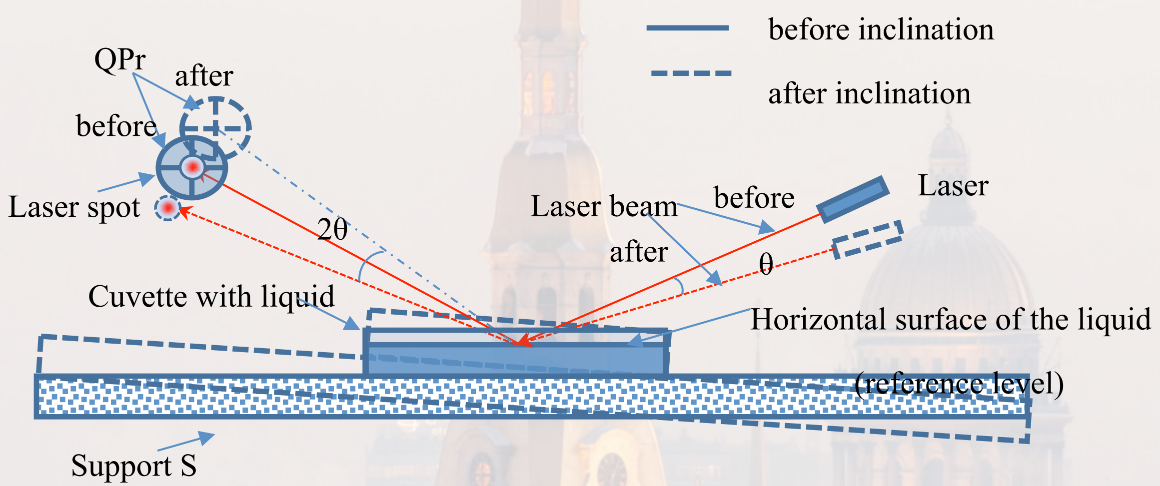

RuPAC
Russia
St. Petersburg
21-25 November
2016

The Monitoring of the Effects of Earth Surface Inclination With the Precision Laser Inclinometer For High Luminosity Colliders

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  - Michael Guinchard
  - Gianluigi Arduini
  - Oliver Bruning
  - Lucio Rossi

