THE MONITORING OF THE EFFECTS OF EARTH SURFACE INCLINATION WITH THE PRECISION LASER INCLINOMETER FOR HIGH LUMINOSITY COLLIDERS

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Abstract

Earth surface movements, provoked for example by earthquakes or industrial noise, can induce a degradation of particle accelerators instantaneous luminosity or even sudden beam losses. This report presents the results from monitoring the effects of earthquakes on the present LHC beam orbit and luminosity, using a novel instrument, the Precision Laser Inclinometer (PLI). The aim is to characterize the response of accelerators to remote or nearby Earth surface movements and propose possible applications of the instrument for minimizing detrimental effects.

INTRODUCTION

The Precision Laser Inclinometer (PLI) is a novel type of instrument able to detect inclination of the Earth surface with high precision [1]. The instrument main characteristics have been studied in comparison with other known instruments and observing natural phenomena as a continuous source of calibrating events: the micro-seismic peak, the effects of the Moon attraction cycle and earthquakes. This report will briefly introduce the working principles of the PLI, the observations of relevant phenomena and finally discuss the possible applications to high luminosity colliders, which are notoriously very sensitive to Earth surface movements from natural and human (cultural noise) sources.

THE PRECISION LASER INCLINOMETER

The Precision Laser Inclinometer (PLI) is part of a large program of survey instrumentation developed at JINR - Dubna in the framework of research and developments for the ATLAS experiment in collaboration with the CERN Survey group. The deployment and the study of the results are being done in collaboration between JINR and CERN (the High Luminosity LHC Project and the Beam Operations).

A set of PLI prototypes have been installed at CERN, since 2015, in the TT1 tunnel, a former transfer tunnel of the Intersecting Storage Rings (ISR) and now used as stable environment for the development of surveyors instrumentation among other usage. The TT1 tunnel offers a suitable environment for the understanding of PLI characteristics.

The Experimental Setup and the First Measurements

The PLI setup is shown in Fig. 1. Schematically the setup is quite simple, a cuvette with liquid is placed on a very stable base plate (support S) and a Laser delivers a light ray, reflected by the surface of the liquid. The reflected light is detected by a quadrant photodiode (QPr).

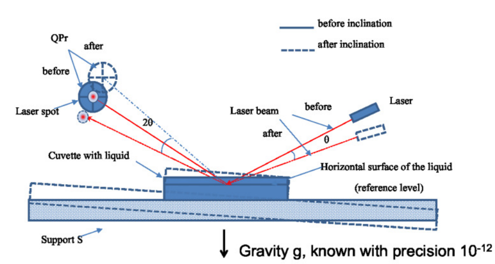

Figure 1: The PLI setup.

When the system is inclined by an angle θ, the surface of the liquid remains, by gravity, horizontal, while the Laser light is deflected by an angle $2\times\theta$ and this movement of the light spot is detected by the quadrant photodiode and recorded by the data acquisition system. The detection is in both planes and therefore it is easy to calculate the combined slope of the movement and its azimuth.

The very stable ground and temperature conditions in the TT1 transfer tunnel allowed to perform several studies of stability versus temperature, influence of industrial noise. Comparative measurements with known instruments [2, 3] allowed to to monitor, over a period of a month, a variety of phenomena inducing Earth inclinations, from industrial to natural kind, where the latter are dominated by the recording of the micro-seismic peak, the Moon attraction cycle and earthquakes. The precision of detection achieved was assessed to be better than 10^{-9} $\mathrm{rad/Hz^{1/2}}$ in the frequency range $[3 \cdot 10^{-7}, 1]$ Hz, where $3 \cdot 10^{-7}$ Hz corresponds to one month period. For daily measurements the precision achieved has been assessed to 10^{-10} $\mathrm{rad/Hz^{1/2}}$ in the frequency range $[10^{-3}, 1]$ Hz [2, 3]. Recently the working range of the PLI has been extended to 4 Hz via carefully selecting a liquid with lower viscosity.

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OBSERVATIONS OF EARTHQUAKES AT THE LHC

It is well known that accelerators and light sources are sensitive to ground oscillations. Earthquakes are rare events, but provide calibrating data to establish the sensitivity of accelerator components and of the detecting instruments (e.g. the PLI).

