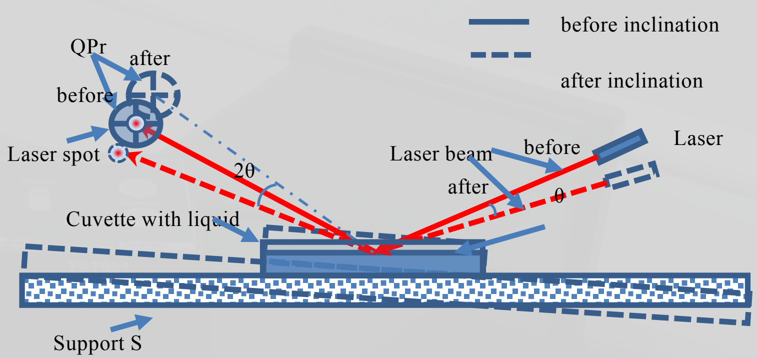
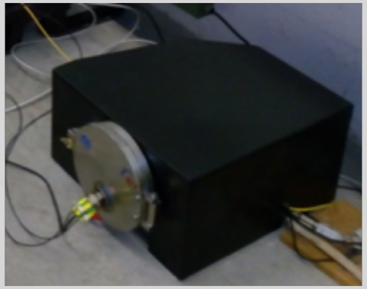


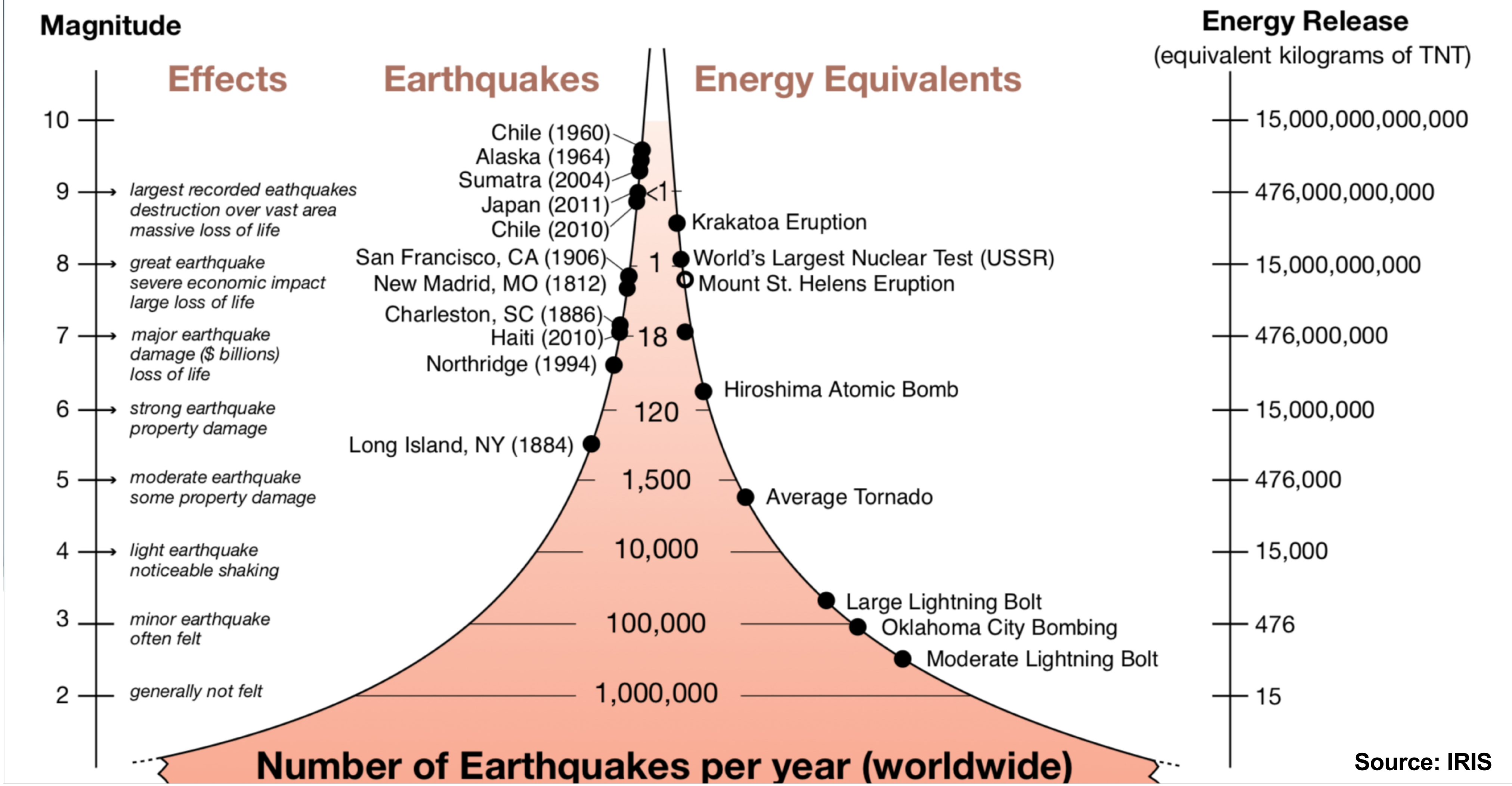


CERN/JINR Collaboration – high precision seismic measurements

The Precision Laser Inclinometer

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

APPEC Technology Forum – Veldhoven – 12-13 November 2018



Earthquakes are always happening somewhere.

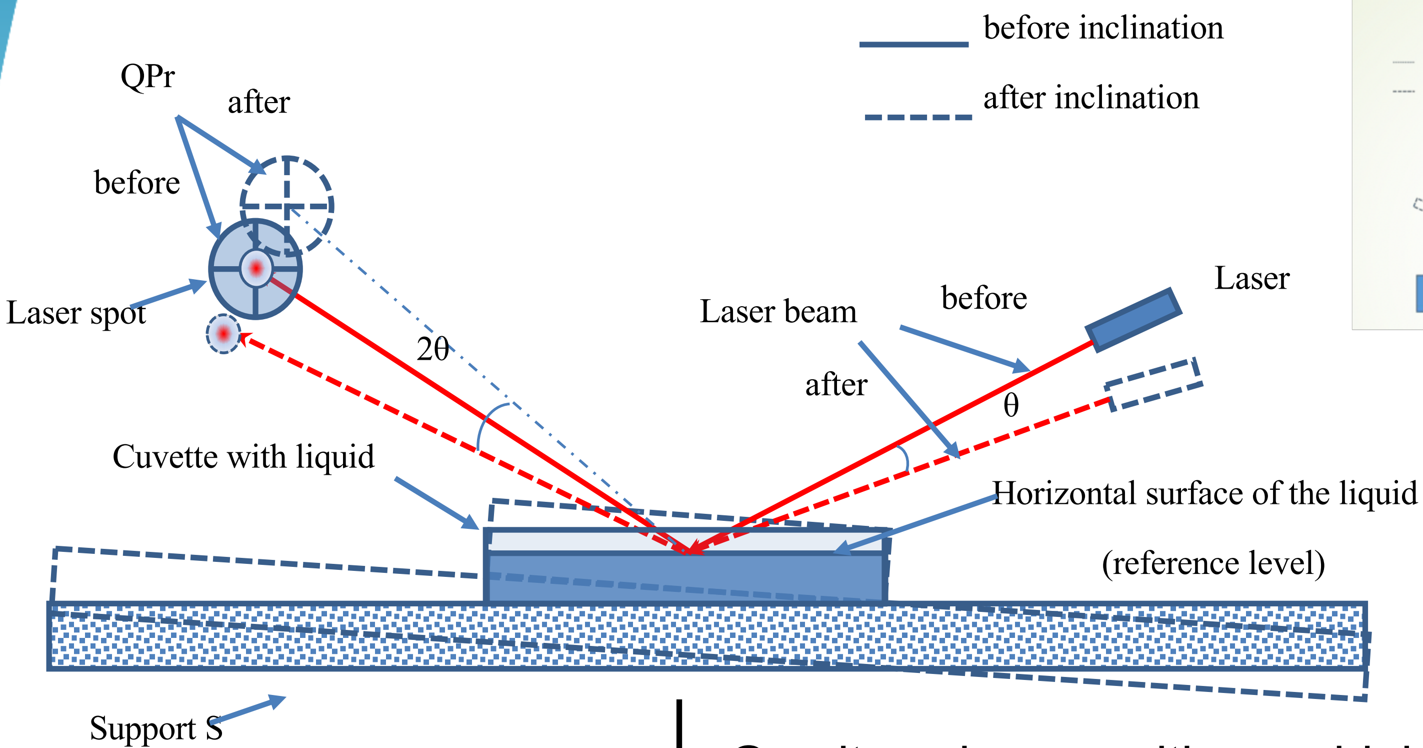
Magnitude 2 and smaller earthquakes occur several hundred times a day world wide. Major earthquakes, greater than magnitude 7, happen more than once per month. "Great earthquakes", magnitude 8 and higher, occur about once a year.

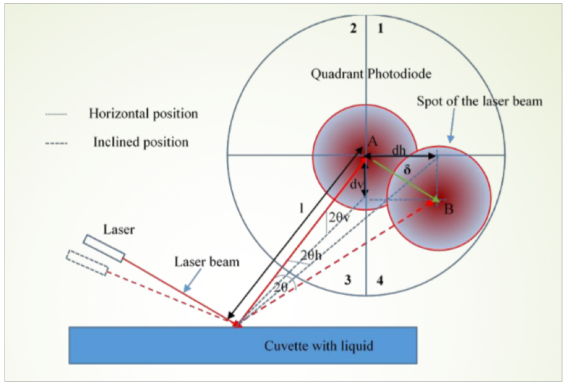
Outline

- The Precision Laser Inclinometer instrument
  - Principle
  - Current applications: metrology and effects on colliders
  - Experimental setup at CERN
  - Measurements and achieved precision
- Applications
- First steps towards a feedback system
- Conclusions

Working principle and current setup of the Precision Laser Inclinometer (PLI)

