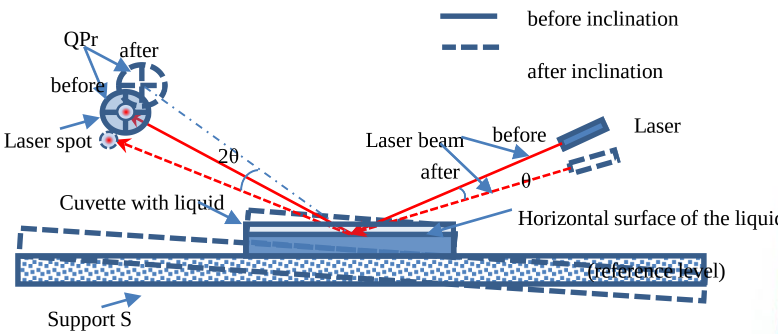
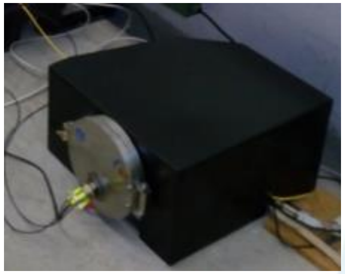




Precision Laser Inclinometer for monitoring and alerting system for seismic events

Beniamino Di Girolamo

ATS-DO

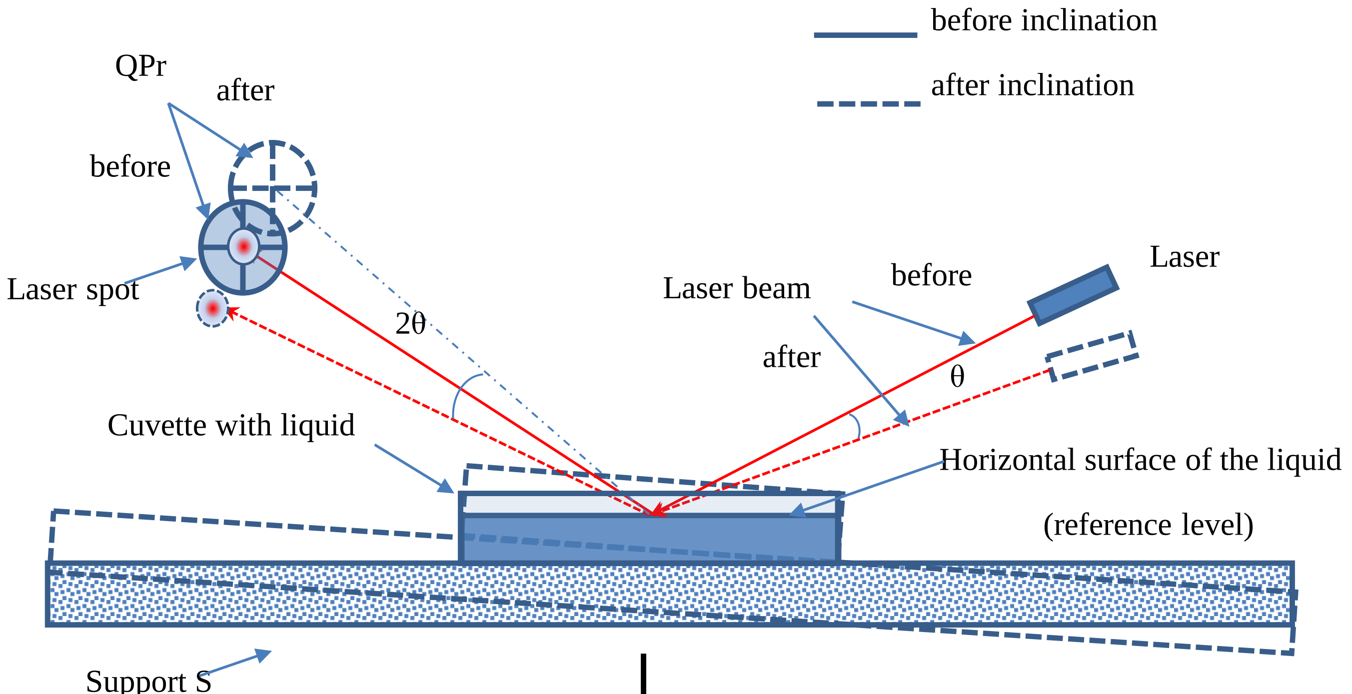
ATS-KT Innovation Day – 26 October 2018

Outline

- The Precision Laser Inclinometer instrument
  - Principle
  - Current applications: metrology and effects on colliders
  - Experimental setup at CERN
  - Measurements and achieved precision
- Applications outside of CERN and HEP
- People involved
- Steps to take it further

Working principle and current setup

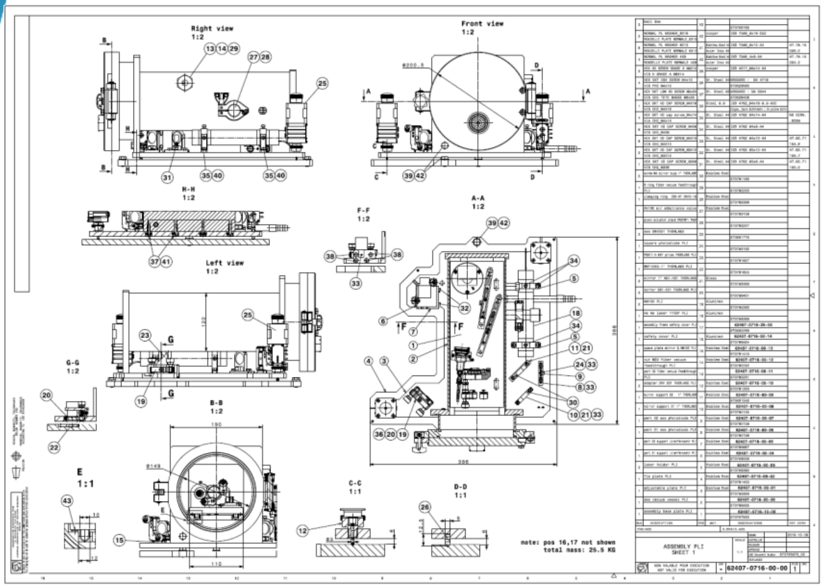
Working principle

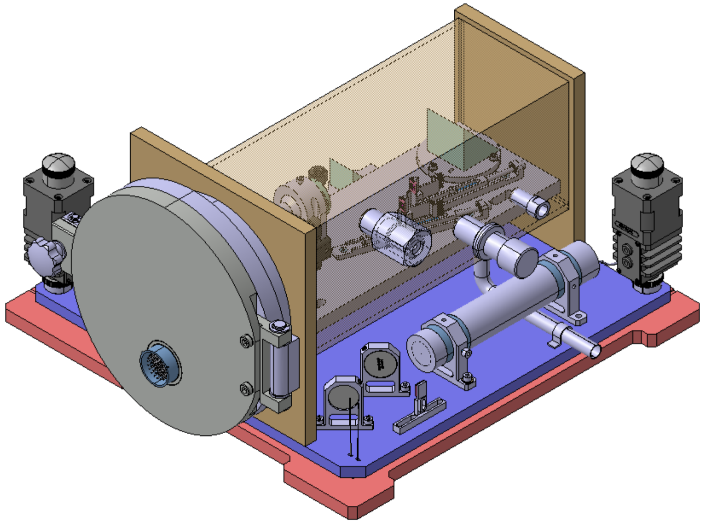


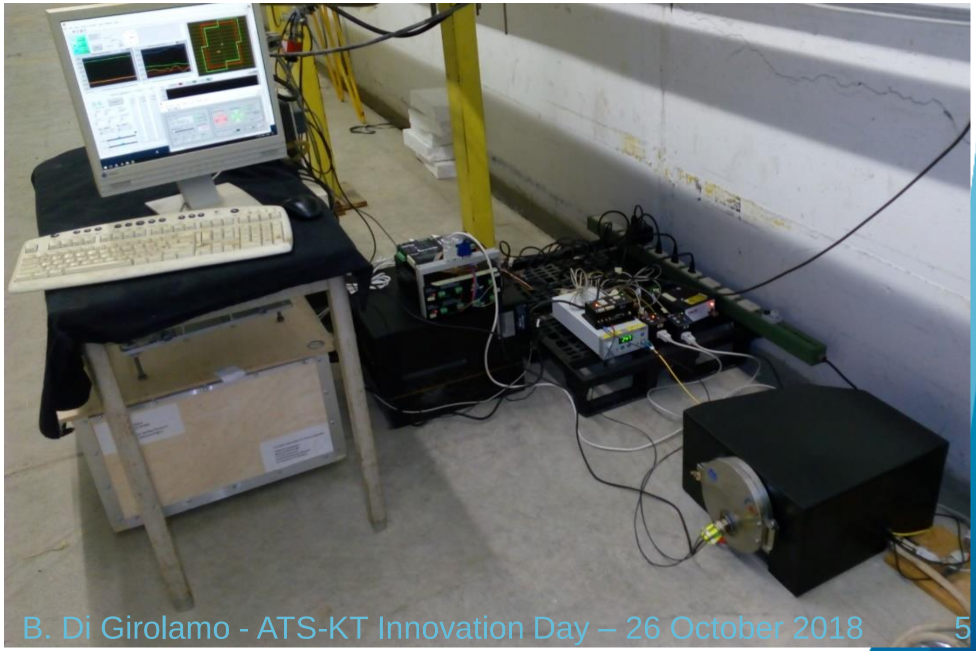
↓ Gravity g, known with very high precision 10^{-12}