The effects can be quantified to determine both the impact of ground motions and the possible deployment of PLIs for their monitoring and ideas for corrective actions.

Waves from Earthquakes

During an earthquake event the different types of body (Pressure, Shear) and surface (Rayleigh, Love) waves and their path and reflections through the Earth produce a complex signature at seismic measurement stations and also at the LHC. The seismic activity in the Geneva area is very low, but distant earthquakes can affect the LHC.

During the past years of operations of the LHC at high luminosity several earthquakes had effects on the beam. Around twenty earthquakes have been observed to affect the LHC beam, during the period March 2015-November 2016. Many more earthquakes occurred in that period, but no beam was circulating during those occurrences. The effects on the earthquakes can be quantified looking at the RMS of the LHC orbit oscillations, estimating the impact as follows:

- $\Delta R \sim 50\ \mu\mathrm{m}$: beam dump unlikely
- $\sim 200\ \mu\mathrm{m} < \Delta R <\sim 100\ \mu\mathrm{m}$: beam dump probable
- $\Delta R >\sim 200 \mu\mathrm{m}$: beam dump definitive

where $\Delta R = 200\ \mu\mathrm{m}$ corresponds approximatively to $1\ \sigma$ at the LHC primary collimation system (TCP).

These are qualitative limits as a beam dump for a certain orbit movement strongly depends on tail population and wave properties among other factors. The orbit stability at the TCP is constantly monitored and it is controlled to the level of $\pm 5\ \mu\mathrm{m}$ during stable collisions.

Earthquake Detection by the LHC and the PLI

About twenty earthquakes have been observed simultaneously by the LHC and the PLI, showing correlations of the effects and improving the knowledge of the response of both the accelerator and the PLI.

A recent earthquake in the Atlantic Ocean at the Ascension Islands occurred on August 29th, 2016. The earthquake magnitude was 7.1 and the ground movements were detected at CERN ten minutes after, at the distance of ~ 5600 km from the epicenter.

Looking at the effect of this earthquake it is possible to observe clear correlations between the ground motion detected by the PLI and the orbit perturbation and losses for the LHC beams. The latter mainly appear at the maximum of the amplitude of the oscillations as shown in Fig. 2. From top to bottom are shown the amplitude plots from PLI and from LHC, the plot of the RMS of the LHC orbit and finally the profile of the losses at the collimation system. It is interesting to notice that, in this occasion, the PLI starts detecting oscillations earlier than the LHC orbit starts significantly to vary.

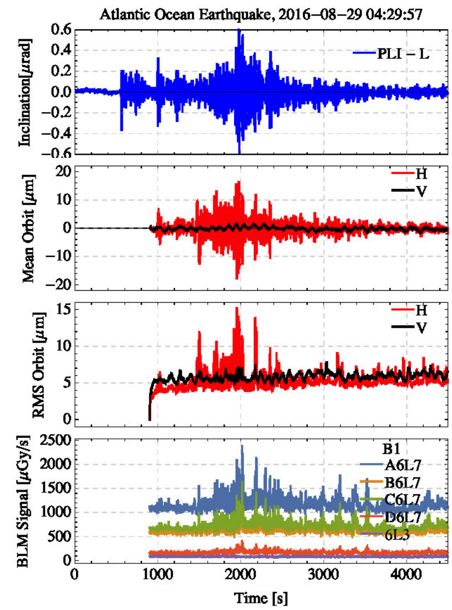

Figure 2: The amplitude plots for the PLI response, the LHC orbit perturbation, the LHC RMS of the orbit and the profile of the losses at the level of the collimation system.

The mean orbit perturbation and the PLI signal amplitude correlated, as well as how well correlated are the beam losses at the collimators and the PLI signal amplitude.

A very clear correlation between the PLI signal and the accelerator behaviour in presence of ground movements is given by looking at the instantaneous luminosity at the experiments. The Fig. 3 shows, as an example, the superimposition of the PLI amplitude signal and the instantaneous luminosity in the ALICE experiment that oscillates in phase with the ground motion and the PLI signal, in very good agreement.