PLI 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

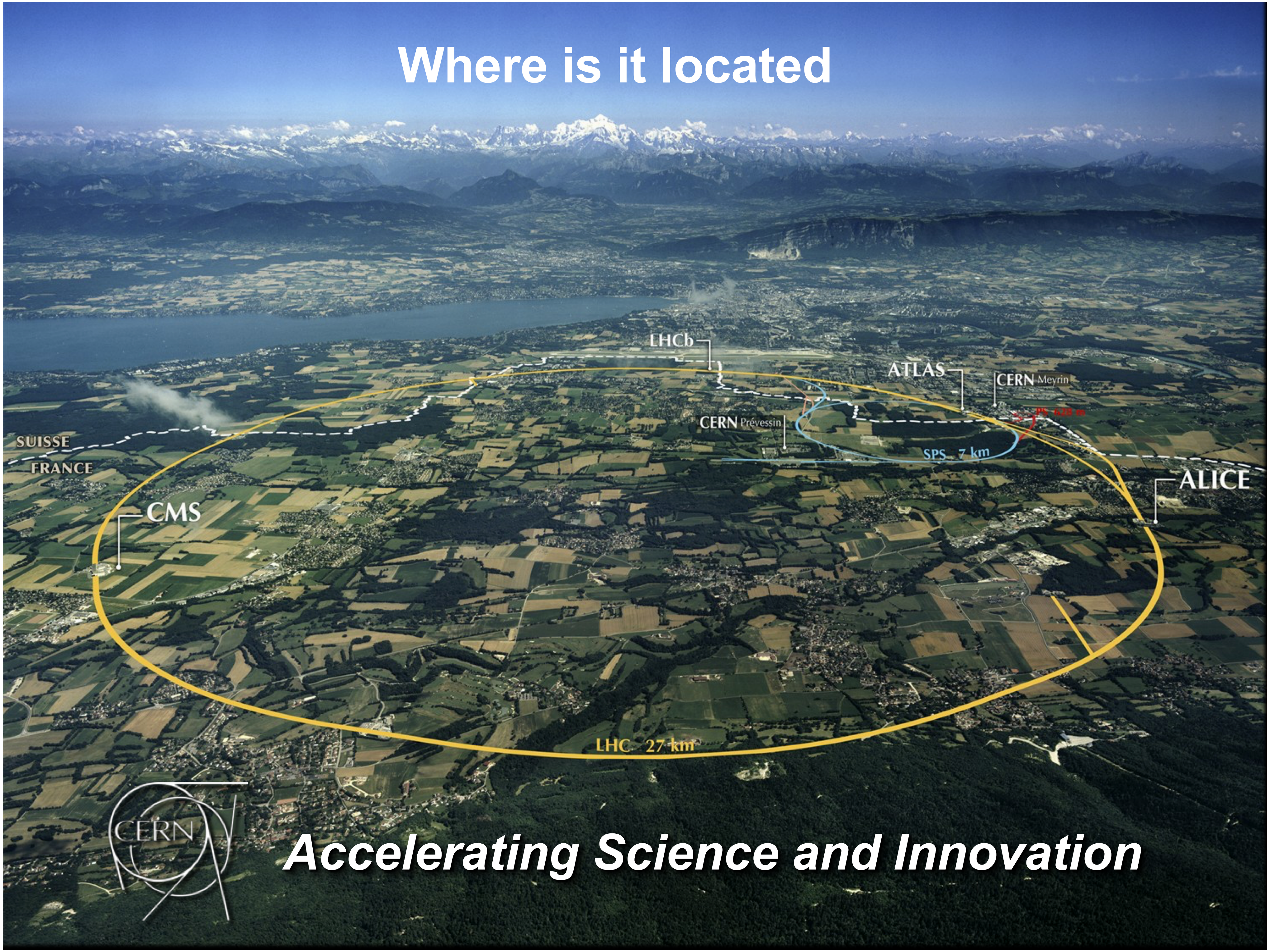
How it looks like in real life

- The assembly has been carefully engineered to house in a compact way the core measurement parts as well an interferometric calibration system. The sensitive volume is under vacuum.

24 bit ADC

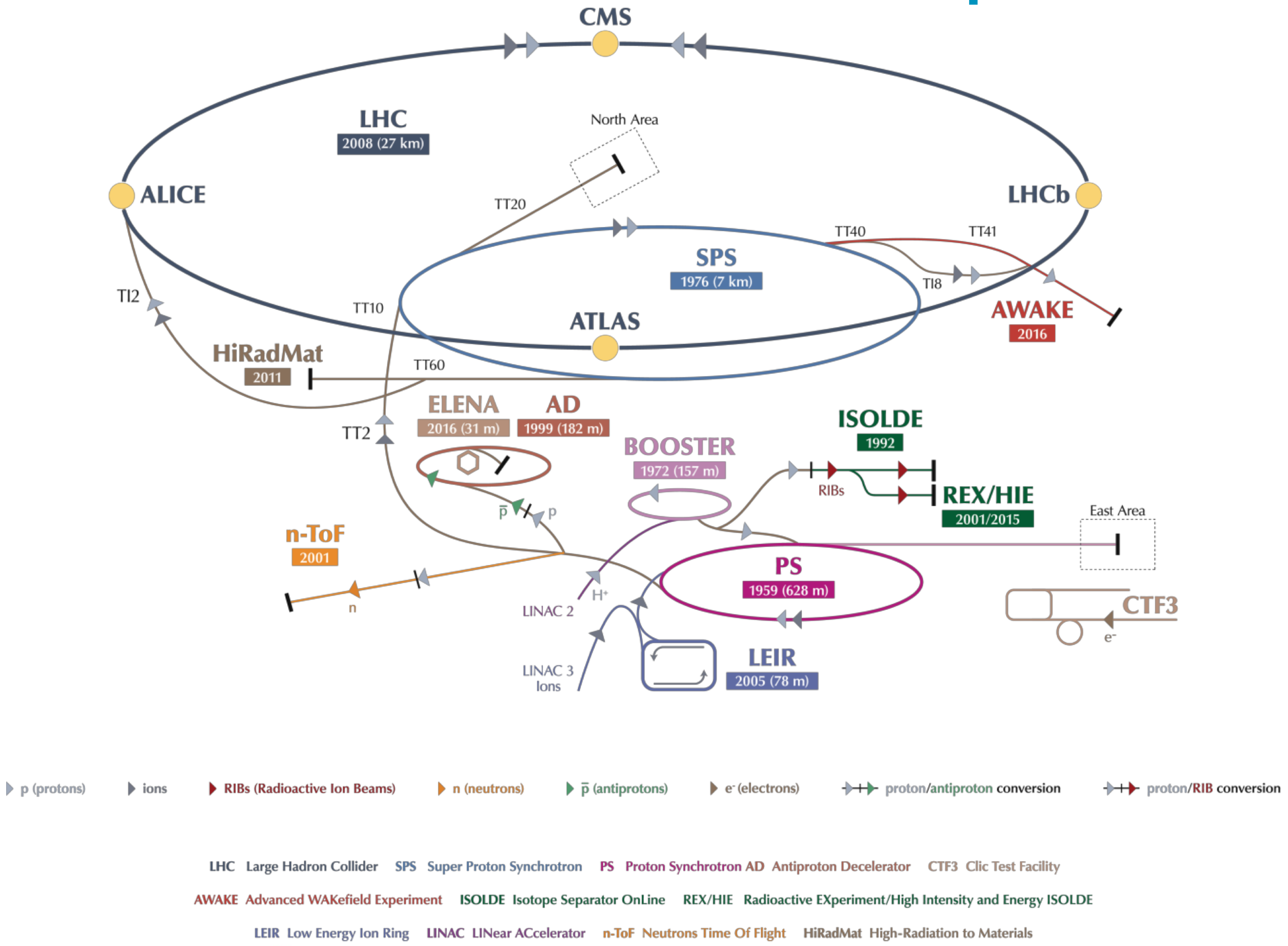
Storage

Where is it located

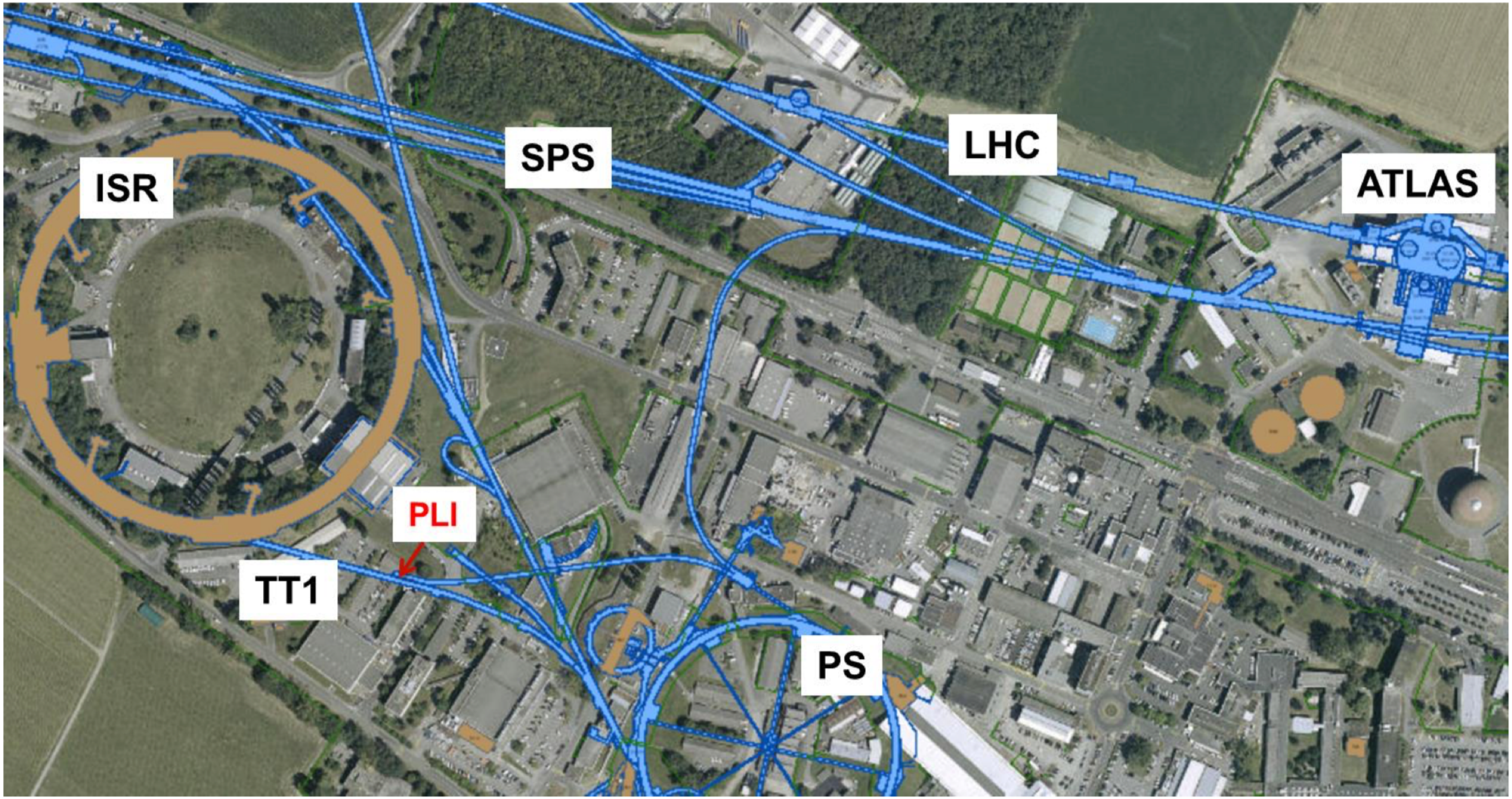


Accelerating Science and Innovation

CERN accelerators complex



Installation at CERN: TT1 Tunnel



Very stable ground and temperature conditions

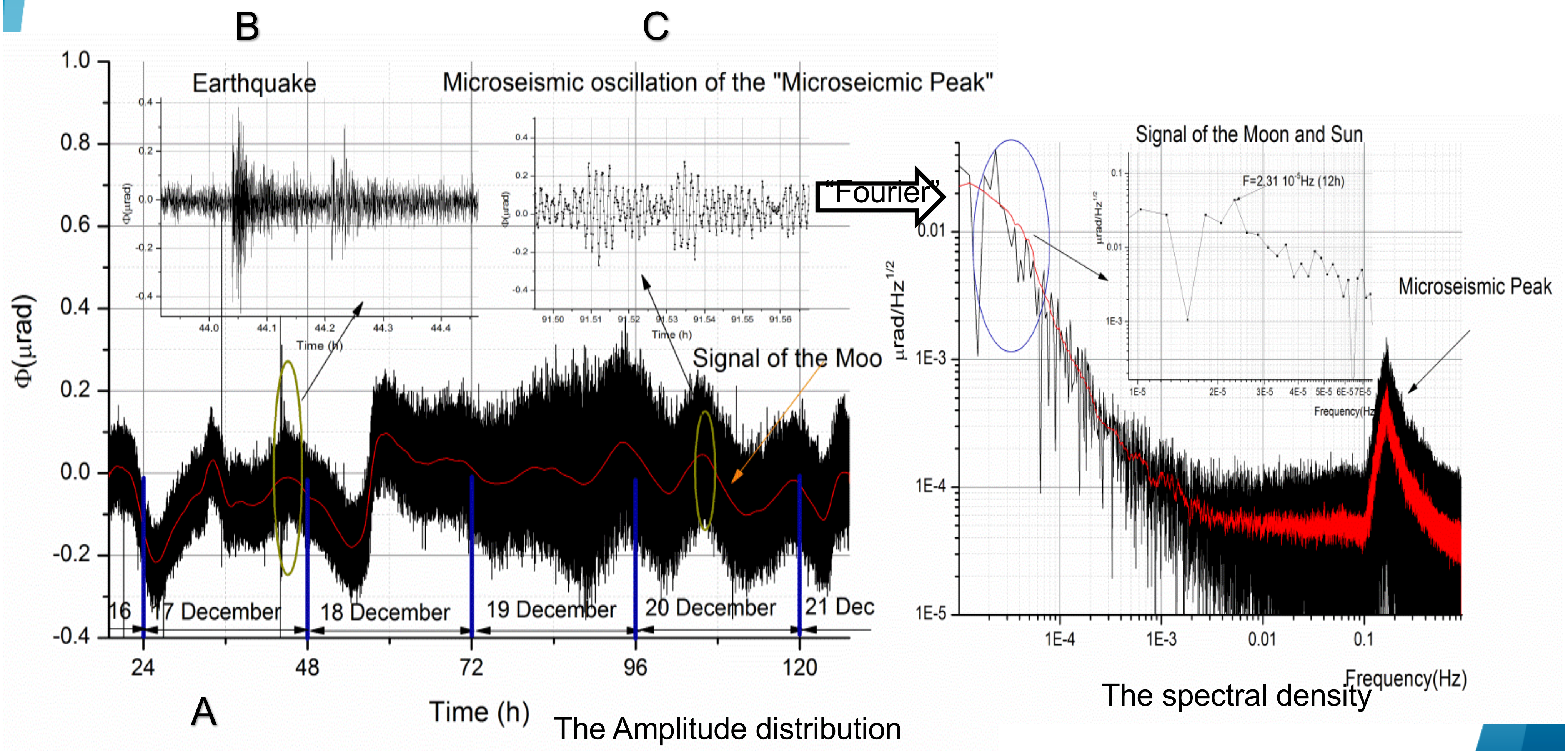
What was it invented for and what has it been also used for

