric field in the second (particle beam sensing) crystal moves the bias point spoiling the transfer function symmetry as shown in Fig. 6 leading to the appearance of odd harmonics in the output signal as shown in Fig. 7.

The electric field of a particle beam was computed using the CST electrostatic solver. The simulation model, presented in Fig. 8, contained two $LiNbO_3$ crystals enclosed in a square metal pipe. The crystals were arranged on opposite sides of a wire that substituted a 20 A DC beam. To evaluate the influence of the beam

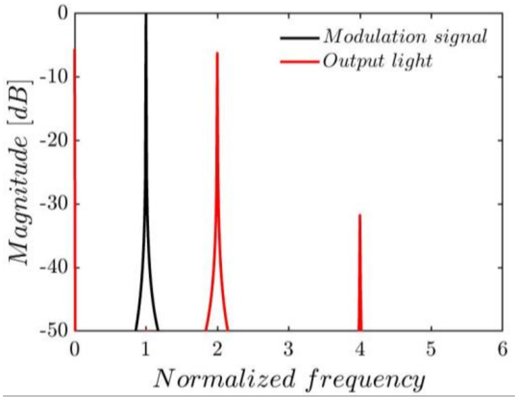

Fig. 5 Modulation of the bias field in the frequency domain

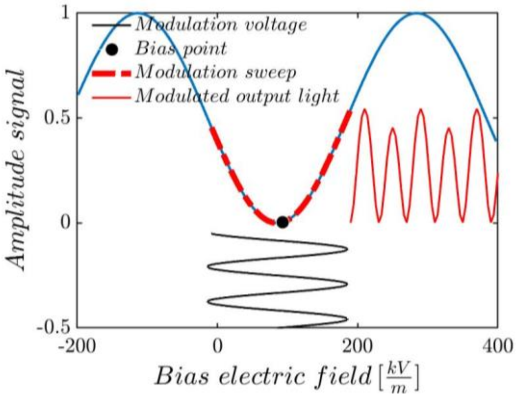

Fig. 6 Shift of the bias point due to the DC beam field

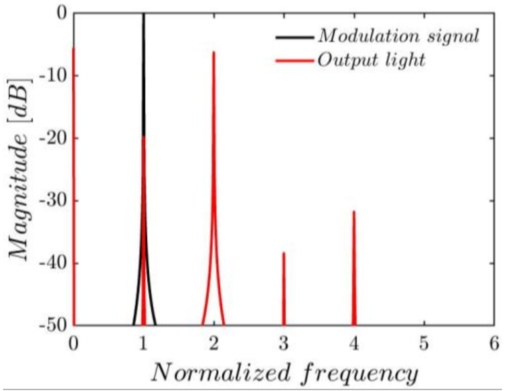

Fig. 7 Appearance of odd harmonics due to the DC beam field

position on the electric field inside the crystals, the wire was displaced towards one of the crystals. Fig. 9 clearly shows the appearance of new harmonics, the intensity of which can be used for DC beam position measurements.

These results served as an input to the analytical model to compute the 1st harmonic intensity of the output signal as the beam position changes. Fig. 10 shows that with two optical chains, the beam position can be calculated using a scaling factor given by the structure geometry.

The developed models were used to optimise the design of a test bench for the proof-of-principle EO-DC-BPM which is under construction with its current state shown in Fig. 11. It consists of a 60 cm long, 45 x 45 mm square pipe, housing two $LiNbO_3$ crystals attached to removable holders installed on the horizontal walls of the pipe.

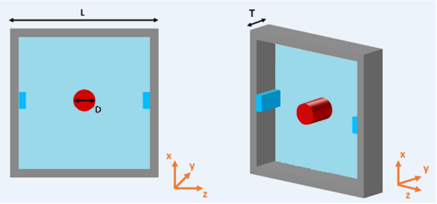

Fig. 8 3-D model for electromagnetic simulations

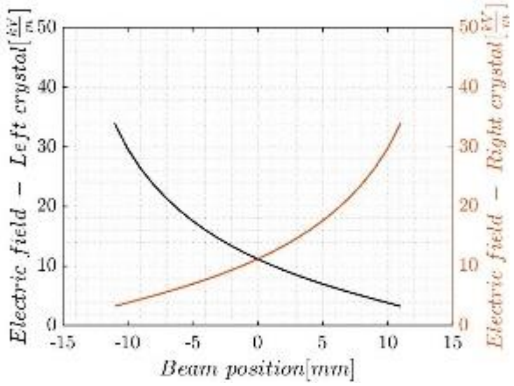

Fig. 9 Electric field in the crystals as the beam position changes

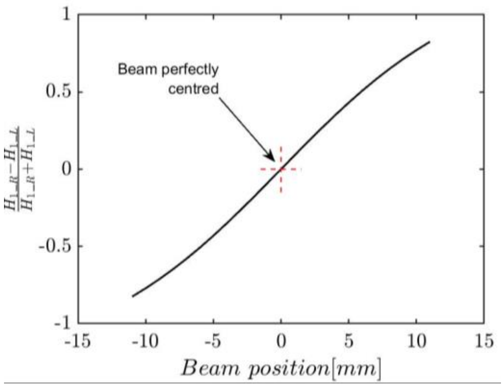

Fig. 10 Reconstruction of the beam position using signals of two optical chains installed on the opposite side of the beam