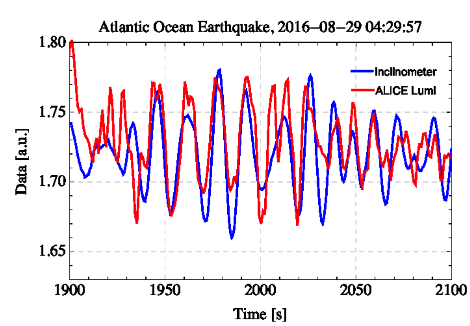

Figure 3: The PLI signal superimposed on the ALICE instantaneous luminosity showing very good agreement.

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A simulation of the LHC ring response to ground movements is under active development. The simulation takes into account the measured displacement and the travel direction of the wave with respect to the LHC. The PLI provides both and it is therefore a good testbench for the simulation results.

A comparison has been done at the simulation level by comparing the current LHC optics with possible schemes of optics for the HL-LHC [4], where beams are more squeezed. The comparison indicates that the RMS orbit response is increased by a factor around two to three for the HL-LHC optics. As an example an earthquake occured in Italy in 2012 caused a RMS obit oscillation of around 60 $\mu(m)$ to which the LHC beam survived, but that would have most probably caused a beam dump with the HL-LHC optics.

APPLICATIONS FOR HIGH LUMINOSITY COLLIDERS

The PLI is a newly born instrument and the development has shown a wide range of possible applications. Concentrating on possible deployments at high luminosity colliders, based on the observations made so far, one can easily identify three possible area of application, which will be detailed here.

Monitoring activity. The monitoring of the PLI started at the beginning of 2015 in the TT1 tunnel. In the future one can propose the installation of four PLI devices in the vicinity of the Inner Triplet areas for the ALICE, ATLAS, CMS and LHCb experiments at the LHC. Relevant experience can be thus achieved.

Active feedback. Once the PLI will be fully commissioned and calibrated with comparison to known instruments it can supply a more active feedback to the operators of a high luminosity collider. It can provide warnings about the occurrence of ground movements preventing possible unwanted beam dumps.

Active stabilization. For the future of the PLI development program a very important role is played by the networking of the devices. By connecting devices in a network over a large area will allow a mapping of the ground movements and of their propagation over such a large area as for example below the LHC inner Triplet quadrupoles. With a sort of "mechanical transistor" the movement detected by each PLI can generate a command to motorised jacks to modify the height of the magnet compensating for ground movements.

NEXT STEPS AND CONCLUSIONS

Several improvements are being considered as next steps in the development of the PLI. Quite recently detailed technical specifications have been prepared for a possible industrial production.

The PLIs will then provide a systematic measurement of any ground movement in the years to come allowing to improve the knowledge of the instrument and of the seismic and micro-seismic activities and the LHC response to them. If installed in 2018 they will be able to provide a measurement during the excavation work for the underground areas for the future HL-LHC (to house power converters, superconducting links) to happen in the years 2019-2020 and will allow the inter-calibration of the PLI with other more classical instruments, like the HLS and geophones or similar.

The PLI can have several others applications in other fields, however since March 2015 is being also used as an instrument to detect ground movement that affect the LHC beams with effects on the beam losses and on the instantaneous luminosity. The beam conditions for the High Luminosity LHC will be more severe with a factor, between two and three, higher level of perturbation for the orbit and beam losses at the primary collimation system level.

The high sensitivity of the PLI (better than 10^{10} $\mathrm{rad/Hz^{1/2}}$) in the frequency range $[10^{-3}, 1]$ Hz allows early detection of events like earthquakes, allowing the PLI to be used as an active feedback system in addition to the monitoring functions already deployed. Being the earthquakes rare events, the attention is also to the monitoring of micro-seismic activities to which high luminosity and low emittance colliders might be potentially affected.The PLI can possibly provide a way of active stabilisation of large magnets by amplification of its detection to correct the position of magnets depending on the ongoing ground movements.

This novel instrument appears to have great potentialities that are being actively investigated for its optimal use.

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