Nanometrology program at JINR Dubna

- JINR has invested in building several instruments for high precision metrology: the PLI is one of them.
- Originally thought to monitor the stability of underground experimental caverns that are naturally lifted and distorted by hydrogeological effects.
- The large multi-tons detectors move and therefore the colliding beams at their center and/or the detector have to be re-positioned.
- Order of magnitude 100 μm/year lift. Typical inner tracker resolutions 10-30 μm. Beam size at collision ~ 15 μm.

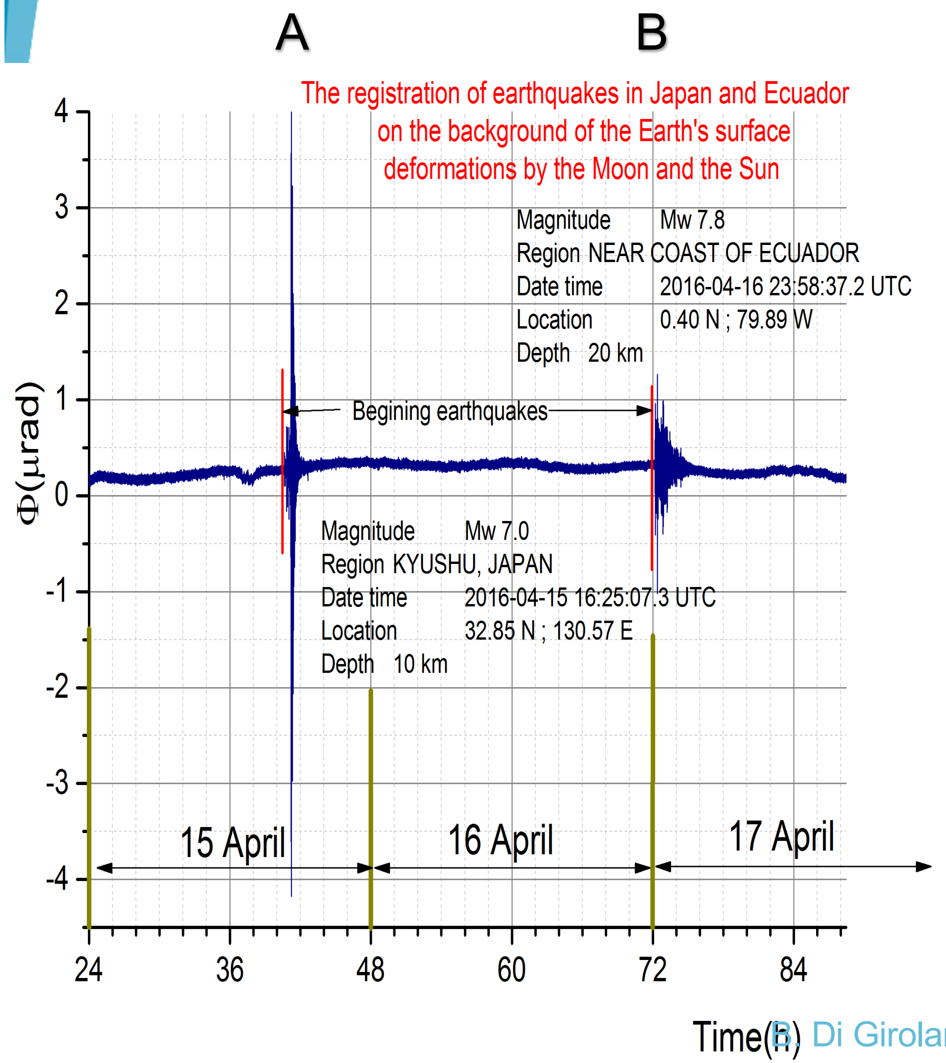
BUT it does more: first basic results

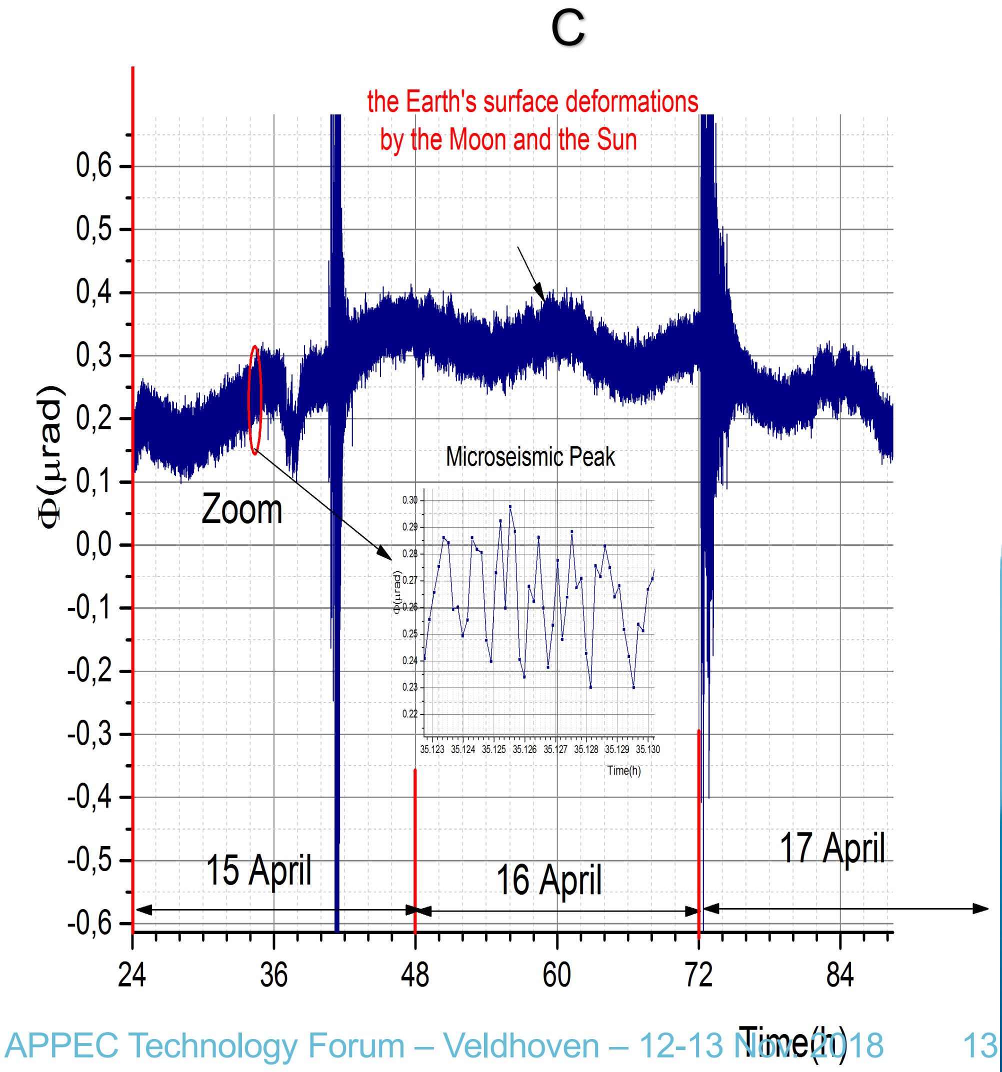
These PLI-detected ground motions are caused by the Moon and Sun (**A**); by an Earthquake in Mexico (**B**); by the “microseismic” kicks (**C**).



Simultaneous measurements

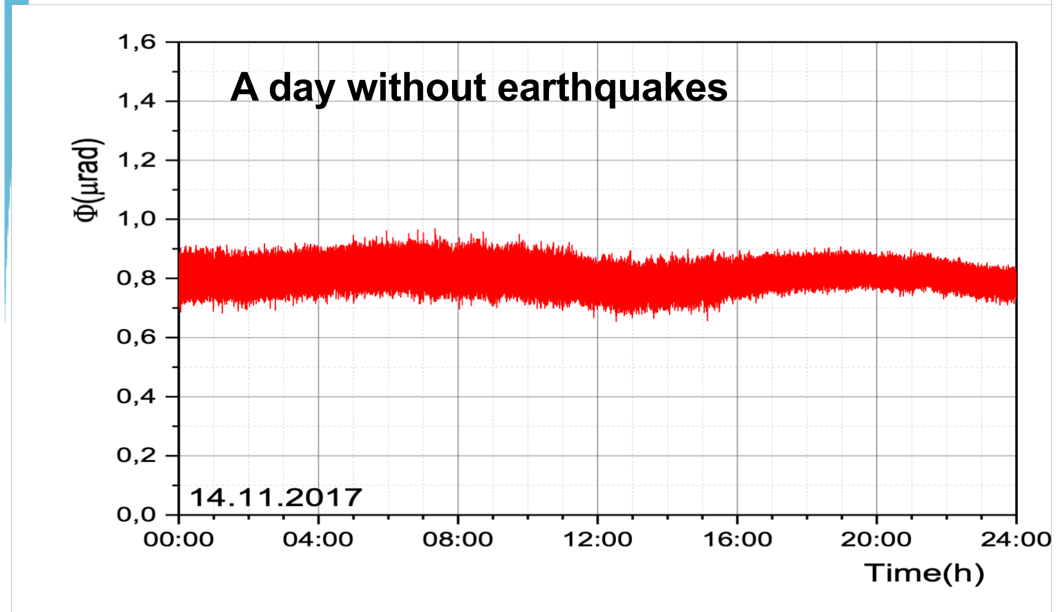
An example of the PLI reliability is the simultaneously recording at CERN of: the Earth Surface distortions by the Sun and Moon (**C**), by Ecuador (**B**) and Japan (**A**) Earthquakes in April 2016.