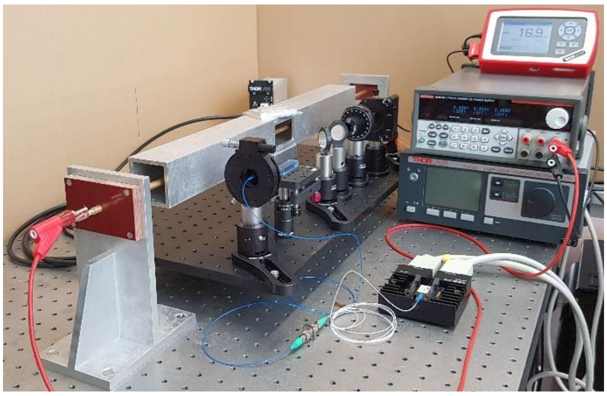

Fig. 11 Test bench for EO-DC-BPM laboratory measurements

The pipe and all other optical components are mounted on a second optical table connected to a motorized, linear translation stage. This second table can therefore move around the stationary wire, which is attached to the main optical table. This minimises any wire vibrations that could lead to a long settling time between two consecutive measurements, or errors in the results.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

At the time of writing the project is transitioning from Technology Readiness Level (TRL) 2 to TRL 3 as defined in [8]. The latter is expected to be reached within the ATTRACT Phase 1 timeline. An additional 2 years are needed to complete TRL 4 with the work focusing on acquisition electronics and data processing techniques. Some hardware modifications can also be expected during this period based on the early measurement results. Due to the high specificity of the particle accelerator environment, TRLs 5-7 can only be reached through tests in an accelerator facility. Delivery of TRL 5 will require significant efforts in mechanical, electro-optical, and electronics design as well as system integration for autonomous operation. These works are expected to last at least two additional years.

5.2. Project Synergies and Outreach

Our consortium has not been able to identify other projects funded through ATTRACT Phase 1 with whom we could exploit synergies. However, to reach TRLs 5-7 the project could benefit from assistance in mechanical design for ultra-high-vacuum, radiation-tolerant electronics design, and real-time data processing techniques. Any organisation with relevant expertise could therefore become a potential partner.

During ATTRACT Phase 1 the main dissemination channel used to communicate the project status and achievements were expert seminars. A scientific paper documenting the achieved results is also being prepared for a peer-reviewed journal. When the project reaches TRL 4, more general dissemination will be sought through international conferences.

5.3. Technology application and demonstration cases

The next project goal will be to reach TLR 4, i.e. validate in a laboratory environment that EO crystals can be used to precisely measured the transverse position of a DC particle beam. In a more general sense, the project will aim to demonstrate continuous monitoring of small variations in a large static field. Any domain were such measurements would prove useful could benefit from our work. A flagship industrial example would be continuous monitoring of high-power DC transmission lines for any abnormalities. This technology could also possibly find a use in weather forecasting through measurements of atmospheric charge build-up. However, due to the relatively low field levels, a dedicated feasibility study would be required to assess the success potential for these applications.

As the project reaches TLRs 4-5, it is expected that the scientific community from other particle accelerators using DC beams will have expressed an interest in this technology. A collaboration with other research institutes would then be possible.

5.4. Technology commercialization

Our consortium believes that commercialization of the developed technology will be viable only after the project reaches TLR 5. A possible strategy to enter the market would be to partner with an international vendor of beam instrumentation with established contacts amongst a variety of accelerator installations. To make the project commercially attractive, the developed product would need to be “plug-and-play” and require minimum maintenance throughout its expected operational lifetime. As this has not been the main focus of the project to date additional development in this direction would be needed.

5.5. Envisioned risks

Unforeseen unavailability of a classified laser laboratory, which is required due to safety regulations, stops any experimental work until a new appropriate space is found. This already happened during ATTRACT Phase 1 and caused a delay until the equipment was relocated to a suitable location. The pending laboratory measurements of the proof-of-principle device might show that the developed technology is viable only for very large electric fields. This would not hinder the prototyping phase as large currents can be used to generate the required signal levels. However, such a limitation might reduce the number of future commercial applications of the developed technology.

5.6. Liaison with Student Teams and Socio-Economic Study

The option of collaborating with student teams provided during ATTRACT Phase 1 was not exploited by our consortium. Should the project be selected for ATTRACT Phase 2 funding, such liaison will be facilitated by providing the students with comprehensive materials explaining our technology and the envisaged performance reach. Regarding the foreseen expert-driven socio-economic study, our consortium could provide any information which would be useful in such an inquiry.

6. ACKNOWLEDGEMENT

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