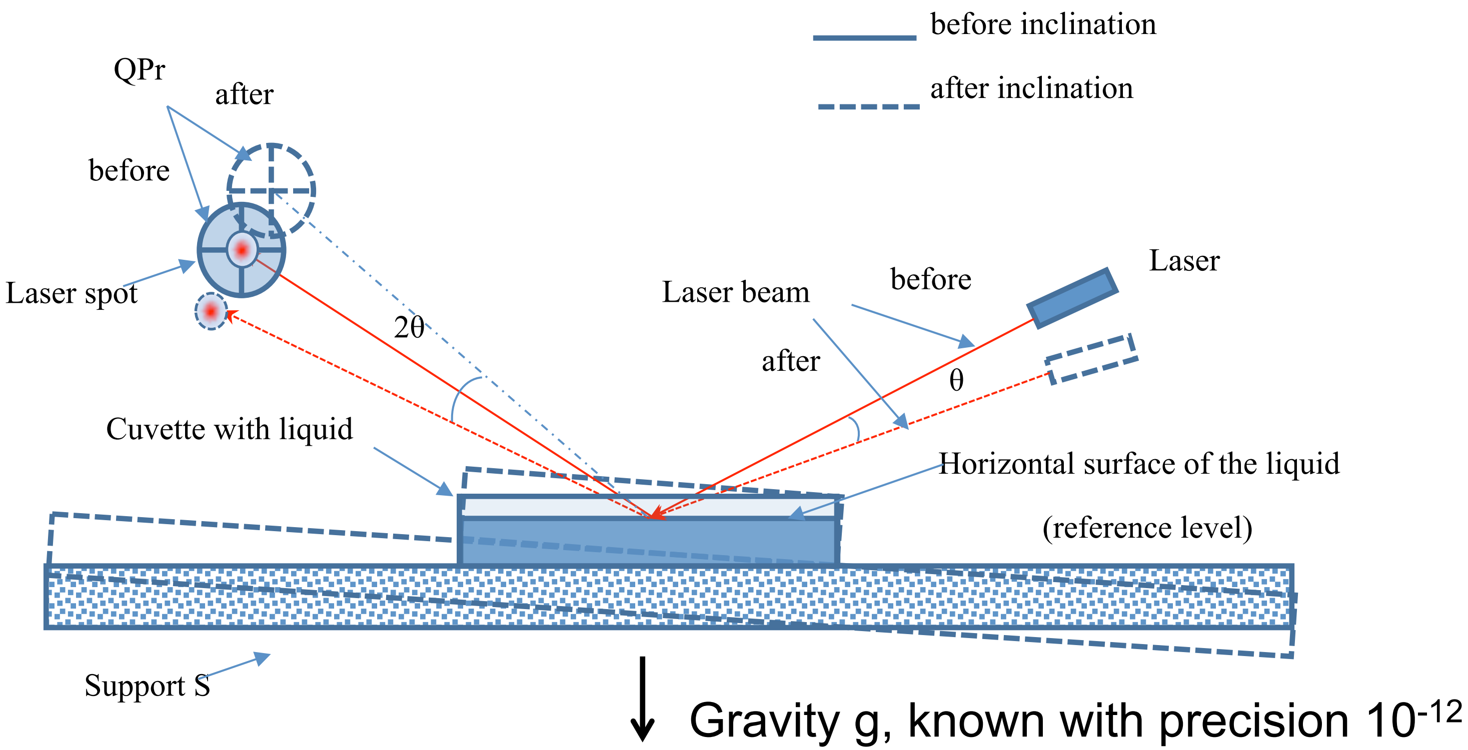
Outline

- The Precision Laser Inclinometer instrument
  - Principle
  - Setup and comparative results
  - Precision and operating ranges
- Monitoring vibrations
  - Micro-seismic peak and Sun-Moon effects
  - Earthquakes
- Application for high luminosity colliders
  - Monitoring
  - Active feedback
  - Active stabilization

The Precision Laser Inclinometer (PLI)