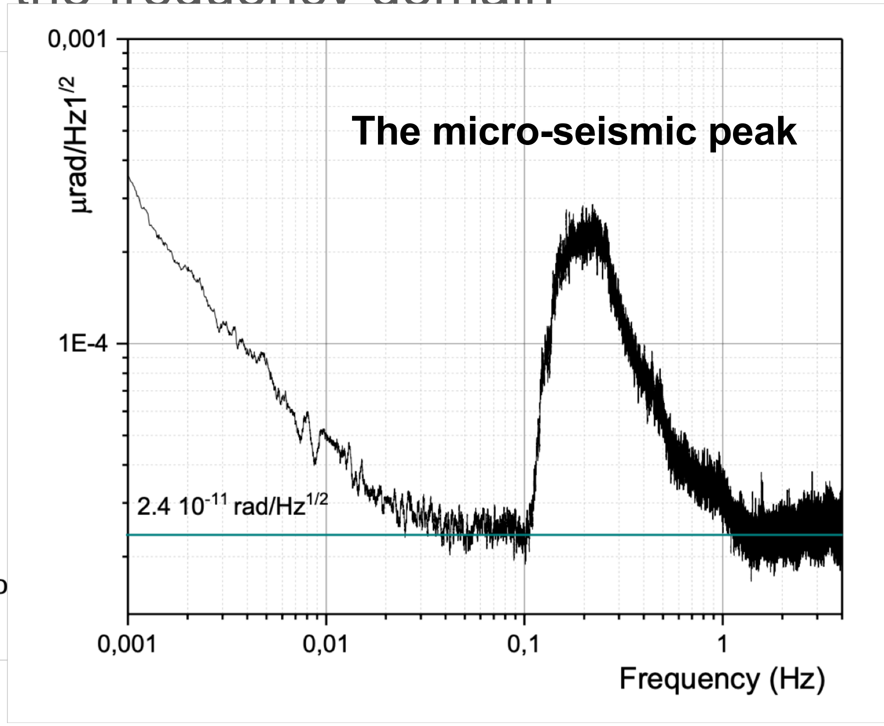




How precise

- No direct measurement is possible due to the constant presence of irregular micro-seismicity and there is no comparable precision instruments: therefore analysis in the frequency domain



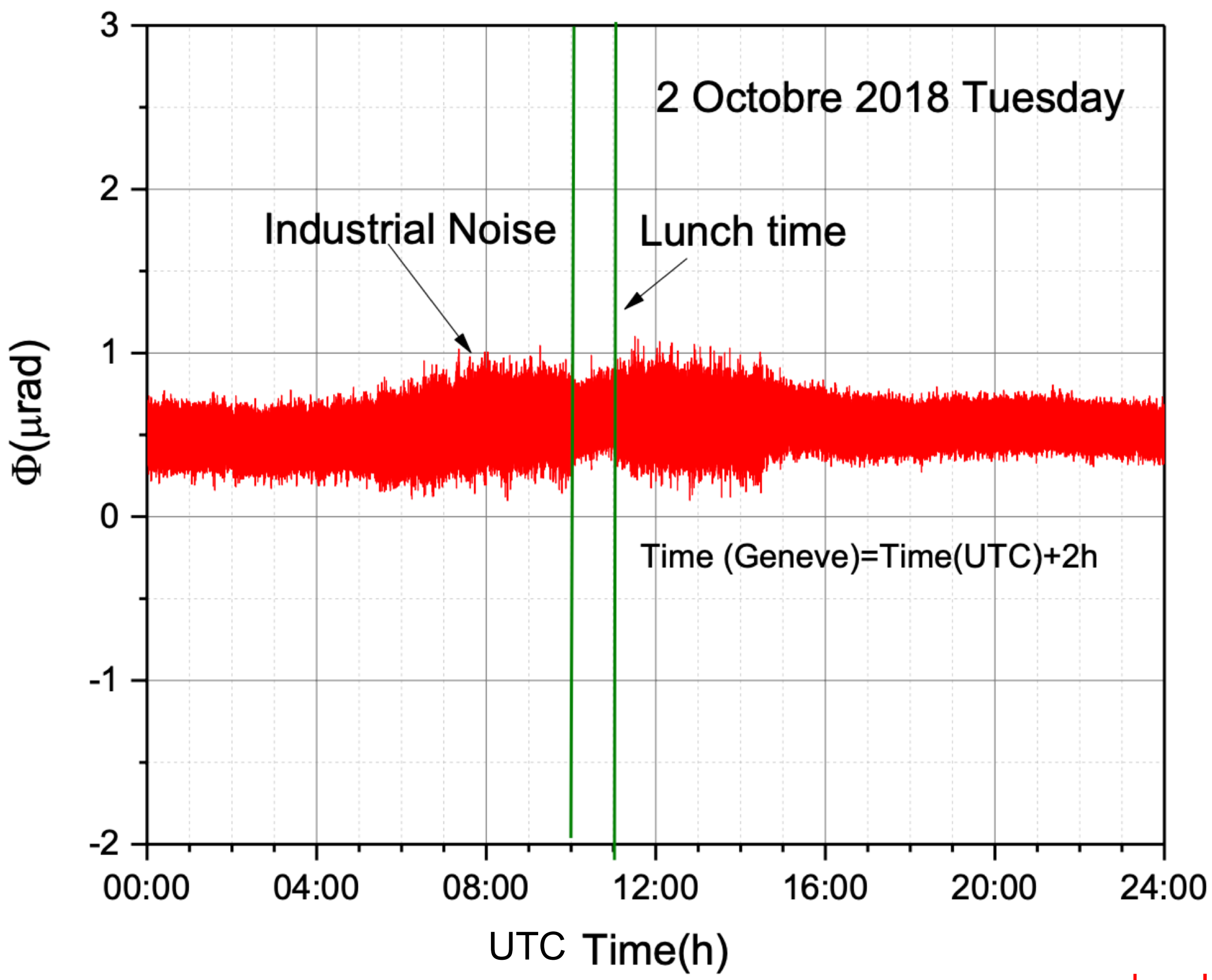


A precision of **$2.4 \cdot 10^{-11}$ rad/Hz$^{1/2}$** in the frequency range **[10^{-3},12.4] Hz**

A precision better than **10^{-9} rad/Hz$^{1/2}$** in the frequency range **[10^{-6}, 10^{-3}] Hz**

Real life: the seismic effects of/at CERN

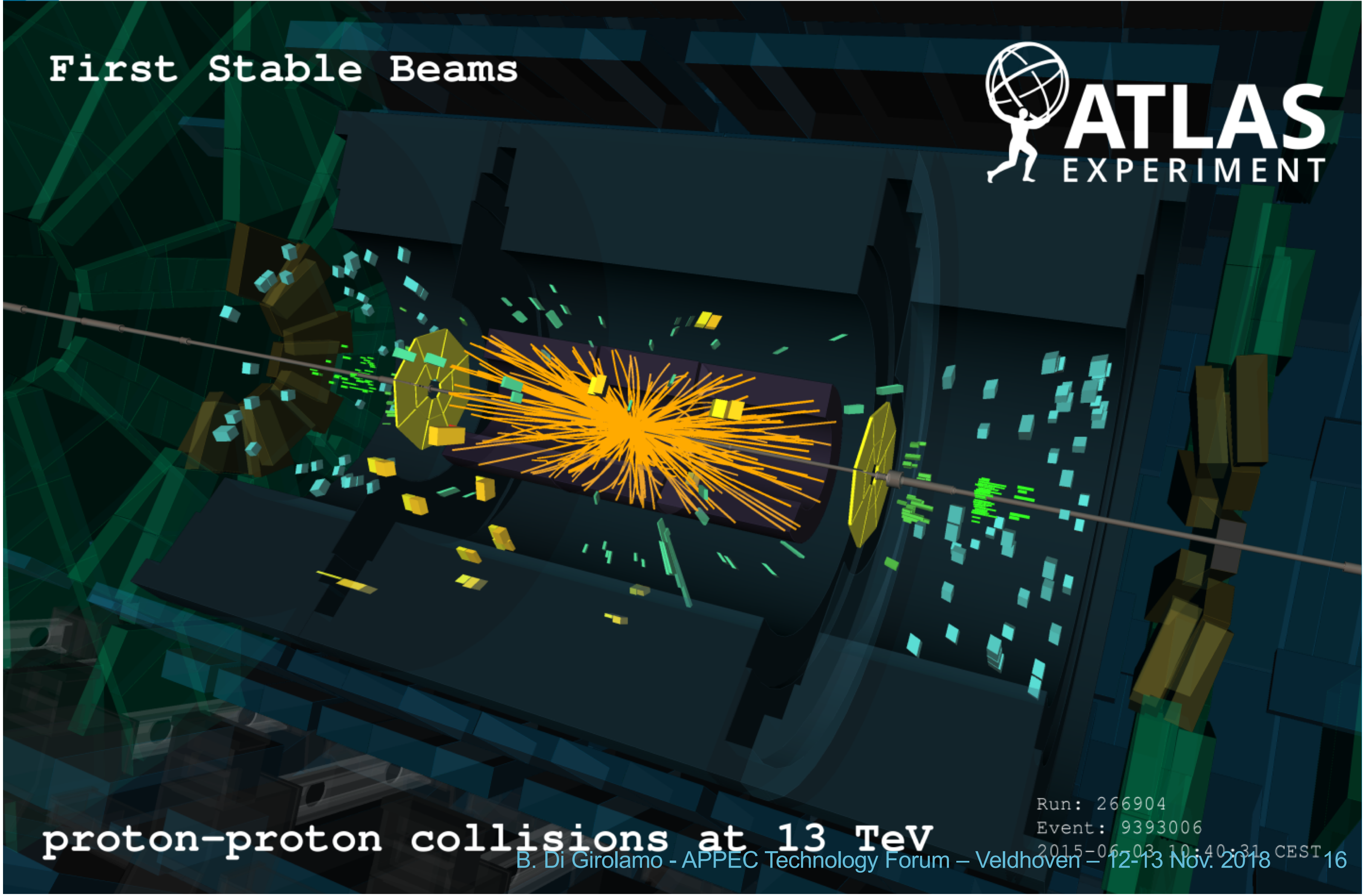
Working day: 0.5-1 μrad during the day; ~ 0.3 μrad during lunch
Start of industrial noise at around 7:00-7:30



High stability during the weekend with maximum amplitude ~ 0.3 μrad

Local time = UTC + 2

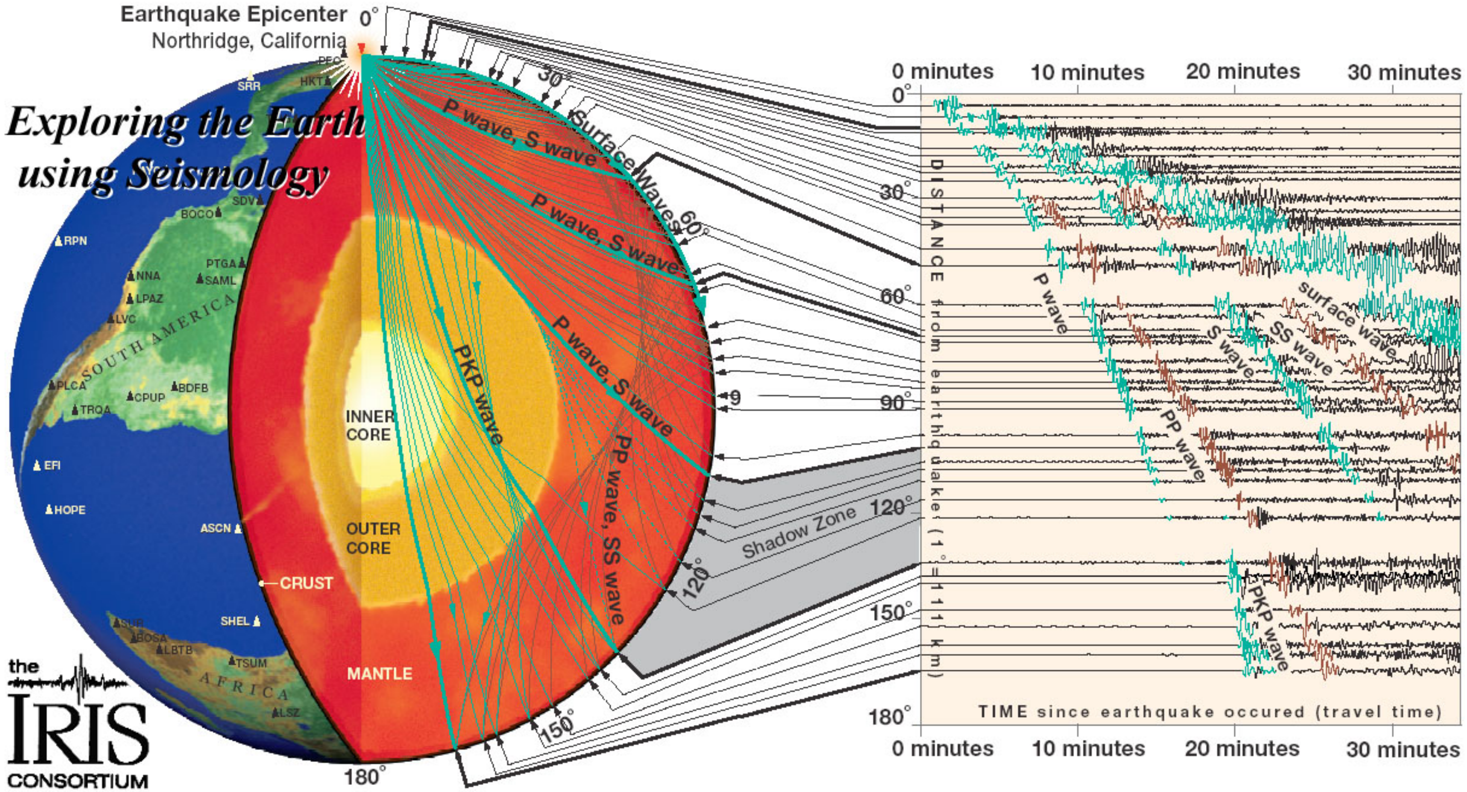
Effects of seismic events on accelerators



Waves from Earthquakes

The different types of body (Pressure, Shear) and surface (Rayleigh, Love) waves, the multiple paths and reflections of the wave produce a complex signature of earthquakes at seismic measurement stations – and also at the LHC.