- The PLI uses the displacement of the laser ray reflected from a liquid surface when the base support is tilted by ground oscillations
- The angle of the reflected light is twice larger than the support tilt angle θ.
- The detection is in both planes, therefore the combined slope and azimuth can be easily calculated

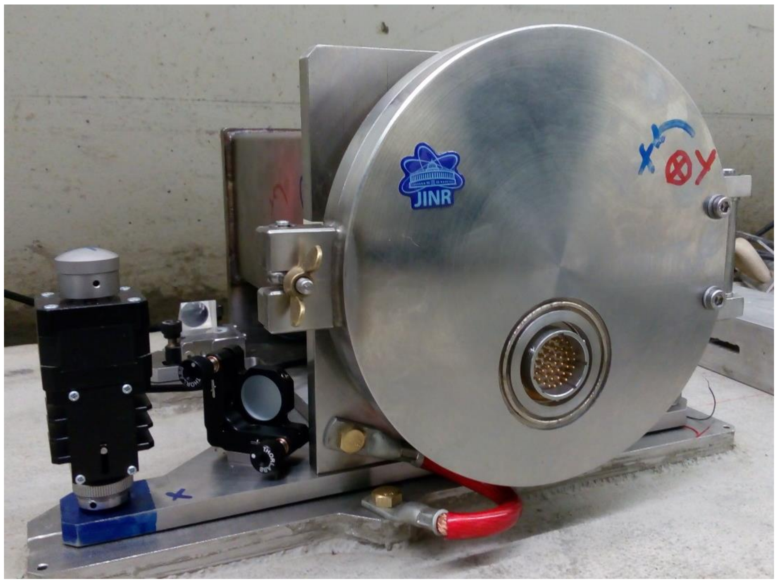
CERN-JINR Agreement P123/A1: production of the first industrialized unit