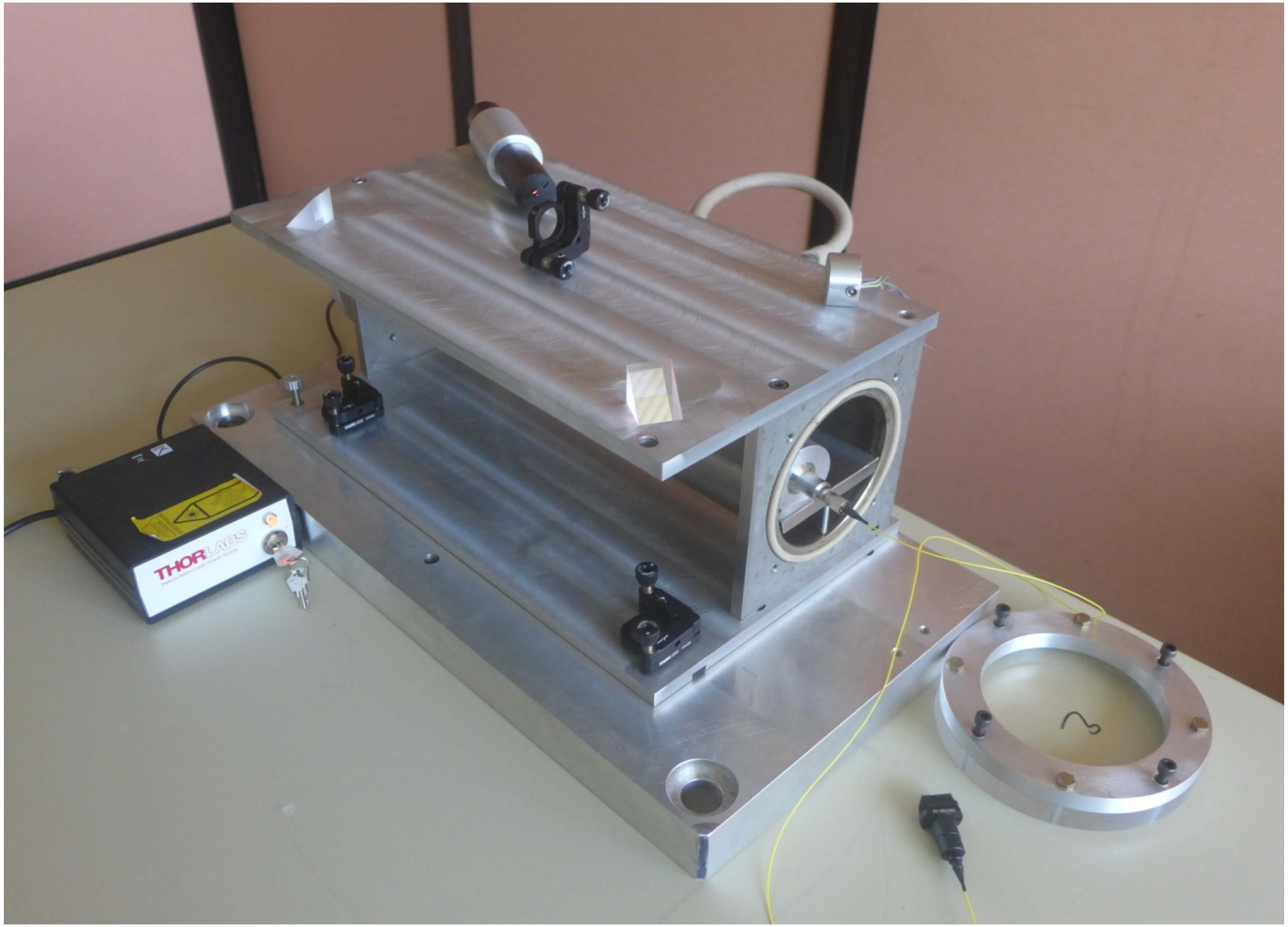
- This novel instrument, the PLI, has been conceived in JINR – Dubna
- It is part of a large program of survey instrumentation
- It has been developed and installed at CERN in collaboration with the CERN Survey and ATLAS
- Interest has been shown for application in the monitoring of the oscillation of LHC induced by earthquakes and other sources

Working principle

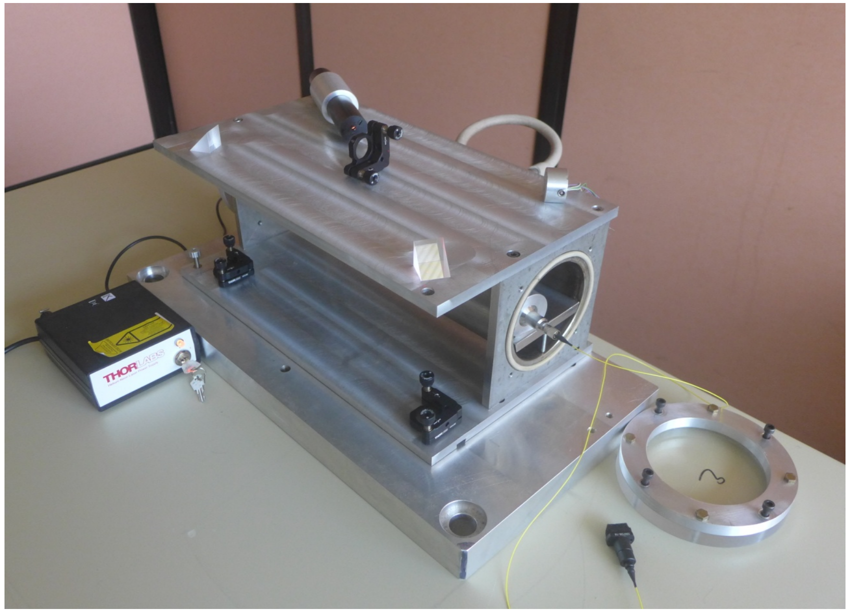


- The PLI uses the inclination of the laser ray reflected from liquid surface when the base support is tilted.
- The angle of the reflected light is twice larger than the support tilt angle θ.
- The detection is in both planes, therefore the combined slope and azimuth can be easily calculated