Although the seismic activity in the Geneva area is very low, waves from far away earthquakes can affect the LHC.



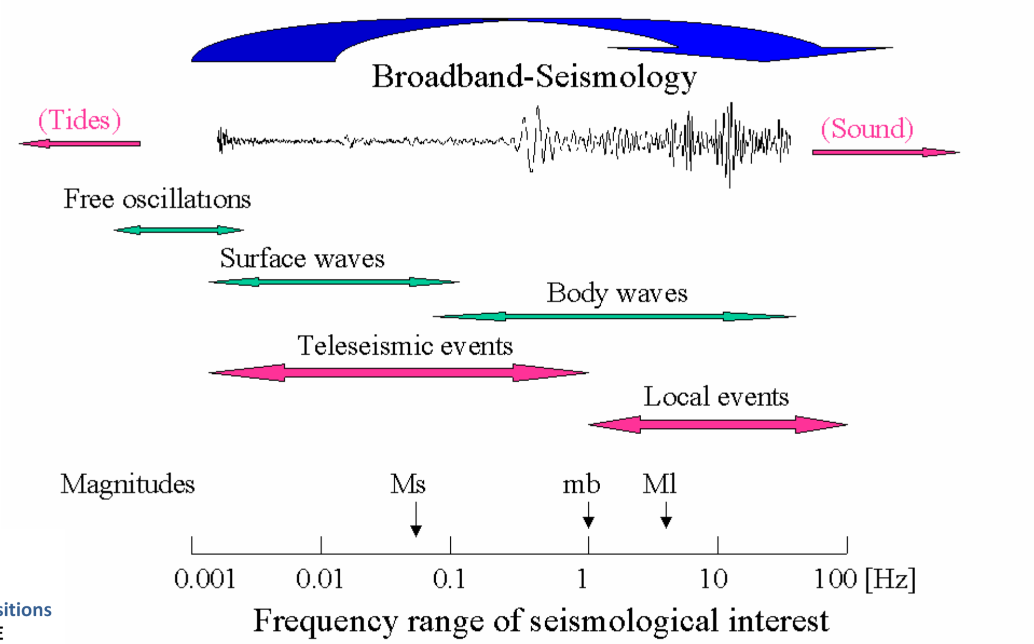
L. Braille (Purdue U.) / The IRIS (Incorporated Research Institutions for Seismology) consortium

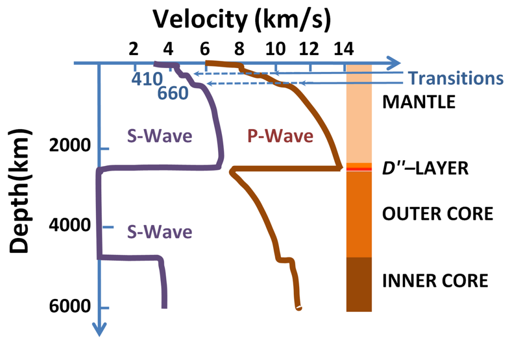
Frequencies of Earthquakes

- 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.

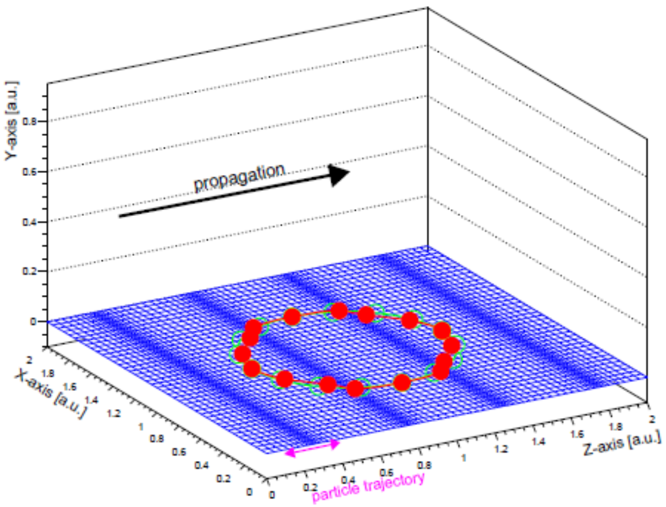
➢ Ground motion from local earthquakes extends to higher frequencies.

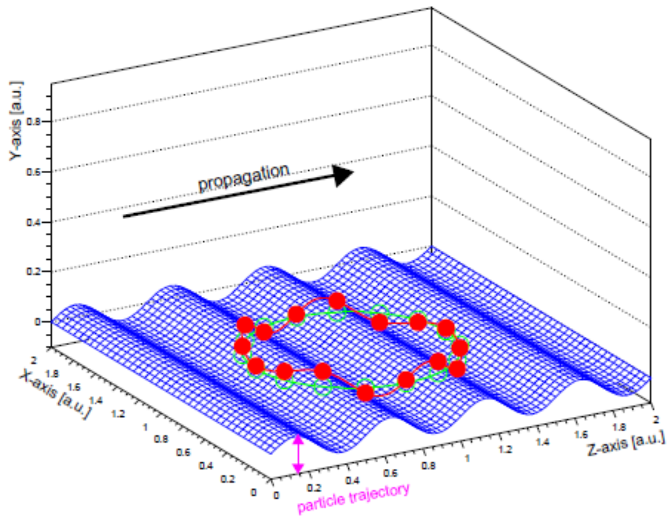




Effect of seismic waves on LHC

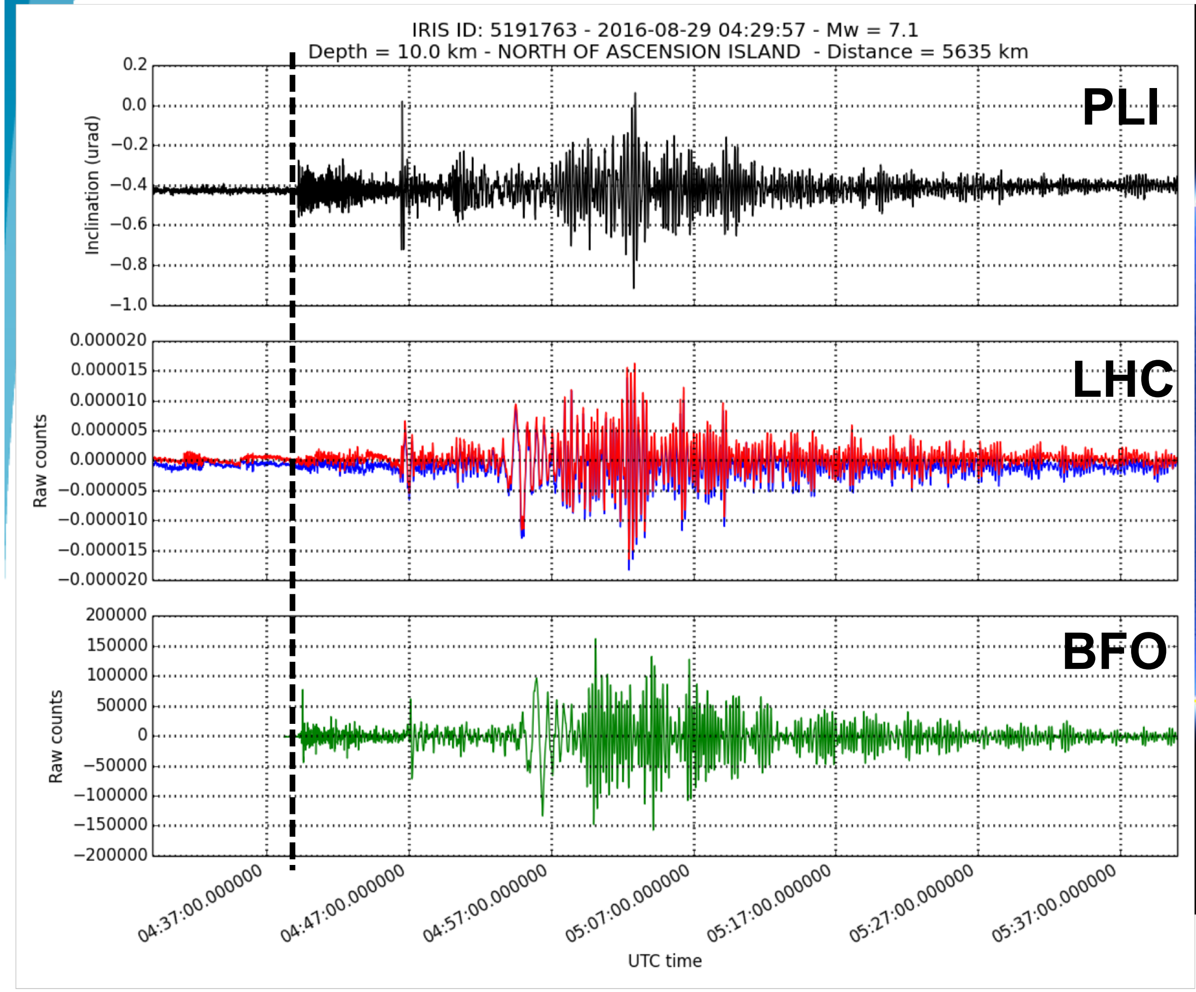
- There are many types of seismic waves, the fastest travel at ~6 km/s, the slower ones at ~4 km/s. The ground movement can be longitudinal or transverse wrt to the propagation direction.
- The impact on LHC of seismic waves depends on amplitude, wavelength (lattice resonances), wave type (longitudinal, transverse).