The production PLI and its readout schematic



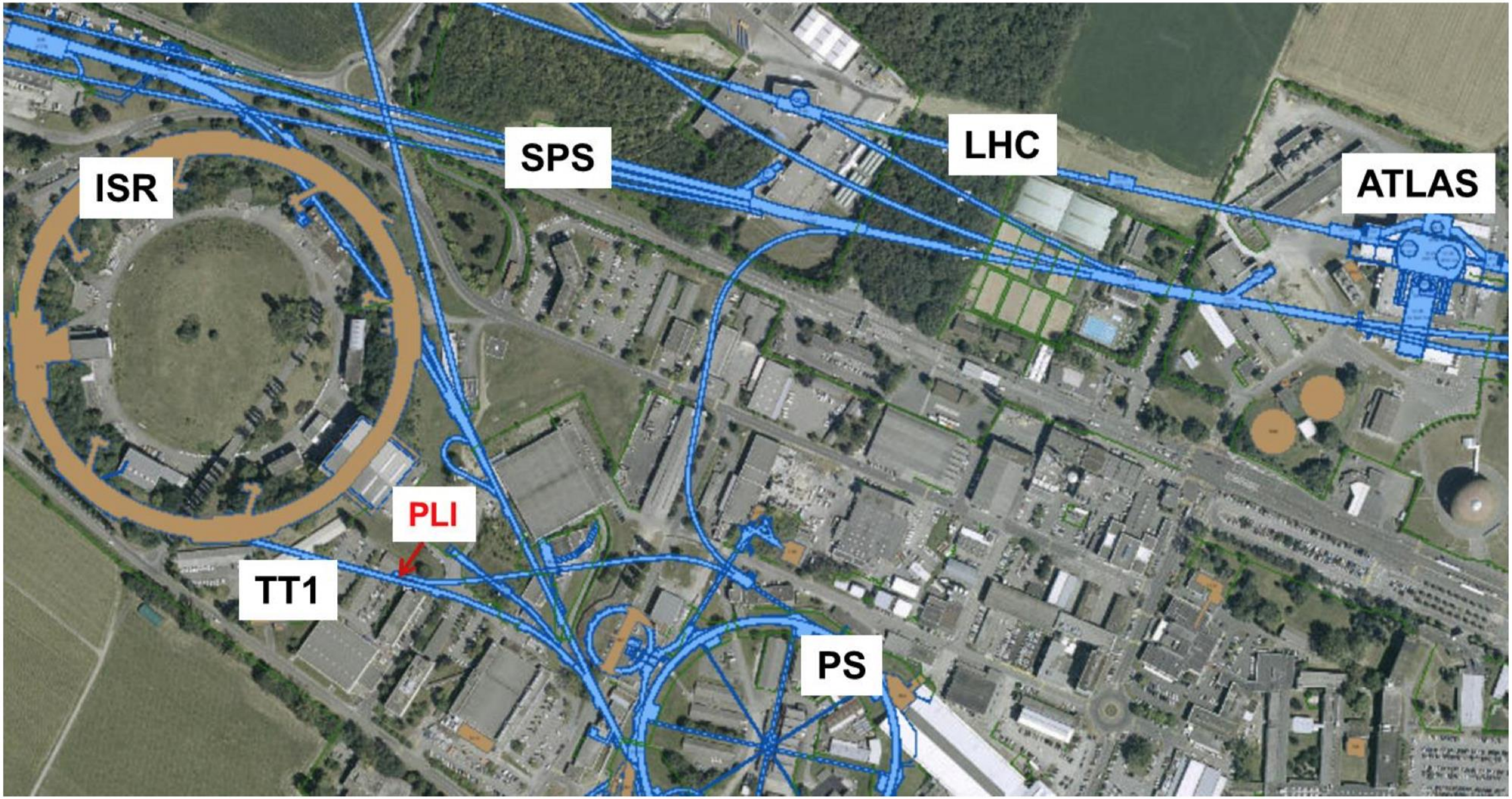
24 bit ADC

<u>Host computer</u>
Control
DAQ
Calibration
Readout
Storage

vacuum

Storage

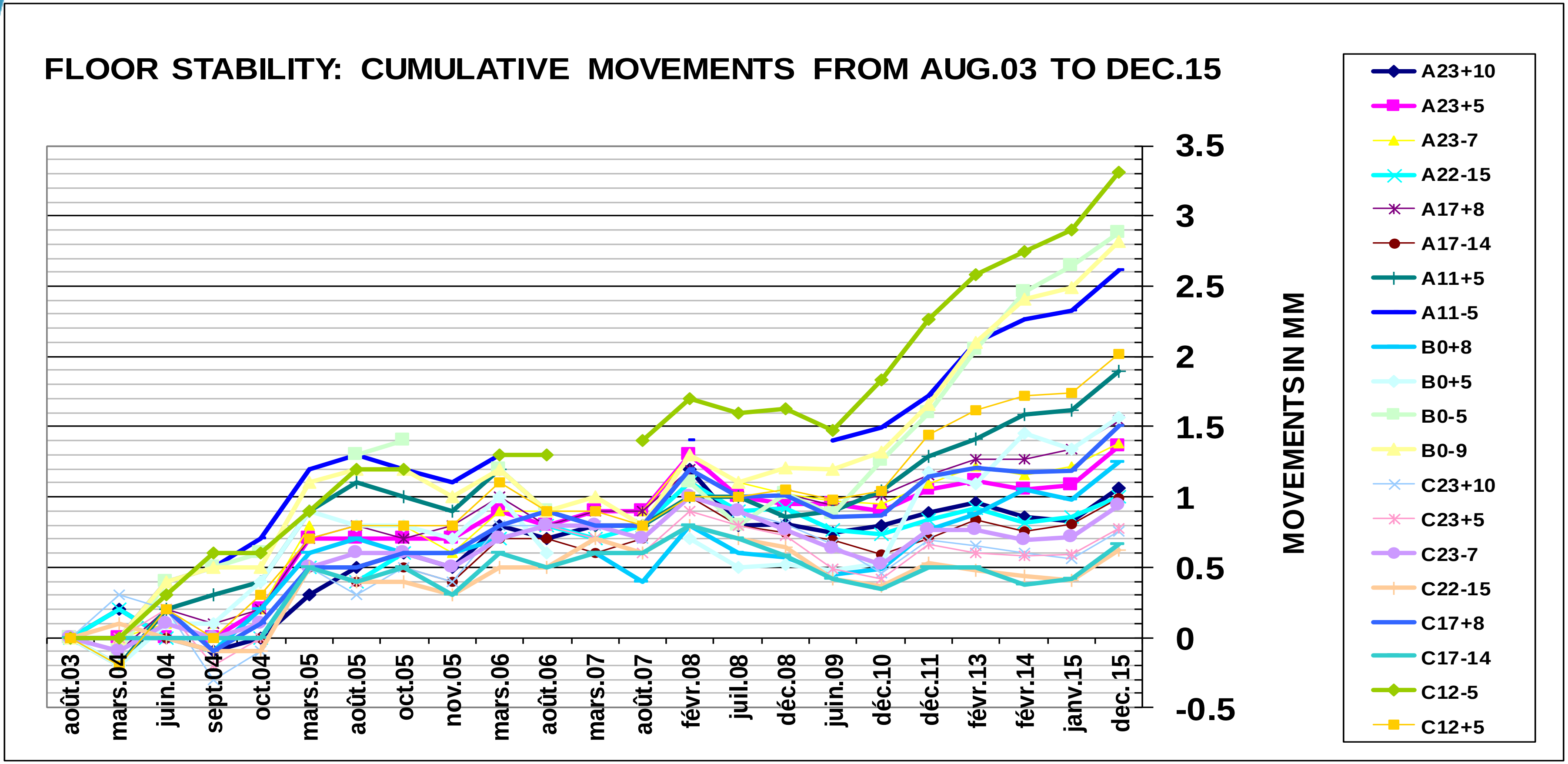
Installation at CERN: TT1 Tunnel



Very stable ground and temperature conditions

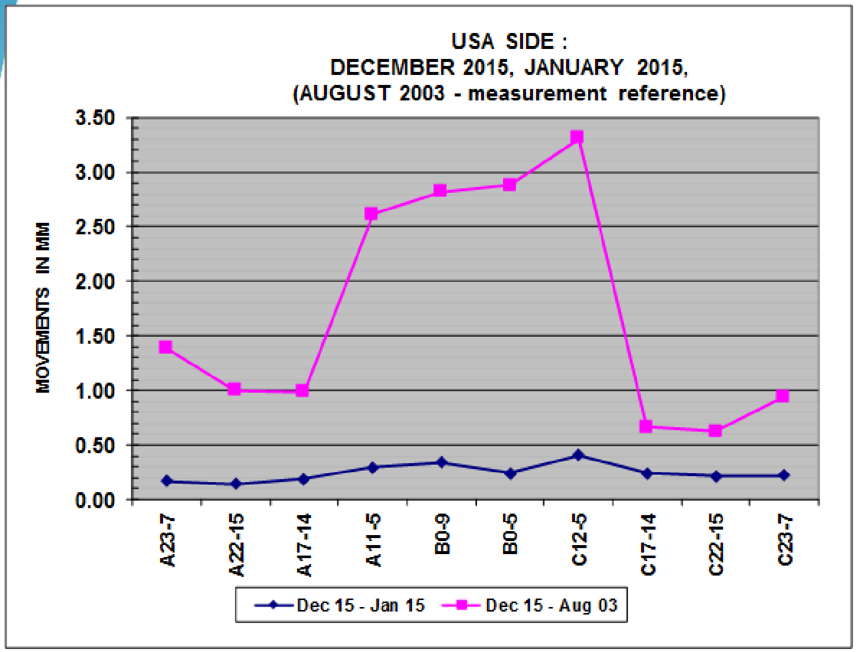
What was it invented for and what has it been also used for

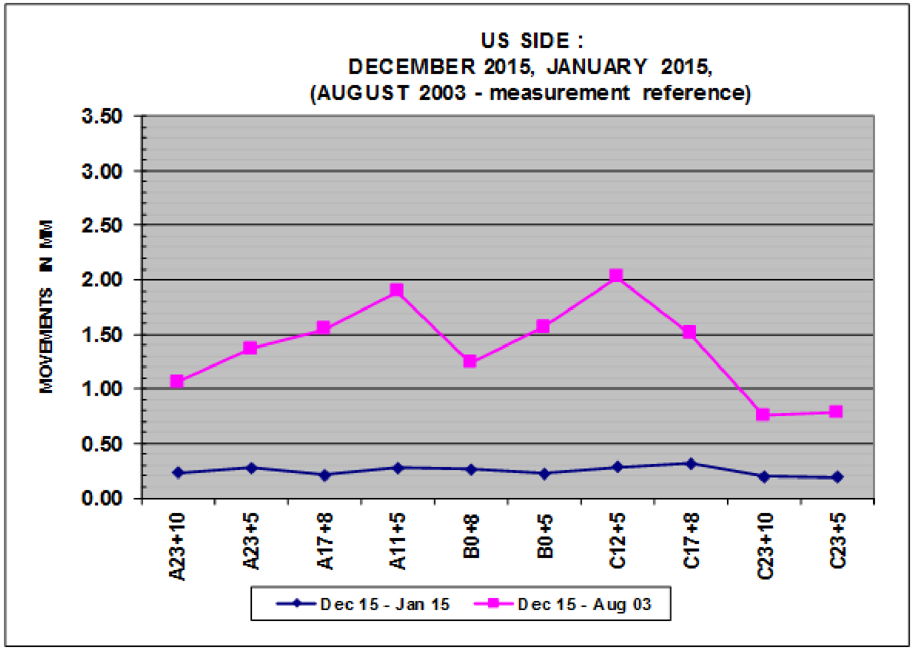
ATLAS Floor Stability Aug 03 – Dec 15



- Reference are deep references in LHC tunnel close to IP1
- Time between measurements varies from 3 to 18 month
- Precision for single epoch 0.2 mm/1 sigma; 0.3 mm between 2 epochs