The PLI in photo



The PLI readout schematic



24 bit ADC

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

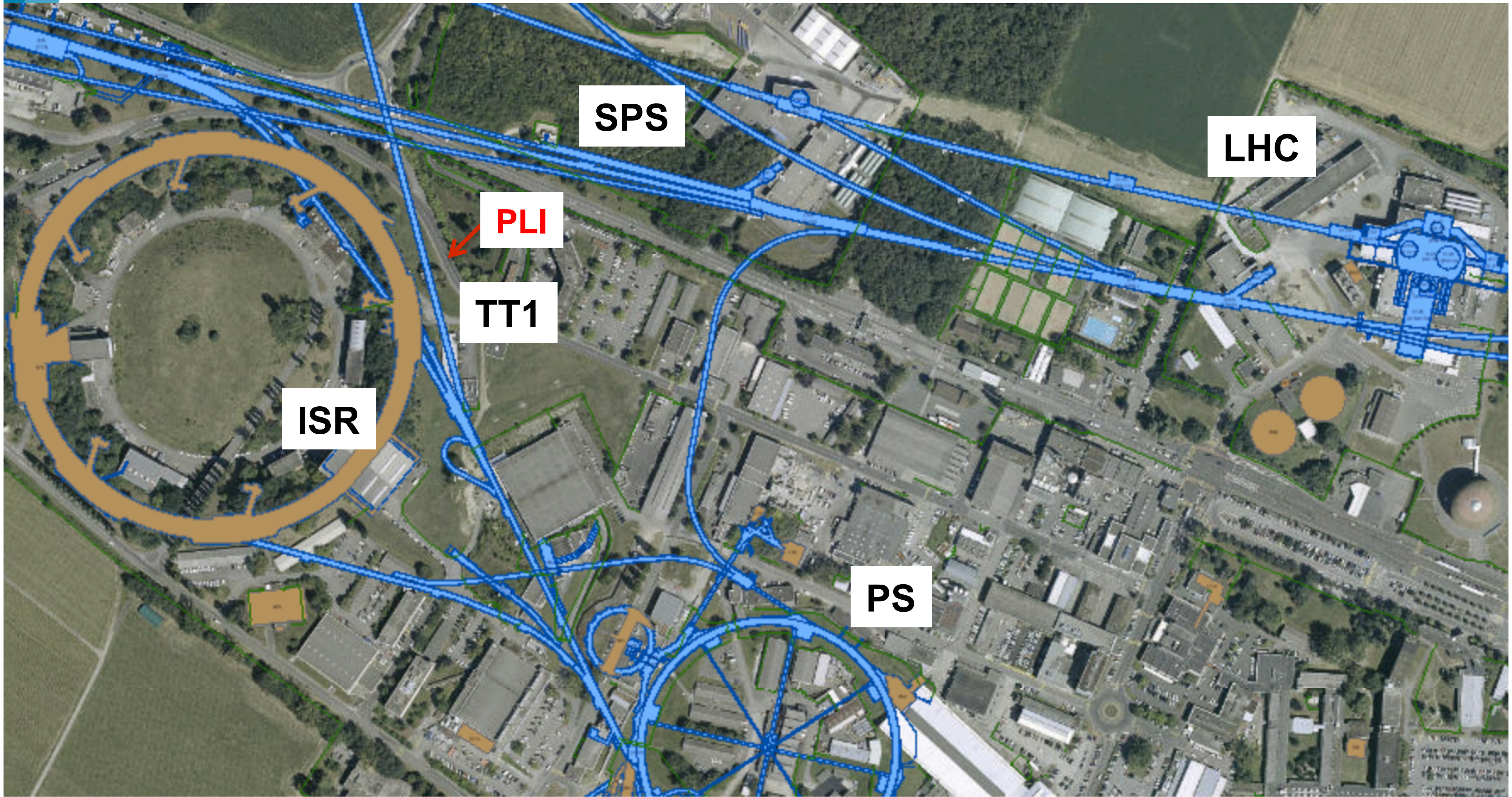
vacuum

Storage

Experimental setup

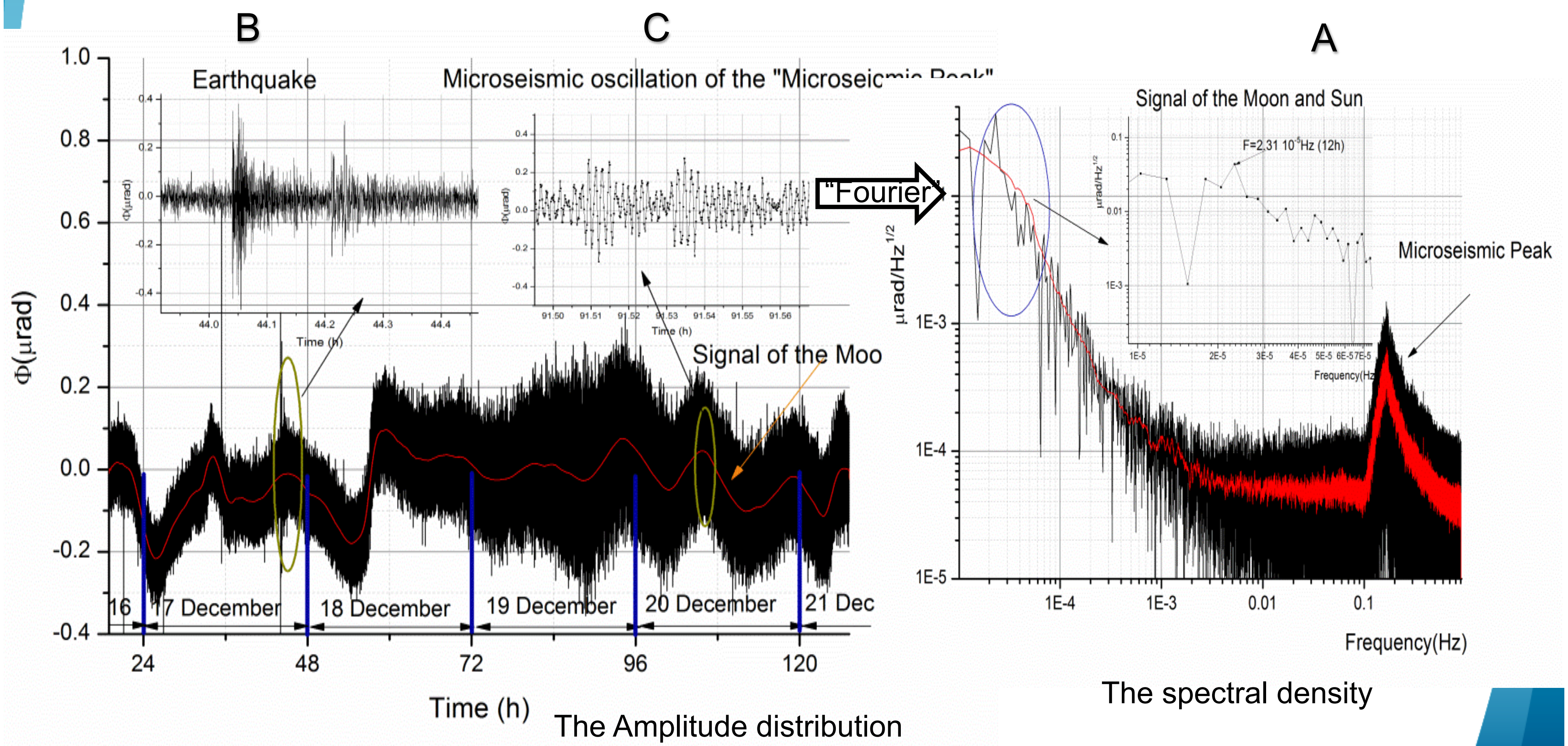
- The PLI is fully operational at CERN in an underground Transfer Tunnel of the ISR (the TT1) since 2015. Very stable ground and temperature
- Several improvements have been done, last being the placement in an under vacuum volume to limit the laser light jittering
- We have performed comparative measurements with Hydrostatic Level Systems (HLS) used by CERN Survey for monitoring the ATLAS cavern and the position of LHC Inner Triplets