Observations with PLI

Far earthquakes: Ascension Island

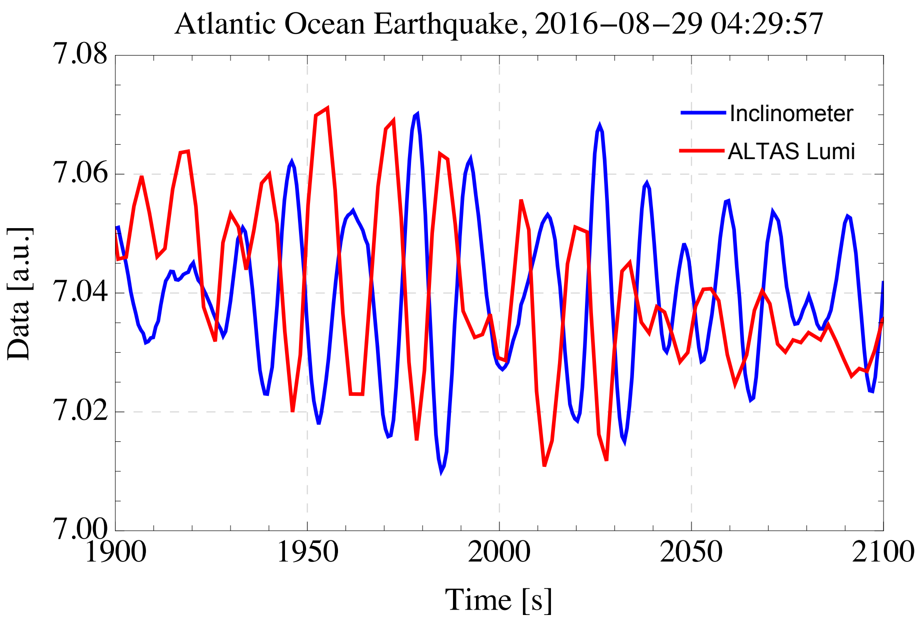


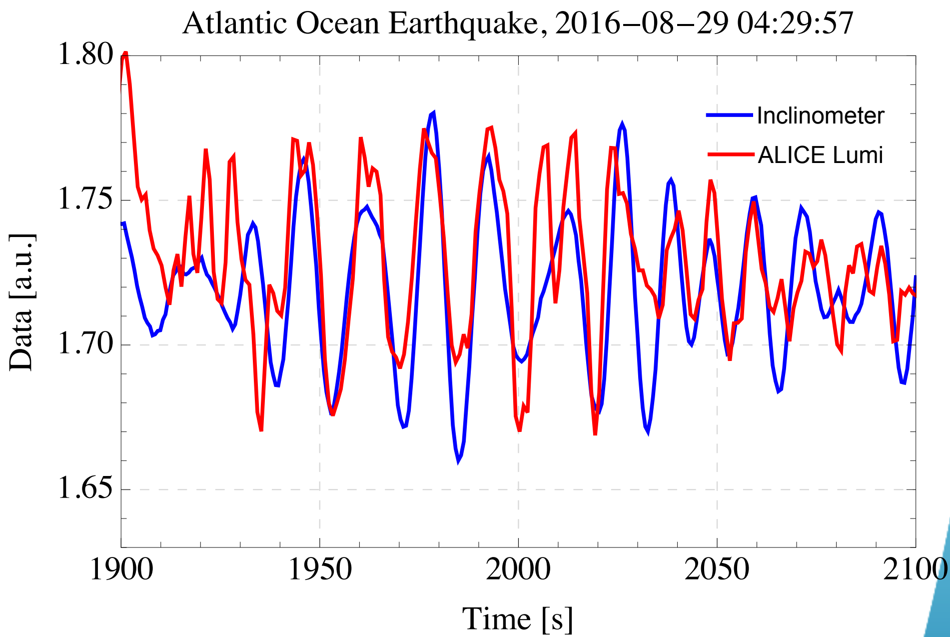
The PLI detection compared to the horizontal orbit oscillations of LHC. As confirmation also the seismogram from the Black Forrest Observatory (which receives it later, as expected).

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.

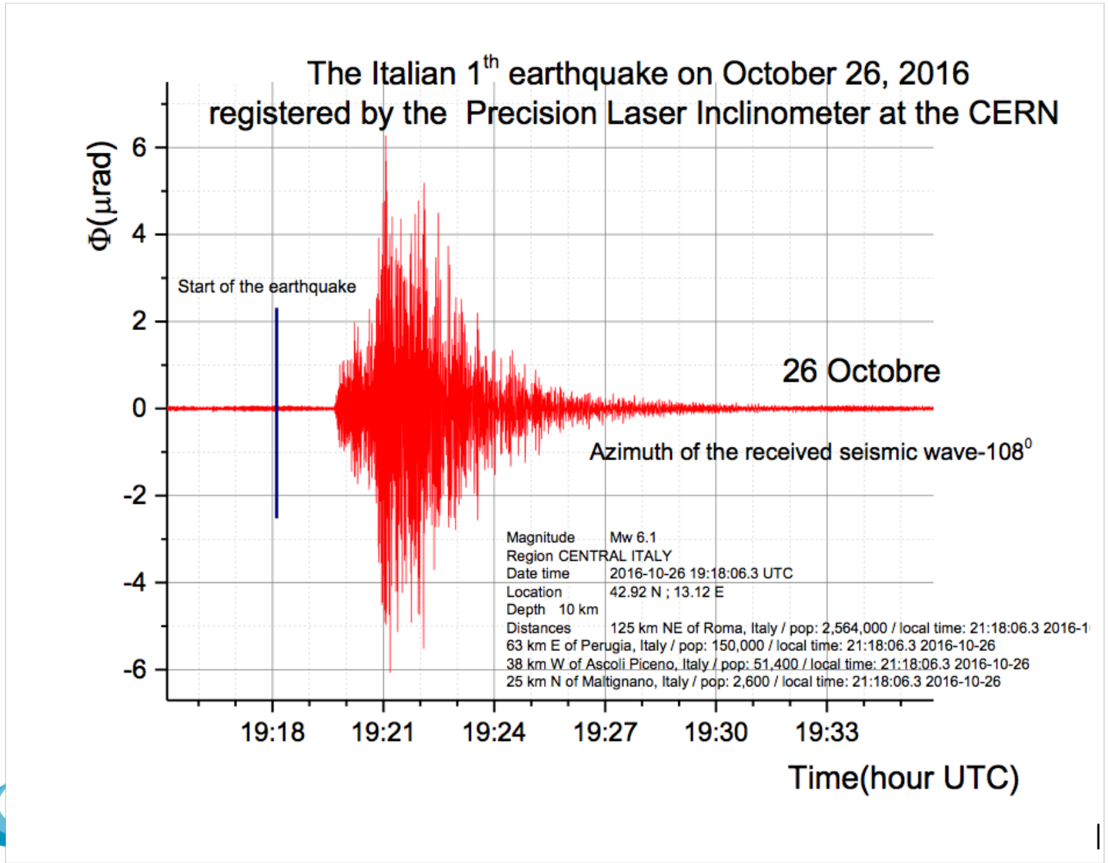


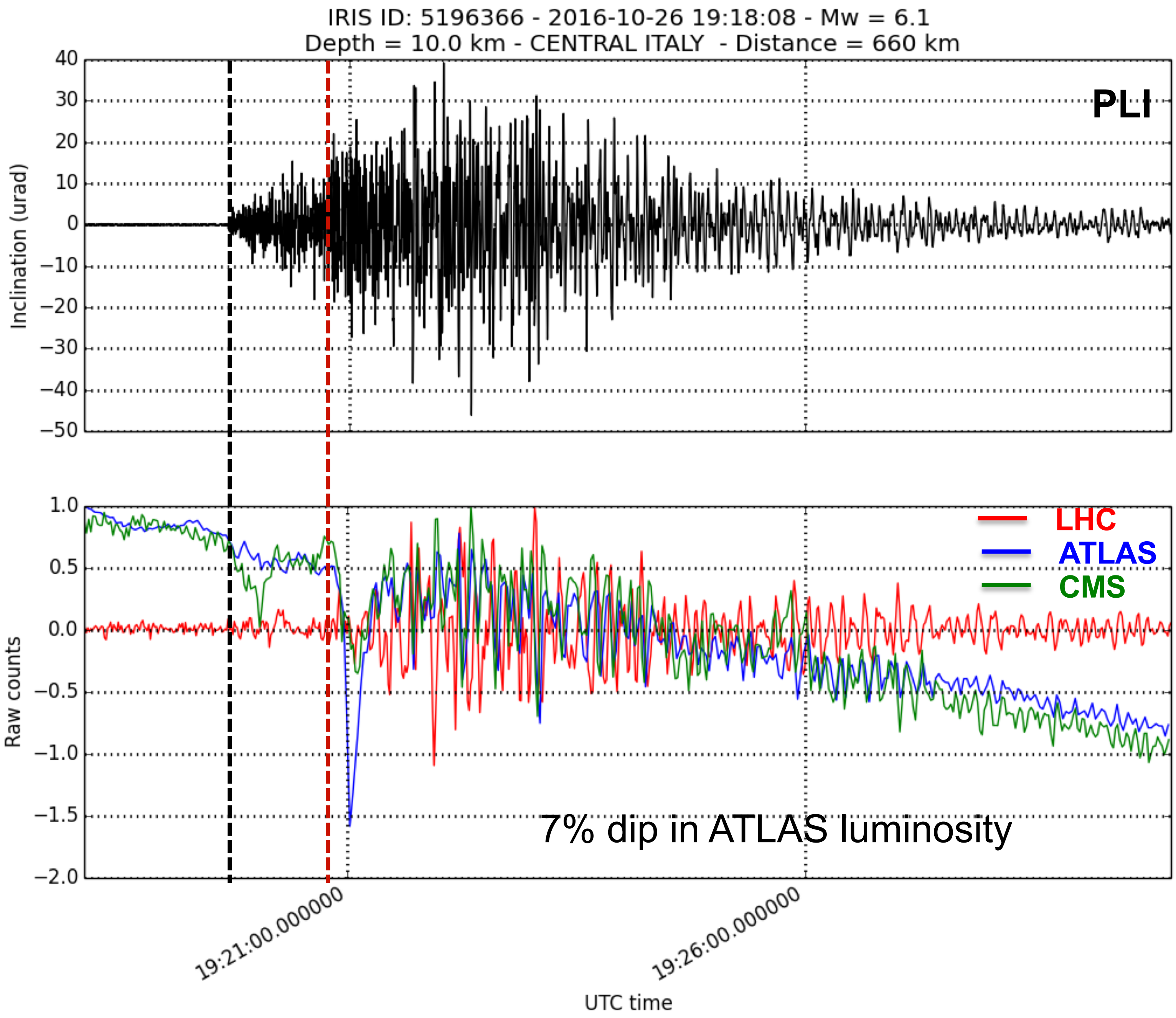


Near earthquake: Italy, 26th Oct. 2016

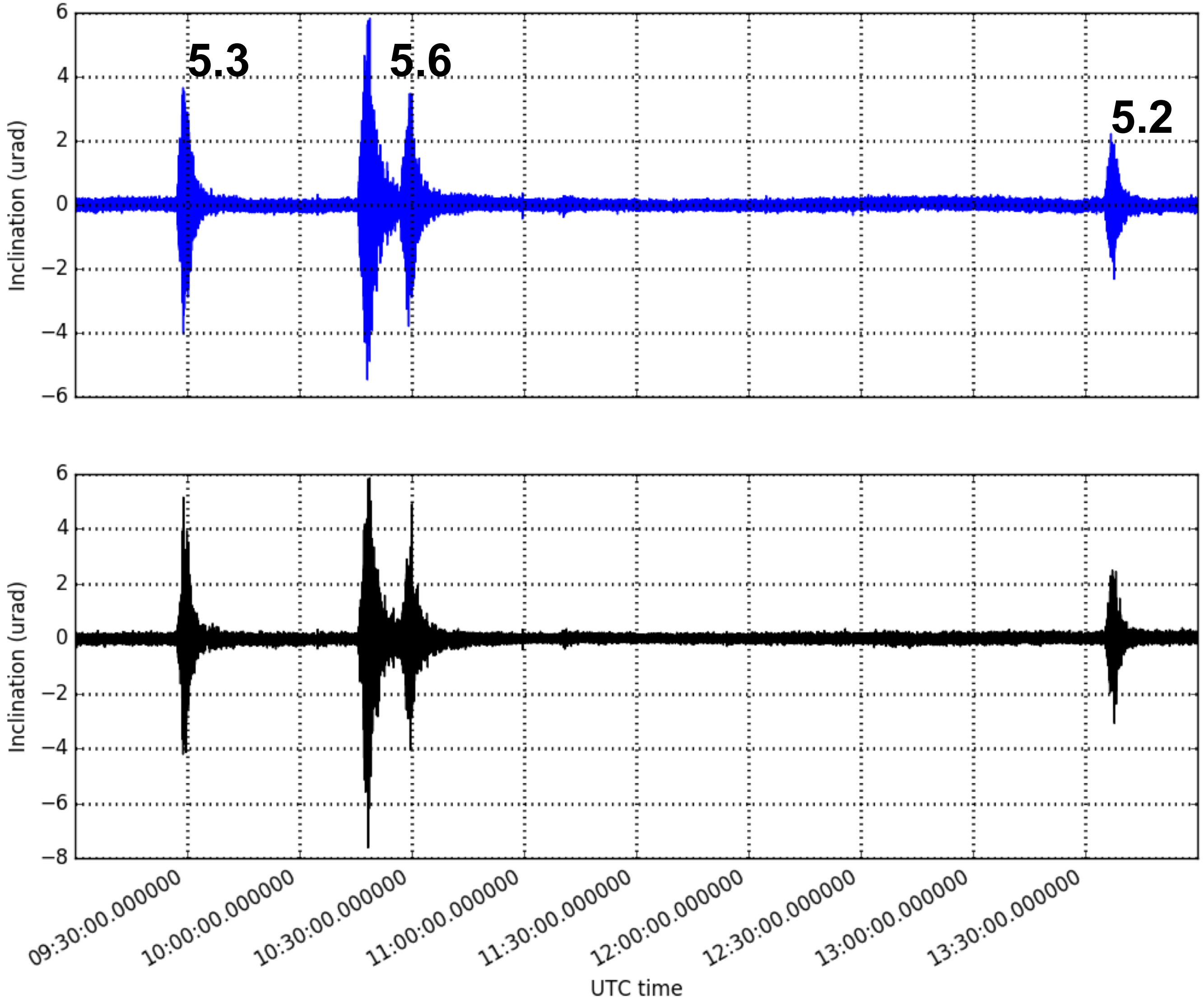
Magnitude 6.1 in ITALY
October 26, 2016 at 19:18:06 UTC