ATLAS Floor Stability Aug 03 – Dec 15



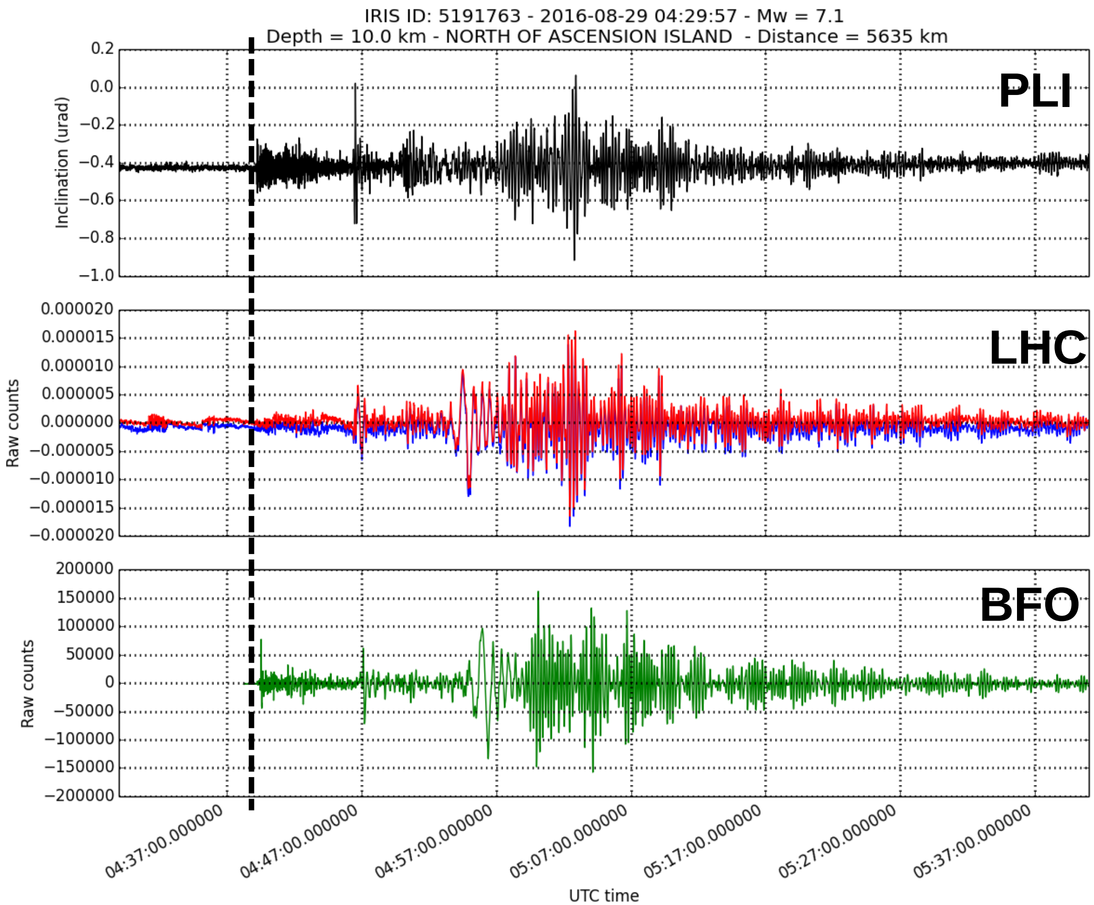


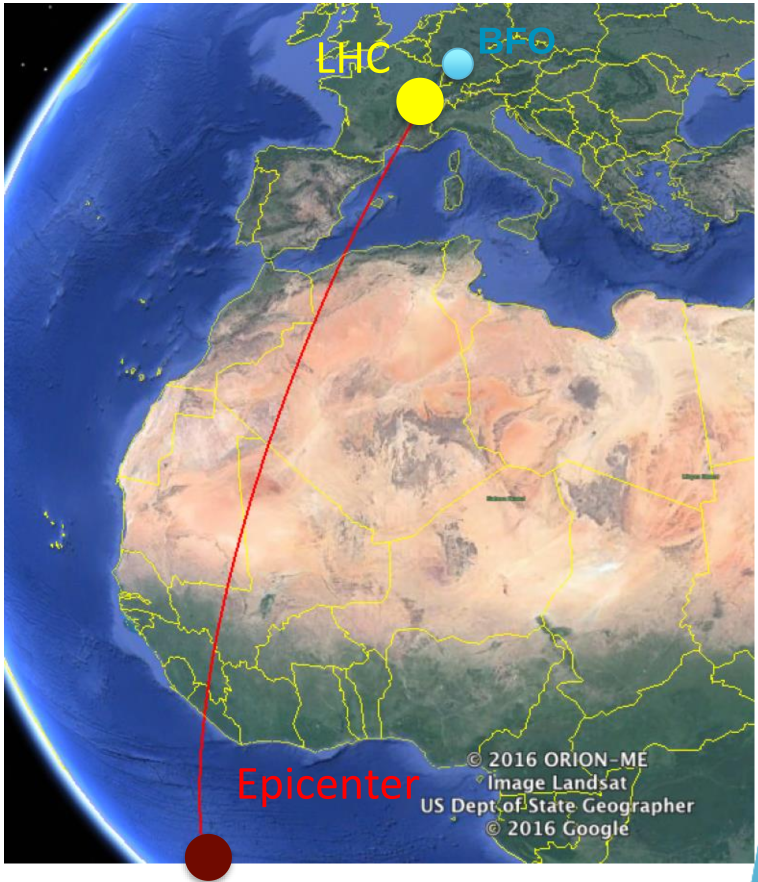
- Movement close to detector is asymmetric and larger on USA side
  - ATLAS detector asymmetric to cavern axis
- Measurements done in different detector configurations (open/close)
- Distance between lateral walls -20 mm/12 years

JINR Dubna metrology lab

Installation of a specially conceived metrology lab seismically isolated
3 M$ investment for the lab and the development of three nanometrology instruments

Far earthquakes: Ascension Island



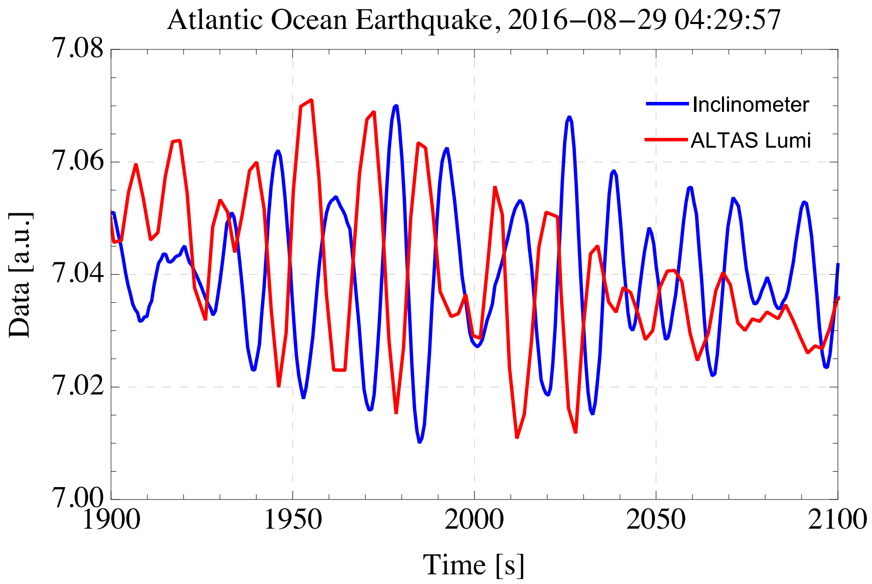


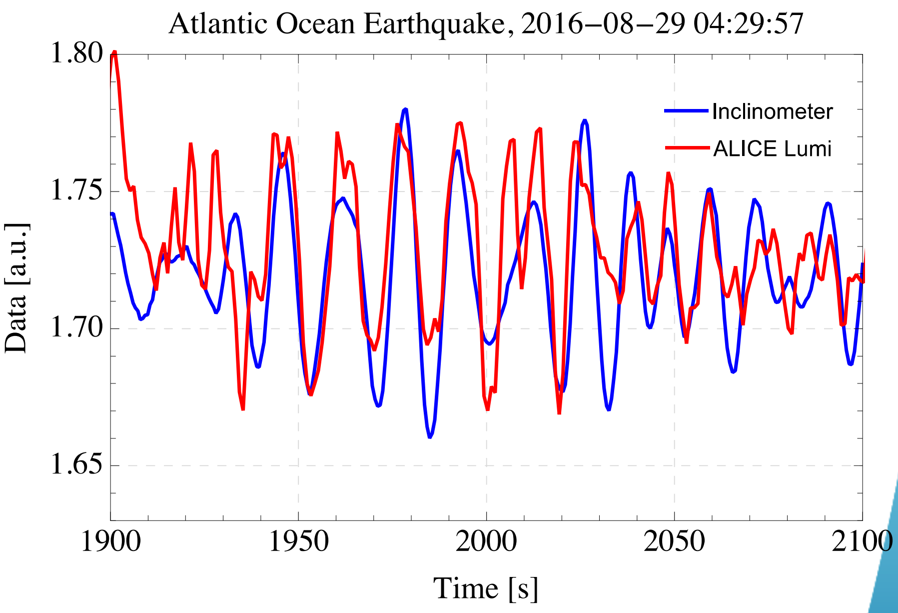
The PLI detection compared to the horizontal orbit oscillations of LHC. As confirmation also the seismogram from the Black Forrest Observatory (which receives it later as expected).

Correlations of Ground Motion with Luminosity

Luminosity shows good correlation with ground motion in TT1.

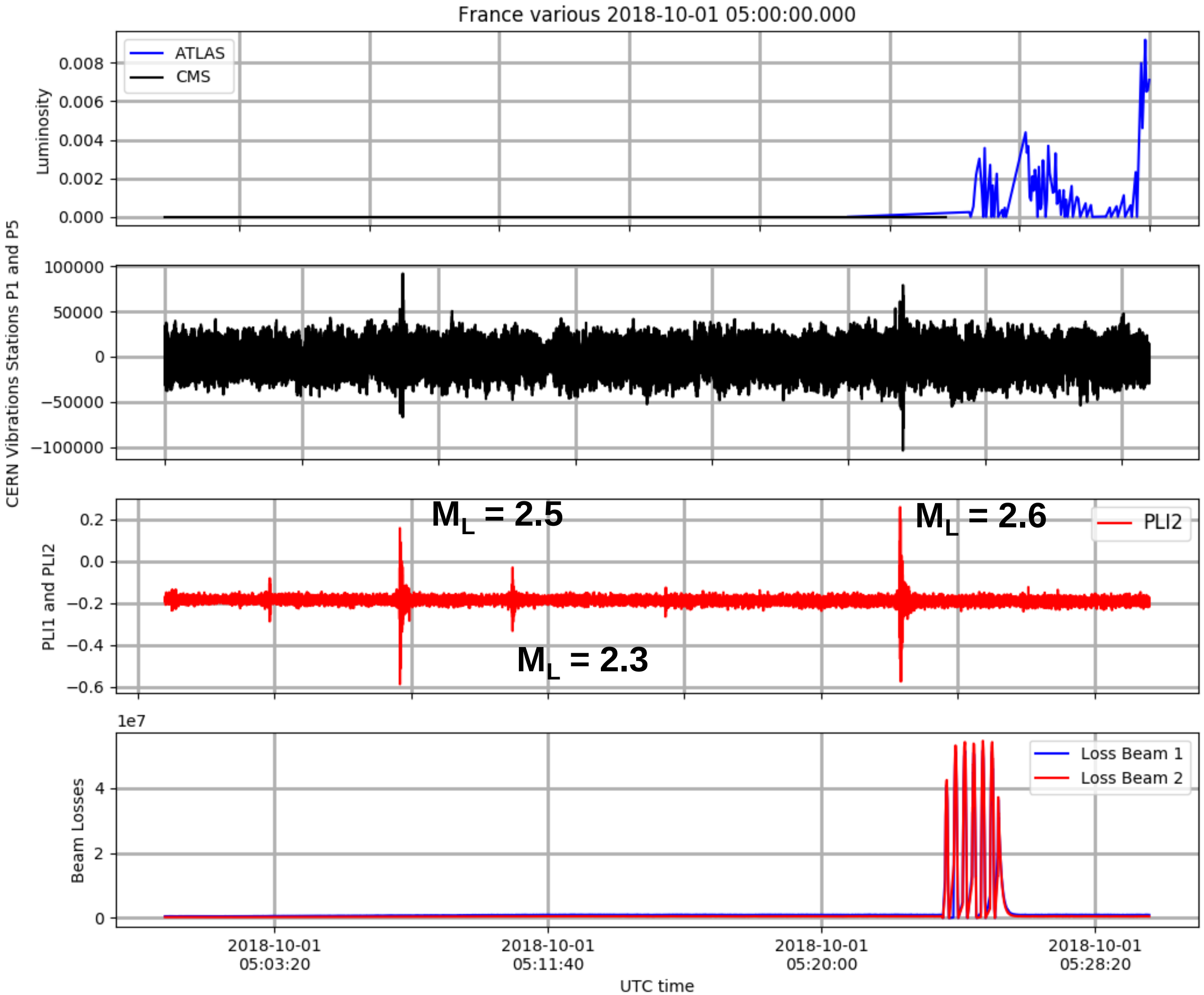
- ALICE/LHCb oscillate in phase with the ground motion.
- ATLAS/CMS oscillate with π/2 phase difference.