TT1 Tunnel - LHC



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**).



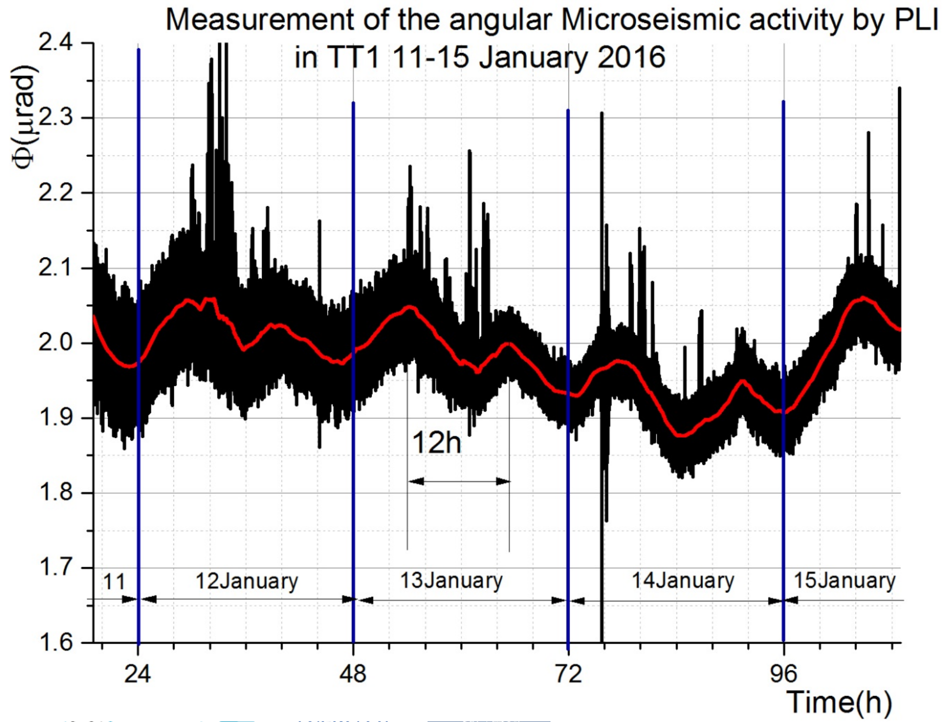
The Amplitude distribution

The spectral density

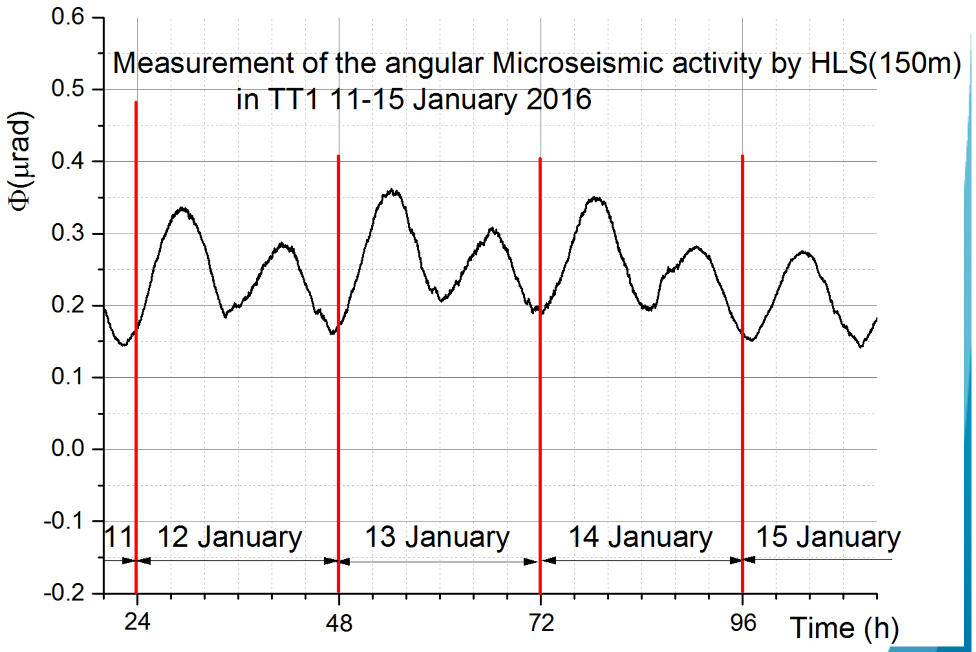
Moon-Sun Earth inclination

Here is a new confirmation of the PLI data (**A**) by the 150m long CERN Hydrostatic Level System (**B**) for the Moon-Sun Earth surface variations