Recording of the event by the PLI.
The record provide the slop in two dimensions, it is therefore possible to **calculate the slope and the azimuth to determine the direction of the wave w.r.t. LHC**



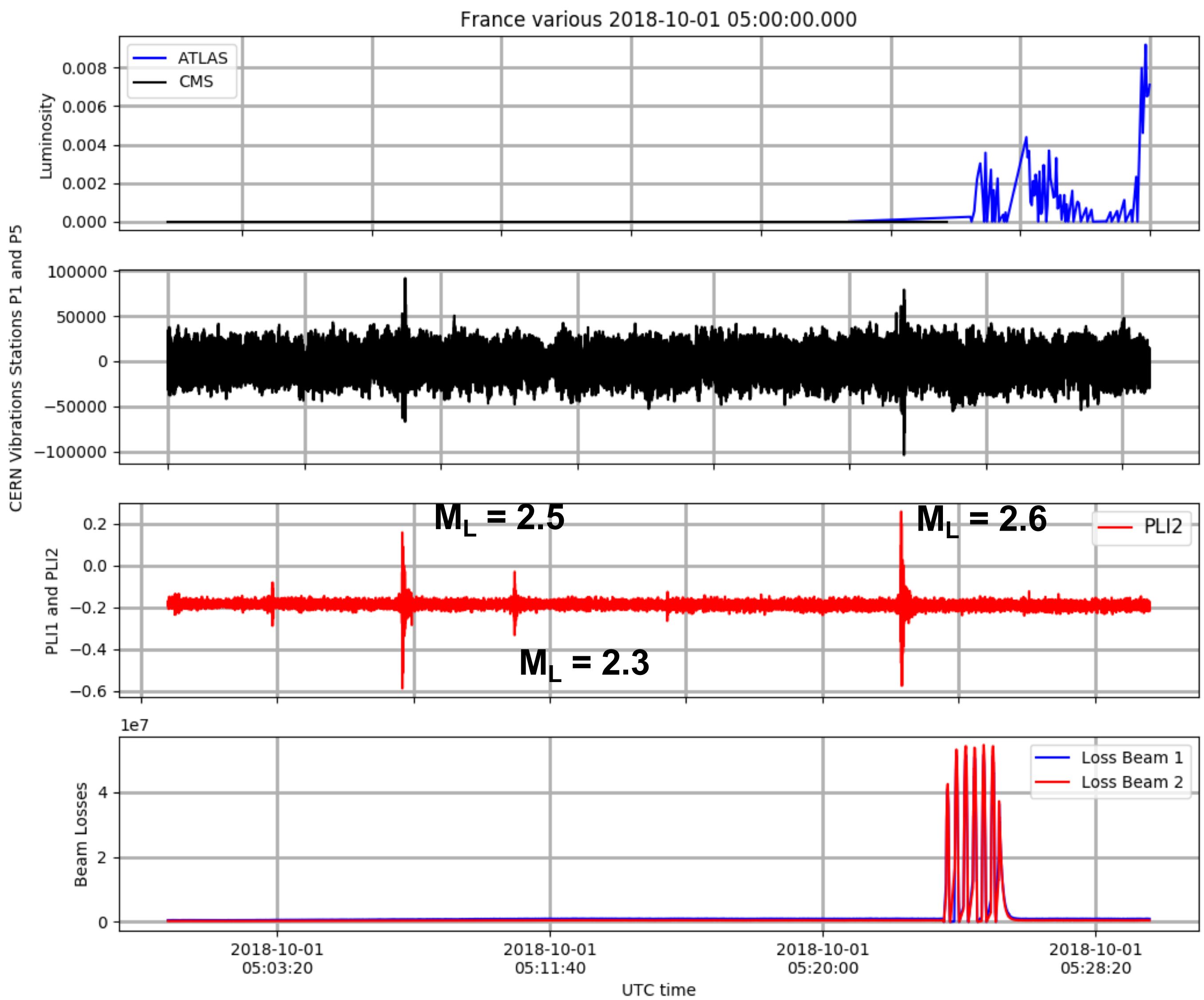

IRIS ID: 5196366 - 2016-10-26 19:18:08 - Mw = 6.1
Depth = 10.0 km - CENTRAL ITALY - Distance = 660 km
PLI
Inclination (urad)
LHC
ATLAS
CMS
Raw counts
7% dip in ATLAS luminosity
19:21:00.000000
19:26:00.000000
UTC time

Italy 18 January 2017



Very recent events

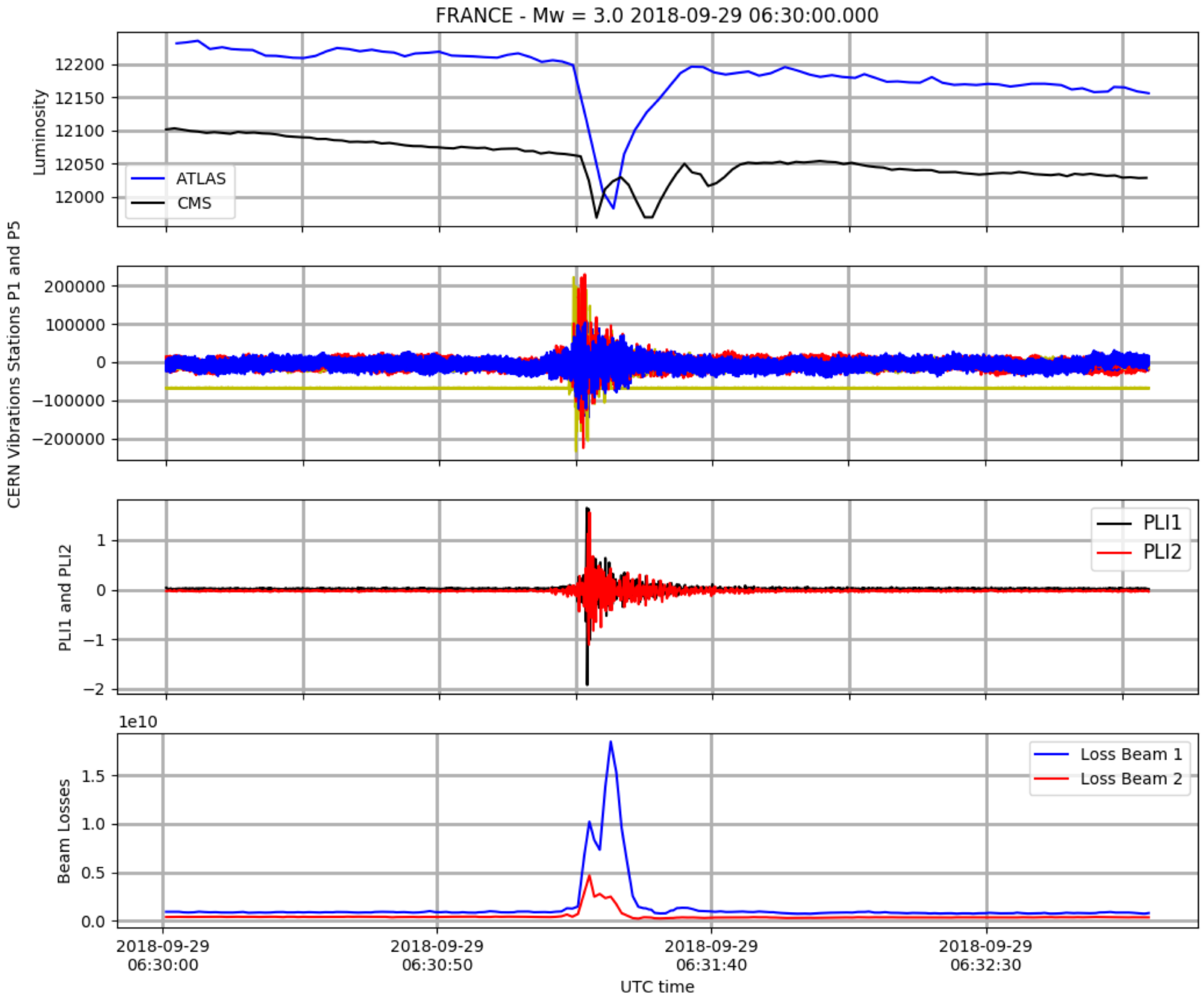
France 1 October 2018



No effects on LHC
Comparison with seismometers in P1 and P5
Small magnitude earthquakes that PLI measures better than ordinary seismometers

Very recent events

France 29 September 2018

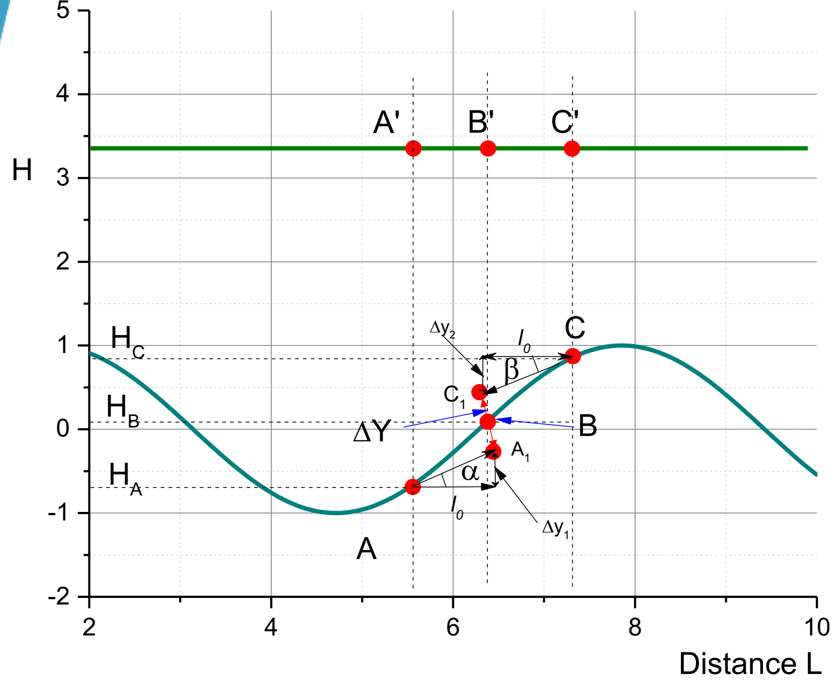


Effect on beam losses and luminosity

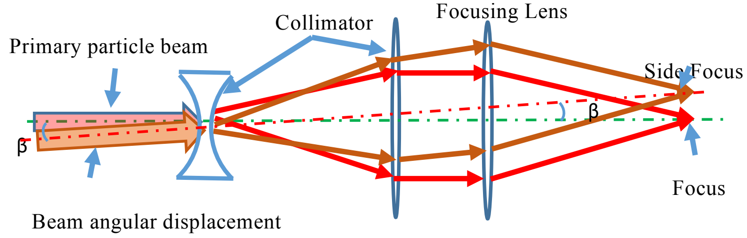
Effect of seismic events

- Proton-proton colliders as LHC are immune from effects of micro-seismic movements
  - While e+-e- future/possible colliders (CLIC, ILC, FCC-ee, etc.) are sensitive also to micro-seismic movements
- The High Luminosity LHC will have a factor 5 higher luminosity by increasing the number of protons and squeezing the beams to very few microns transverse sizes
  - Near earthquakes (mainly in Italy) can provoke beam dumps