Very recent events

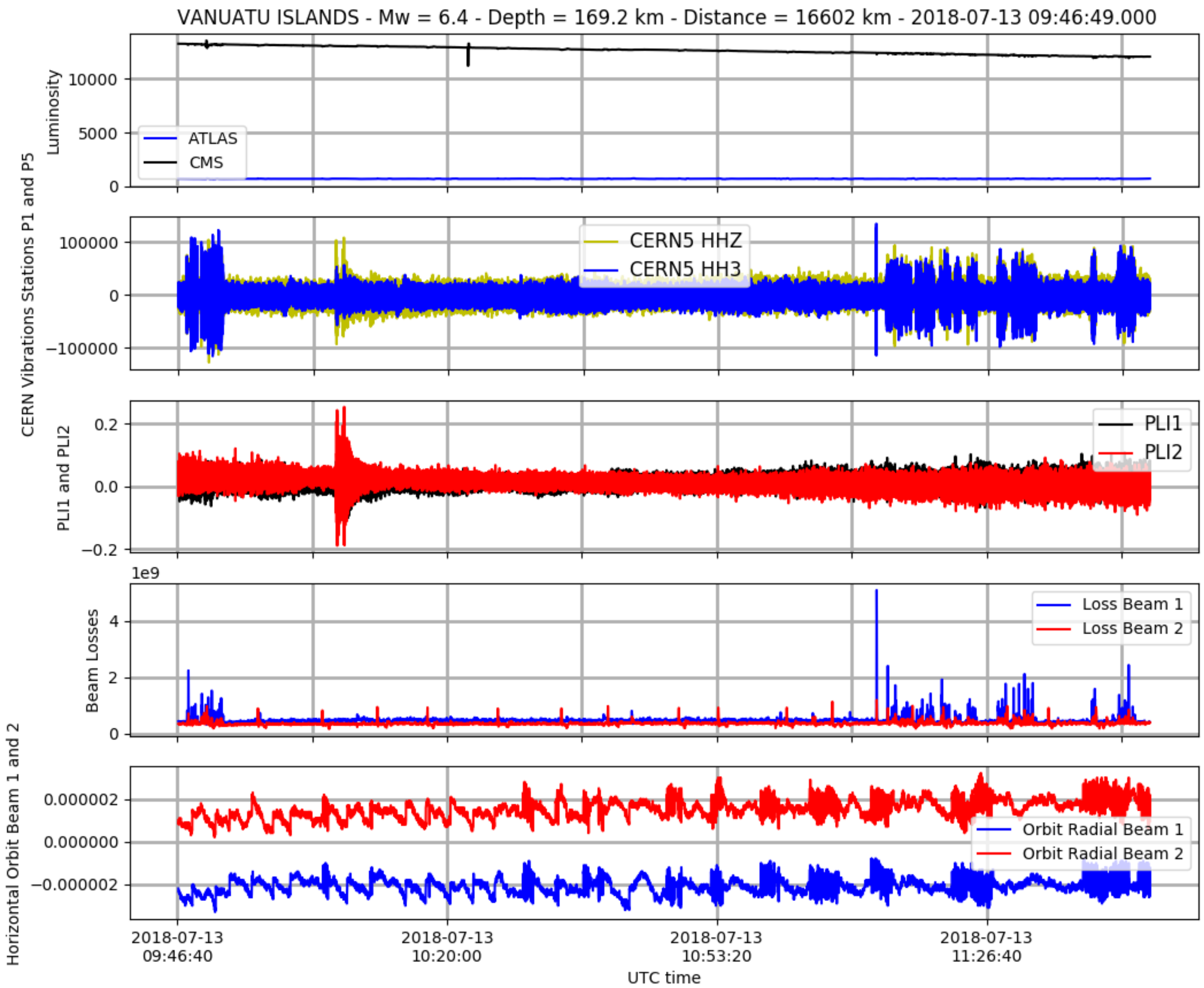
France 1 October 2018



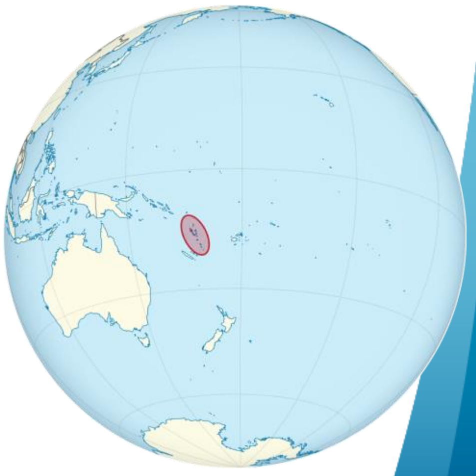
No effects on LHC
Comparison with seismometers in P1 and P5
Small magnitude earthquakes

Very recent events

Vanuatu 29 September 2018

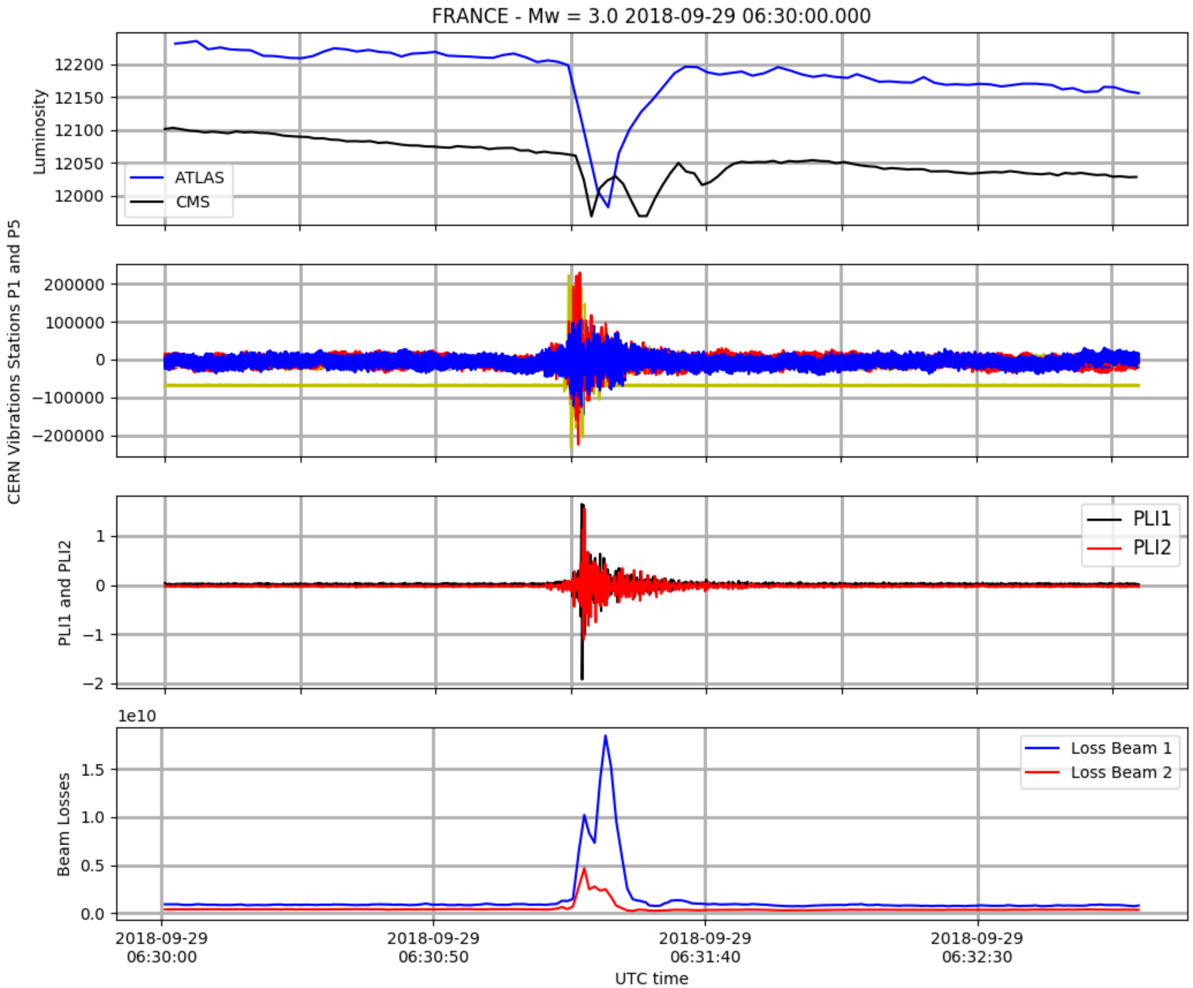


No effects on LHC, instead affected by the action of the road roller in Point 5



Very recent events

France 29 September 2018



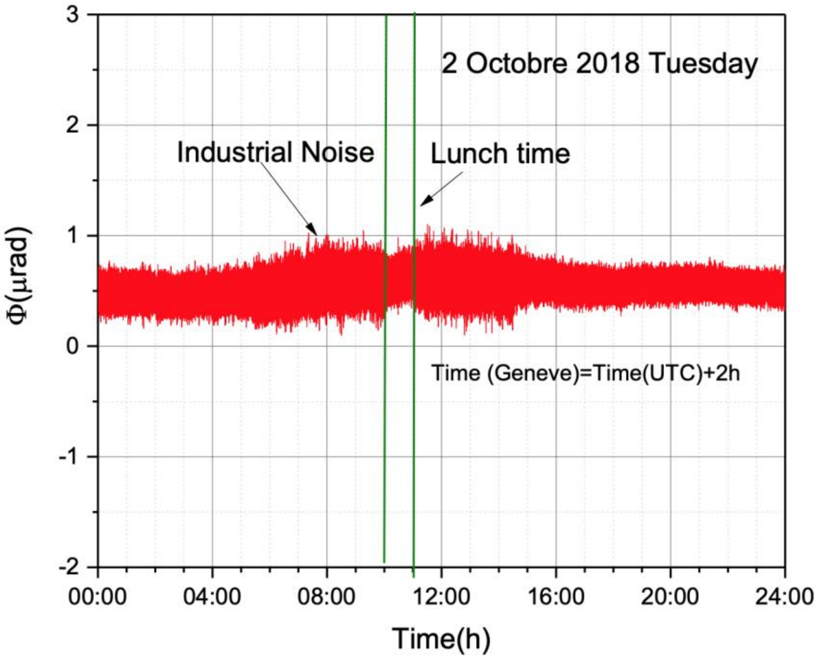
Effect on beam losses and luminosity

Applications outside of CERN and HEP

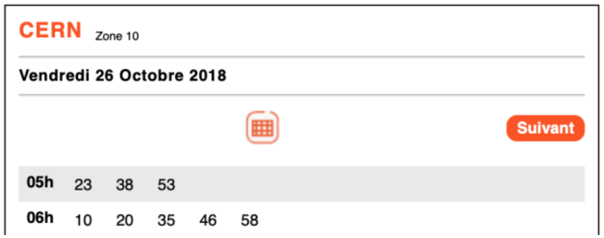
Monitoring of seismic events

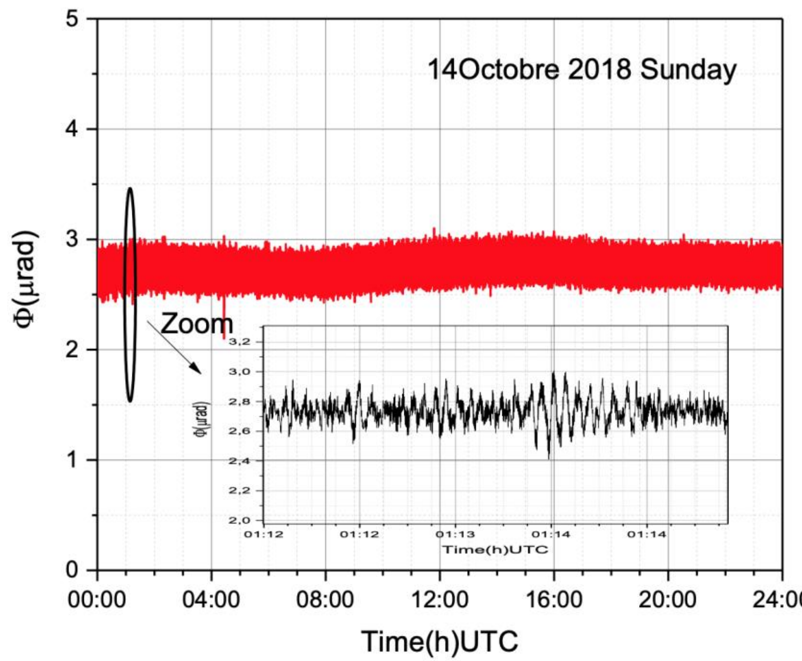
- Earthquakes, seismic movements (micro-seismic peak) and human activity can be monitored
  - CERN at working time, lunch time and weekends
  - Storms on Geneva lake
  - Differences between effects of storms in Atlantic Ocean (<depth> = 3.6 km), North Sea (<depth> = 95 m) and Mediterranean Sea (<depth> = 1.5 km) and combinations of them
- Analysis in the frequency domain allows to disentangle the nature of the oscillations

The seismic effects of CERN and surrounding



Working day: 0.5-1 μrad during the day
~ 0.3 μrad during lunch
Start of industrial noise ~ start of 18 tram
Then clear effect of CERN work



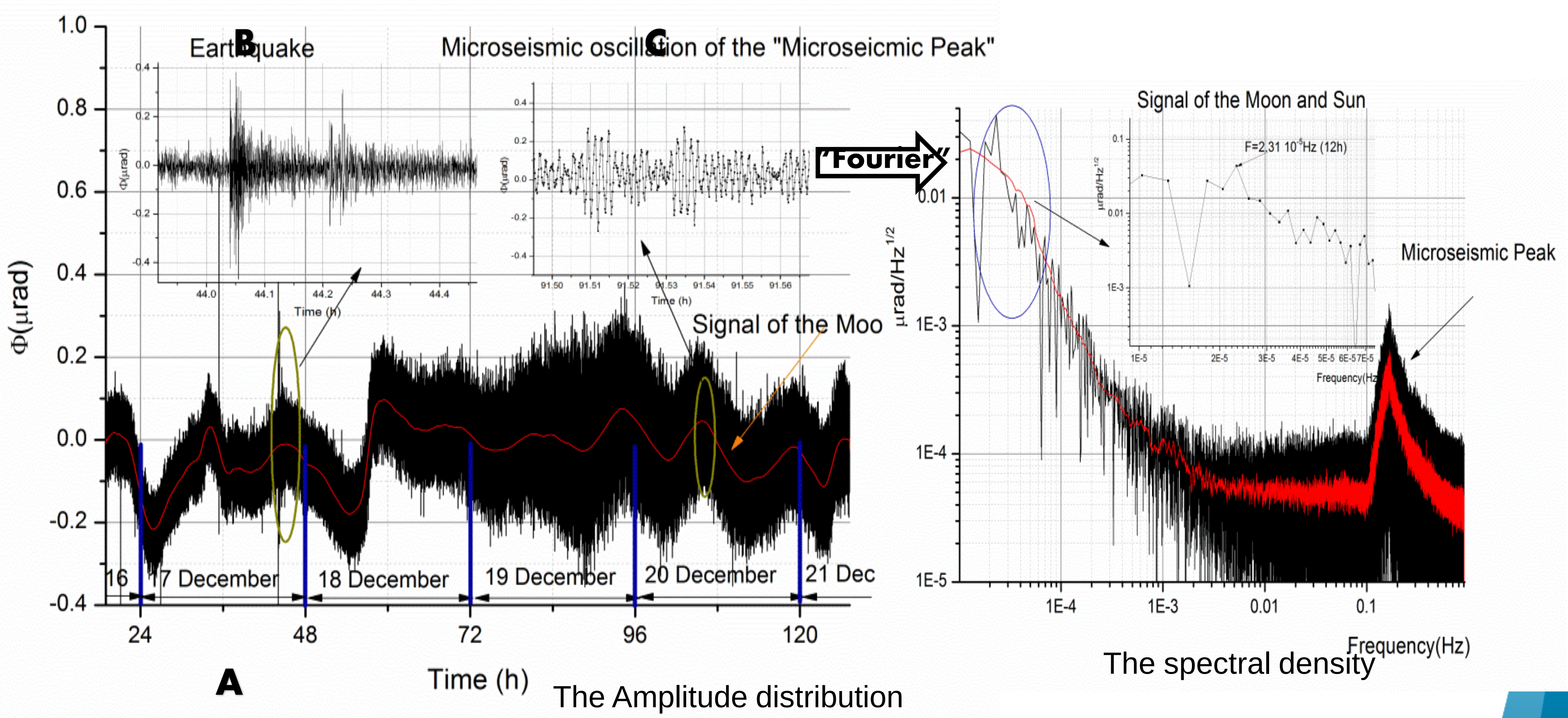


High stability during the weekend
with maximum amplitude ~ 0.3 μrad

B.

First basic results

These PLI-detected ground motions are caused by the Moon and Sun (**A**); by an Earthquake in Mexico (**B**); by the "microseismic" kicks (**C**).