Effects on linear colliders



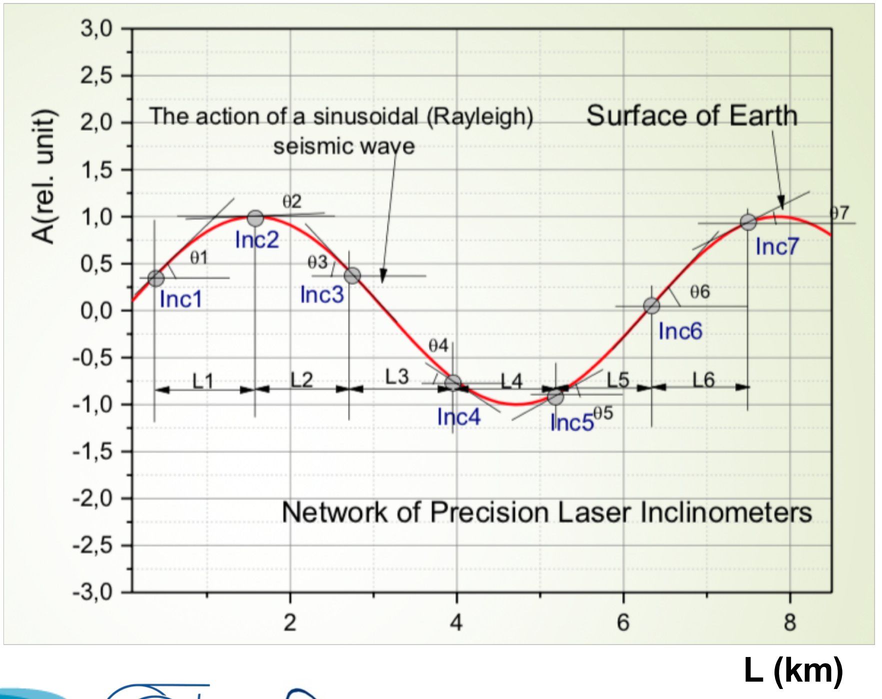
Divergence of the collider focuses caused by the sinusoidal deformation of the linear accelerator and effects on the beam focus



- We estimated from LHC-PLI data that in a linear collider like CLIC the micro-seismic ”noise” can induce a displacement of order of 100 μm over the ~2 km long focusing section and CLIC type of beams have transverse dimensions of 2x500 nm

A seismic telescope

- The data has been collected so far with a single station
- Now we are building a seismic telescope with 5 to 6 PLIs



This will enable a precise reconstruction of the effects of seismic waves and allow to visualize in 3D the earth deformations

The PLI feedback: work in progress

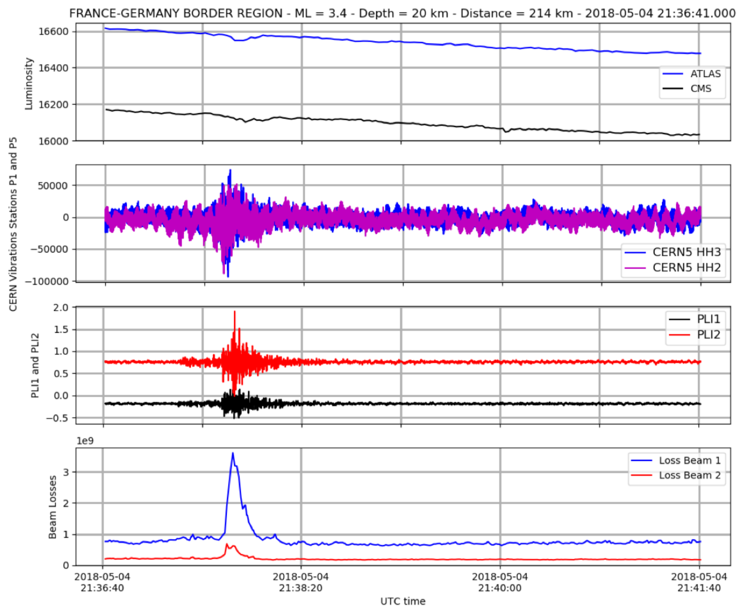
- The PLI data can be used for
  - Monitoring seismic activities with high precision
  - Providing an active feedback for alerts
  - Providing an active stabilization via input to actuators for any platform/mirror
- Activity ongoing for signal treatment to improve quality and provide filtering in frequencies
- Fast recognition of P-waves to create alerts for the arrival of S-waves: deployment of neural network techniques

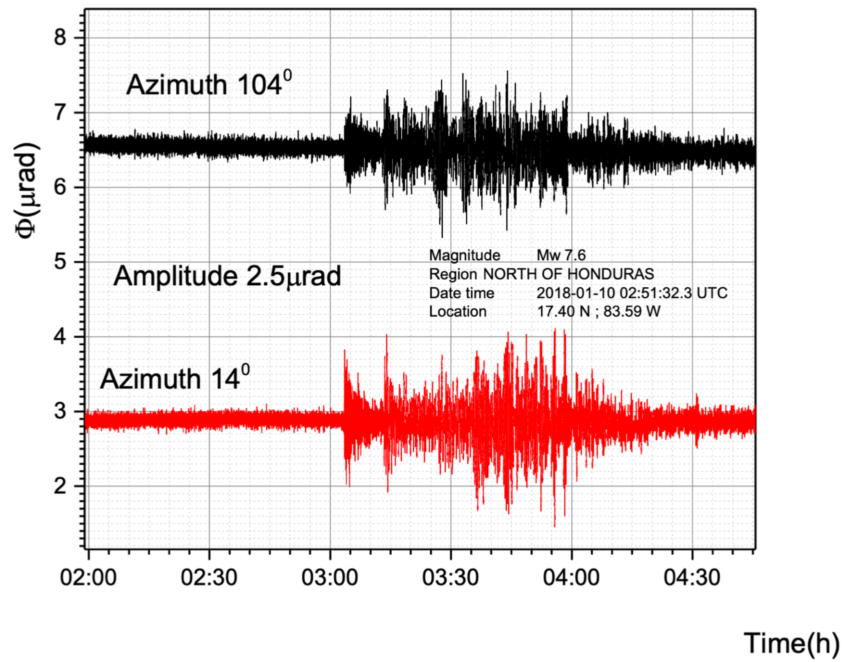
The PLI feedback: what shall it do

- Parameter for a feedback system: reaction speed, frequency range of operation
  - The maximum frequency of the registration of the micro-seismic signal by PLI is today around 10 Hz, a reading every 0.04 s.
  - Fast actuators can react in 0.5 ms, corrector magnets can change current in the same range ~ 1 ms
  - A fast orbit feedback system at LHC or any accelerator should be at ~ 20-25 Hz
  - How fast is required to be for a mirror stabilization? Stabilization of a mirror in a gravitational antenna should be in the frequency range 0.5-5 Hz (the range of the main resonances of the self frequencies of the mirror suspensions), consequently a fast feedback system at gravitational antenna should be at ~ 20-25 Hz

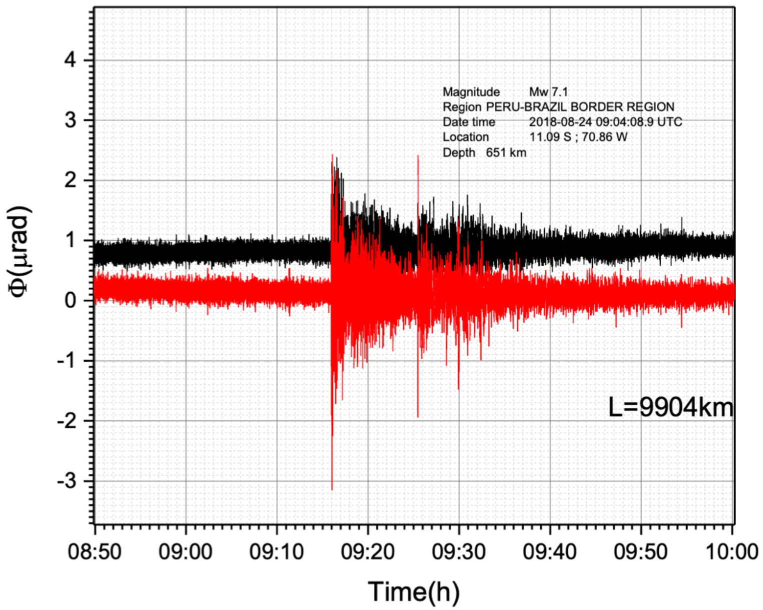
Conclusions

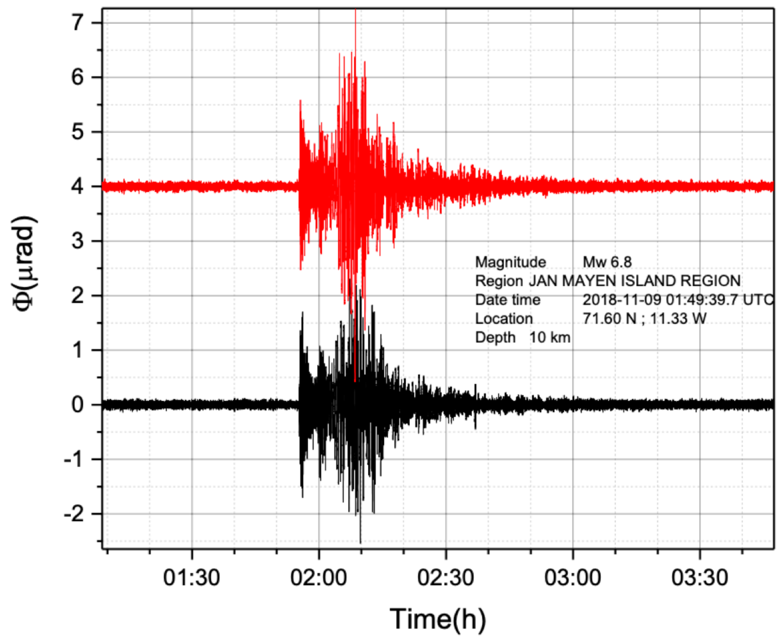
- Earthquakes, seismic movements (micro-seismic peak) and human activity can be monitored by the PLI and soon by a seismic telescope of several PLIs
  - CERN at working time, lunch time and weekends
  - Storms on Geneva lake
  - Differences between effects of storms in Atlantic Ocean (<depth> = 3.6 km), North Sea (<depth> = 95 m) and Mediterranean Sea (<depth> = 1.5 km) and combinations of them
  - Near and far earthquakes
- Continuous efforts for this instrument, installed since 2015 at CERN, made it progress in precision, cost, operability
- It is a young baby and the hope is with big future in many applications


FRANCE-GERMANY BORDER REGION - ML = 3.4 - Depth = 20 km - Distance = 214 km - 2018-05-04 21:36:41.000
Luminosity
ATLAS
CMS
CERN Vibrations Stations P1 and P5
CERN5 HH3
CERN5 HH2
PLI1 and PLI2
PLI1
PLI2
Beam Losses
Loss Beam 1
Loss Beam 2
UTC time


Azimuth 104⁰
Amplitude 2.5μrad
Azimuth 14⁰
Magnitude Mw 7.6
Region NORTH OF HONDURAS
Date time 2018-01-10 02:51:32.3 UTC
Location 17.40 N ; 83.59 W
Φ(μrad)
Time(h)

Thank you


Magnitude Mw 7.1
Region PERU-BRAZIL BORDER REGION
Date time 2018-08-24 09:04:08.9 UTC
Location 11.09 S ; 70.86 W
Depth 651 km
L=9904km
Φ(μrad)
Time(h)


Magnitude Mw 6.8
Region JAN MAYEN ISLAND REGION
Date time 2018-11-09 01:49:39.7 UTC
Location 71.60 N ; 11.33 W
Depth 10 km
Φ(μrad)
Time(h)