Precision of detection

- The precision is dependent on the observation period and the frequency of calibration
- Comparative measurements with well-established HLS system at CERN has shown for monitoring ground earth oscillation
  - A precision of $2.4 \cdot 10^{-11}$ rad/Hz$^{1/2}$ in the frequency range $[10^{-3}, 12.4]$ Hz
  - A precision better than 10^{-9} rad/Hz$^{1/2}$ in the frequency range $[10^{-6}, 10^{-3}]$ Hz
- Inclinometers on the market have resolutions of 10^{-5}-10^{-6} rad

Precision of detection: conversion table

	μm/m	mm/m	arcsec	arcmin	degree	mRad	Rad
1 μm/m →	1	0.001	0.20627	0.00344	$5.730\ 10^{-5}$	0.001	$1\ 10^{-6}$
1 mm/m →	1,000	1	206.265	3.43775	0.0573	1	$9.99\ 10^{-4}$
1 arcsec →	4.848	0.00485	1	0.01667	$2.778\ 10^{-4}$	0.00485	$4.848\ 10^{-6}$
1 arcmin →	290.89	0.29089	60	1	0.01667	0.29089	$2.909\ 10^{-4}$
1 degree →	17,455.1	17.46	3,600	60	1	17.45	0.01745
1 mRad →	1,000	1	206.26	3.43775	0.0573	1	0.001
1 Rad →	$1.557\ 10^{6}$	1,557	206,264.8	3,437.75	57.3	1,000	1

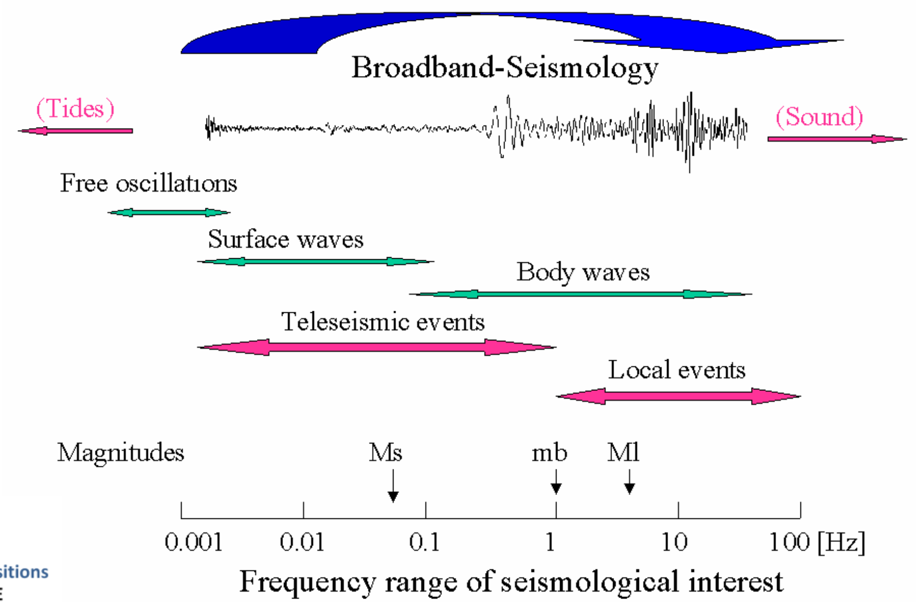
Important: 1 μRad = 1 μm/m is only valid in the range of very small inclinations (angles)!

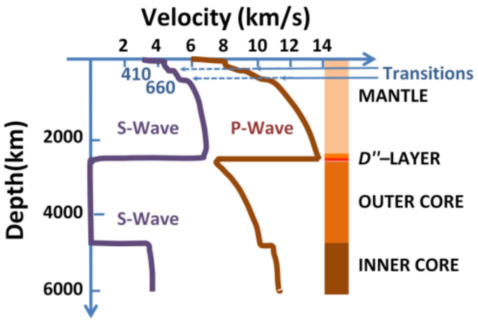
Frequencies of Earthquakes

- Frequency spectrum of waves induced by earthquakes ranges from **~ mHz** (earth oscillations and surface waves) to **~100 Hz** for local seismic events.

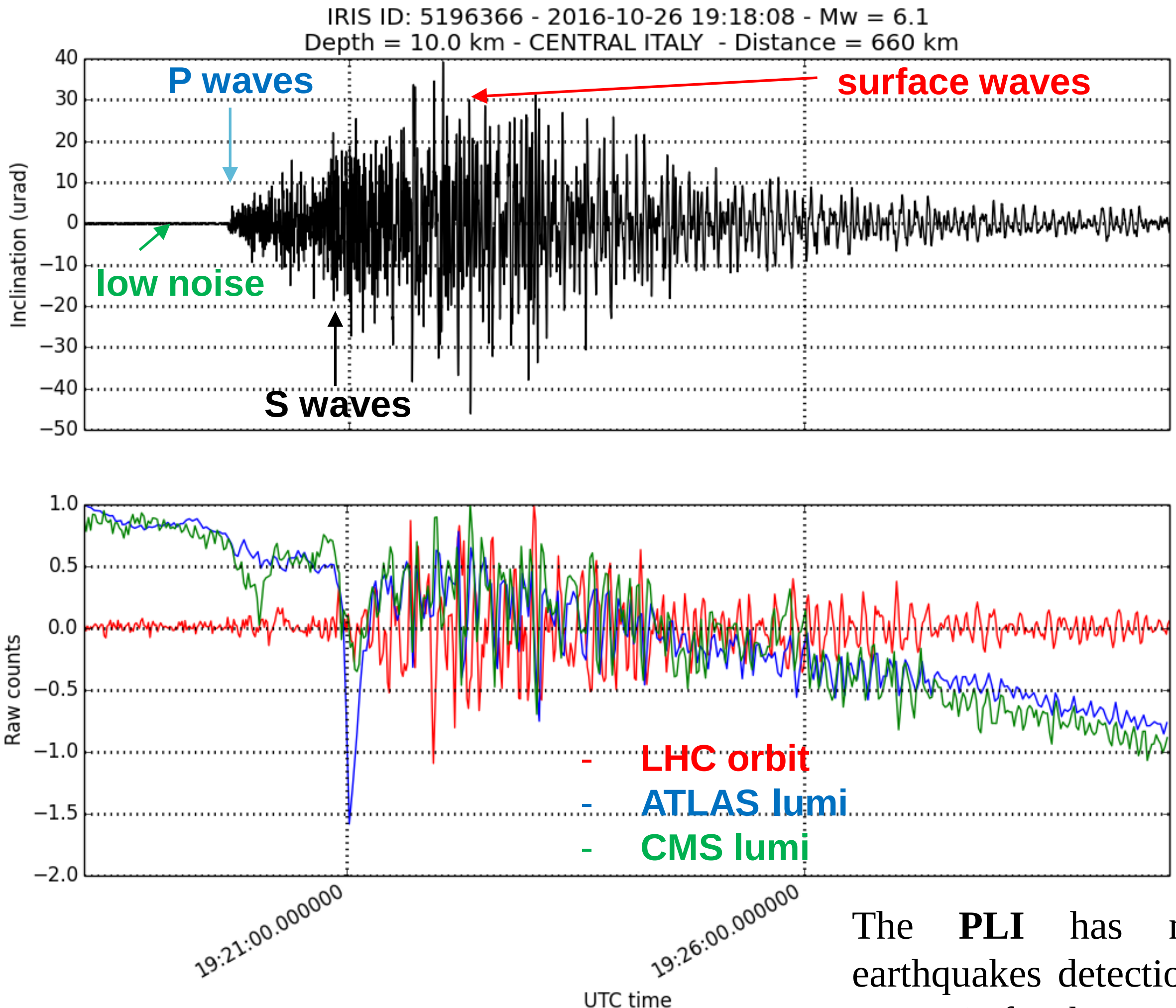
➢ The signatures of large and distant earthquakes are dominated by low frequencies < 1 Hz.

➢ Ground motion from local earthquakes extends to higher frequencies.





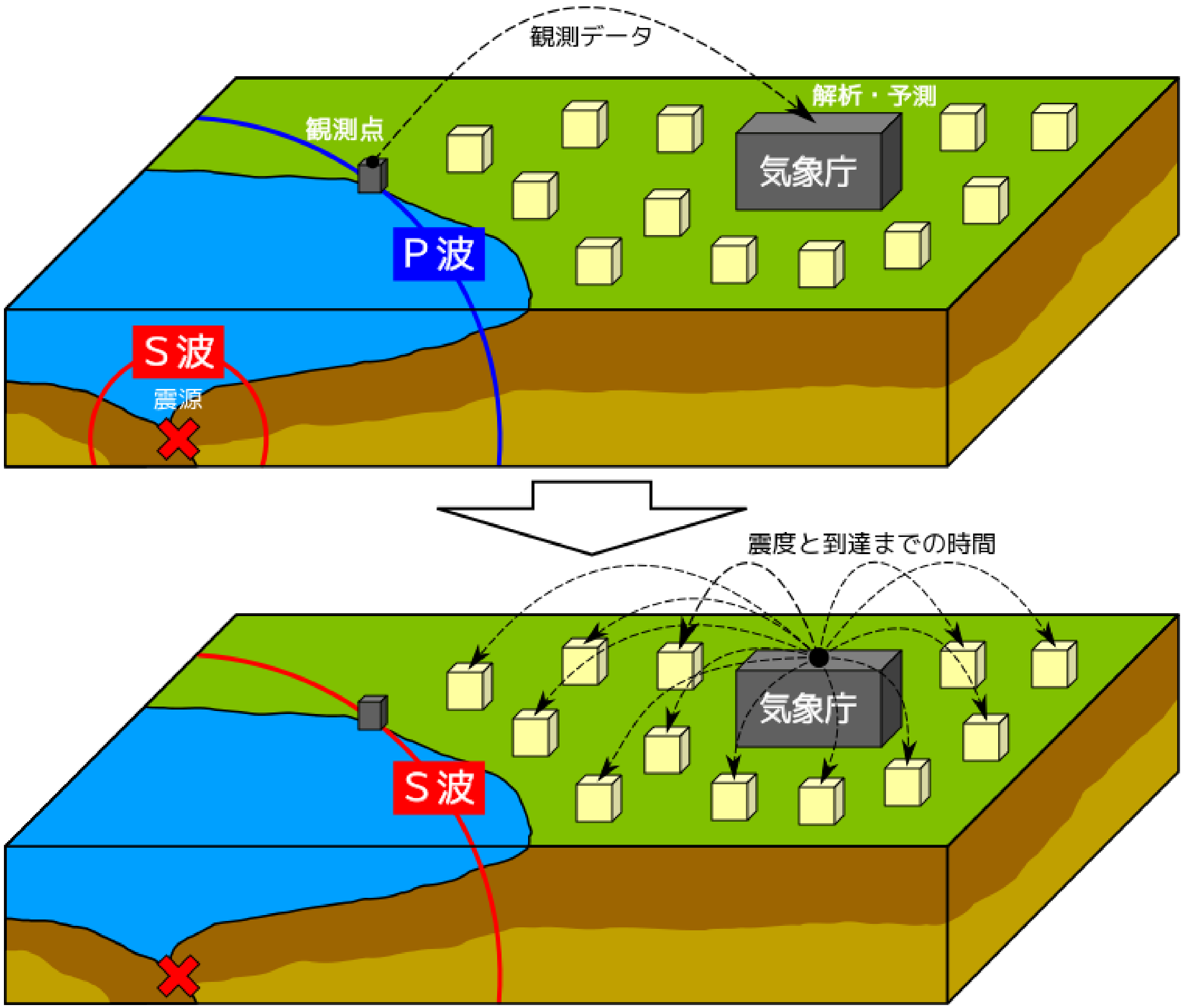
FAST EARTHQUAKES WARNING: single and multiple devices



The arrival of P waves allows to warn for the arrival of much stronger **S** and surface waves. The warning time depends on the distance from the epicenter. In Japan the majority of the earthquakes are originated in the sea, therefore it is possible to have from few seconds to minutes warning. Elsewhere most of the earthquakes are originated in populated areas, therefore any possibility of warning has to rely on extremely **low noise** and **high sensitivity** devices… like the **PLI**.

The **PLI** has multiple possible applications: earthquakes detection and warning (it is deployed in Armenia for the monitoring of seismic activity), active feedback for the stabilization of very sensitive devices, site protection, human activity detection, anomalies of Sun-Moon cycles and many others still to discover…

Japan Earthquakes early warning



Earthquake Early Warning in Japan: When two or more seismometers[1] detect P-waves (top image), the JMA immediately analyzes the readings and distributes the warning information to advanced users such as broadcasting stations and mobile phone companies, before the arrival of S-waves (bottom image).

Alerting system based on observations

- Prediction of earthquakes is probably impossible
  - The list of “precursors” is long and there is not a magic one, but rather the use of multiple indicators (electromagnetic effects, recent seismic activities, gas emissions, etc.)
- A network of PLIs can monitor a large geographical area: LHC ring or a specific seismically active area
  - As an example in Armenia there are 3-4 earthquakes/day, around active volcanic areas smaller earthquakes can be precursors of eruption (Vesuvius and Pozzuoli area, Etna)

Who has been involved in the development

Personnel involved

- CERN
  - Myself since the ATLAS time. General coordination, IoT-based development, Python-based time and frequency domain analysis, NN architecture
  - Two experts surveyors for consultancy and evaluation of the results
- JINR and Armenia
  - General coordination, long standing collaboration (25 years) in many experiments.
  - Expert surveyors and particle physicists: Readout development, IoT-based development, instrumentation and setup, expertise in gravitational waves detection, Origin-based analysis, NN development
  - Mechanical engineers and designers for the construction
  - Geologists from Armenia: deployment of devices, network software, IoT-based readout development
- Past funding: JINR and HL-LHC budgets

Author list and publication

- N. Azaryan, I. Bednyakov, J. Budagov*, B. Di Girolamo*, J.-Ch. Gayde, V. Glagolev, M. Lyablin, D. Mergelkuhl, A. Pluzhnikov, G. Trubnikov (CERN & JINR) * Team leaders
- Support from V. Matveev, V. Bednyakov, L.Rossi, O. Bruning for the developments
- 11 published articles and 5 in preparation for publication


LETTERS PEPAN

Joint Institute for Nuclear Research

Diploma

of the winner for 2015

for the best publication in "Physics of Elementary Particles and Nuclei, Letters" journal, Joint Institute for Nuclear Research

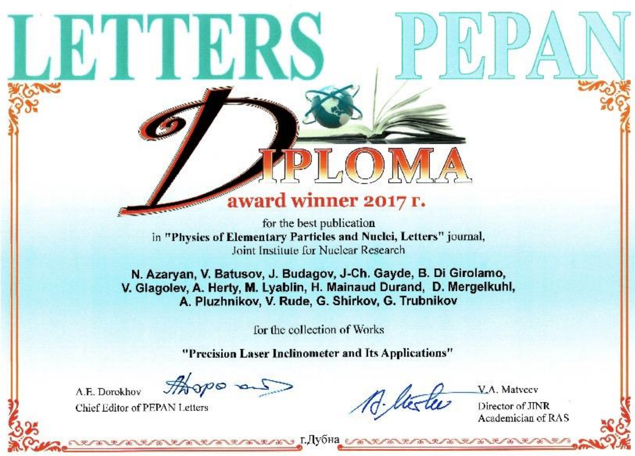
Beniamino Di Girolamo

for the cycle of works "The Precision Laser Inclinometer" (2013-2015)

Director of JINR, Academician of RAS — V.A.Matveev

Editor-in-Chief — A.E.Dorokhov

Dubna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N. Azaryan, V. Batusov, J. Budagov, J-Ch. Gayde, B. Di Girolamo, V. Glagolev, A. Herty, M. Lyablin, H. Mainaud Durand, D. Mergelkuhl, A. Pluzhnikov, V. Rude, G. Shirkov, G. Trubnikov

for the collection of Works

"Precision Laser Inclinometer and Its Applications"

A.E. Dorokhov, Chief Editor of PEPAN Letters

V.A. Matveev, Director of JINR, Academician of RAS

г.Дубна

What is needed to bring it further

Scope: deployment of PLI networks

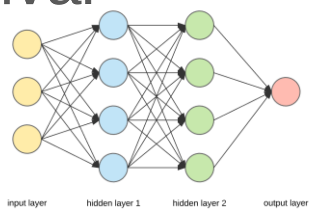
- We have built the mechanics for 6 PLIs
  - They can be deployed at CERN to develop the networking software and monitor seismic activity
  - They can deployed in LHC or around an experiment to finalize the preparation of more devices for deployment in remote areas

What is needed: first phase

- We need to instrument the produced mechanics with optical and movement devices
  - Lenses, prisms, lasers etc.
  - Piezo actuators and controllers for the calibration system
- We need to develop a software for signal combination from the network of PLIs
- We need to have an installation with inter-distances matching the frequencies of the seismic events to be monitored

Second phase: make it better, make it cheaper

- More powerful analysis with deployment of fast artificial neural networks and other techniques used in earthquake studies
  - Used in the past for the identification of arrival phases, extensive literature
  - Experience from particle physics analysis



- Simplification: from a scientific instrument to easy to use device
  - Minimization of components and study of associated drawback: it has been built in a modular way
  - Move of readout to IoT approach: already started

A rough financial estimation over three years

- Optical equipment for the full seismic telescope: 40 kCHF
- Readout system (present and development): 25 kCHF
- Ancillary equipment: 5 kCHF
- Computing hardware for high performance computing studies: 10-12 kCHF
- Development of commercial version: 50 kCHF
- Man power: 2 PJAS for three years for development, assembly, installation, maintenance

Conclusions

- The Precision Laser Inclinometer device and a seismic telescope built with few PLIs can have a high societal impact
  - Monitoring of active areas for early warning of possible events
  - Monitoring of highly active seismic areas for alerting system with very high resolution devices
- It is based on the work of a robust international team
- It needs development to become a more affordable and easy to use device and explore extension of sensitivity ranges
- Funding has been obtained in the past for HEP applications
- There is interest by gravitational waves detection (EINSTEIN Telescope,…) and μ to e transition precision (COMET, MUoNE,…) experiments in HEP
- We need help to direct the studies for applications outside HEP: we had interests expressed by Japanese colleagues and electronics industry, but we need the baby still to grow