A

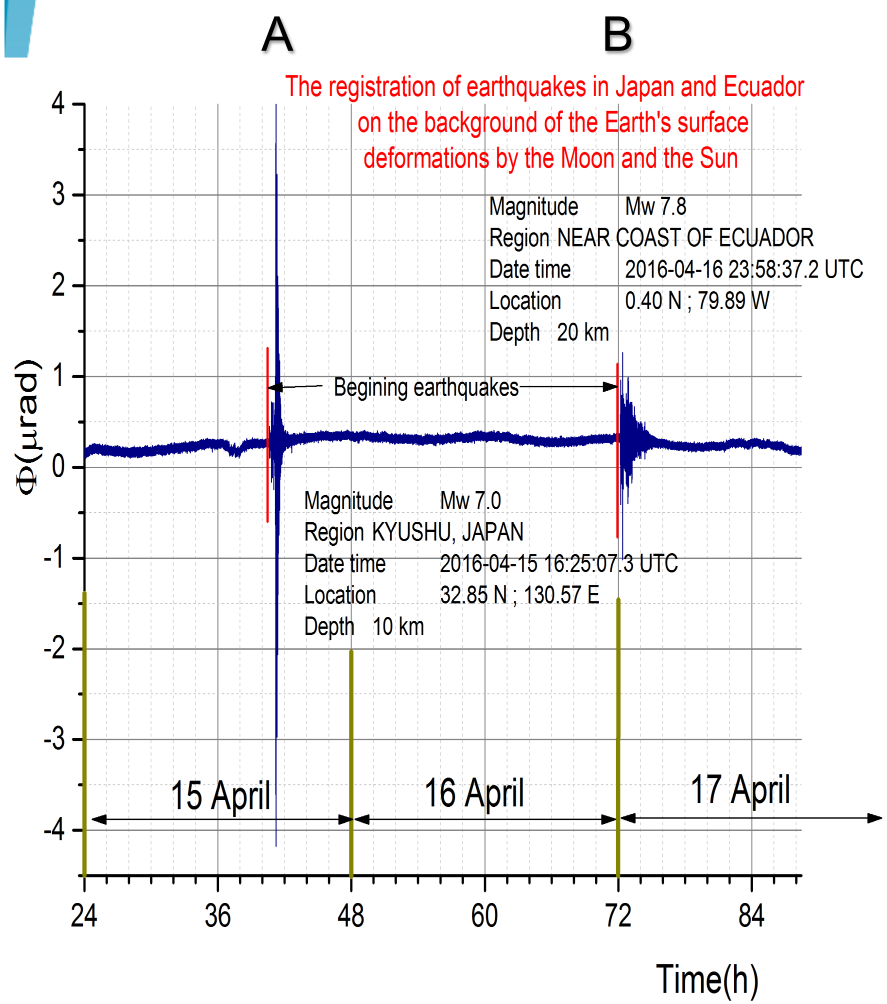


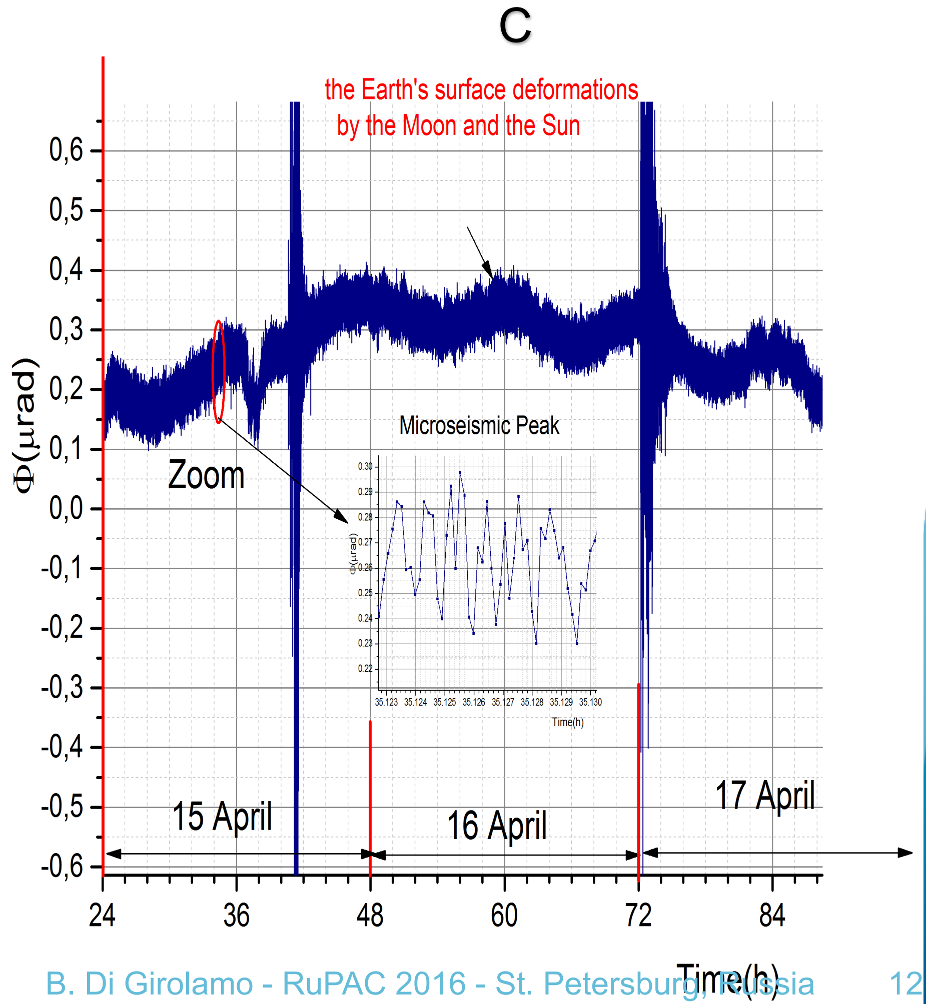
B



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.





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 10^{-10} rad/Hz$^{1/2}$ in the frequency range $[10^{-3}, 1]$ Hz
  - A precision better than 10^{-9} rad/Hz$^{1/2}$ in the frequency range $[3 \cdot 10^{-7}, 1]$ Hz, $3 \cdot 10^{-7}$ Hz corresponds to one month of observation

Azaryan N. et al. Comparative Analysis of Earthquakes Data Recorded by the HLS and the PLI Instruments // Part. Nucl. Lett. (submitted)

Importance for high luminosity colliders

- It is well known that accelerators and light source are sensitive to ground oscillations
- Earthquakes are rare events, but very good calibration providers
- Industrial and human noise are sometimes unavoidable constraints
- High luminosity, low emittance colliders can suffer dramatically from ground oscillations (unforeseen dumps, impact on luminosity, among others)

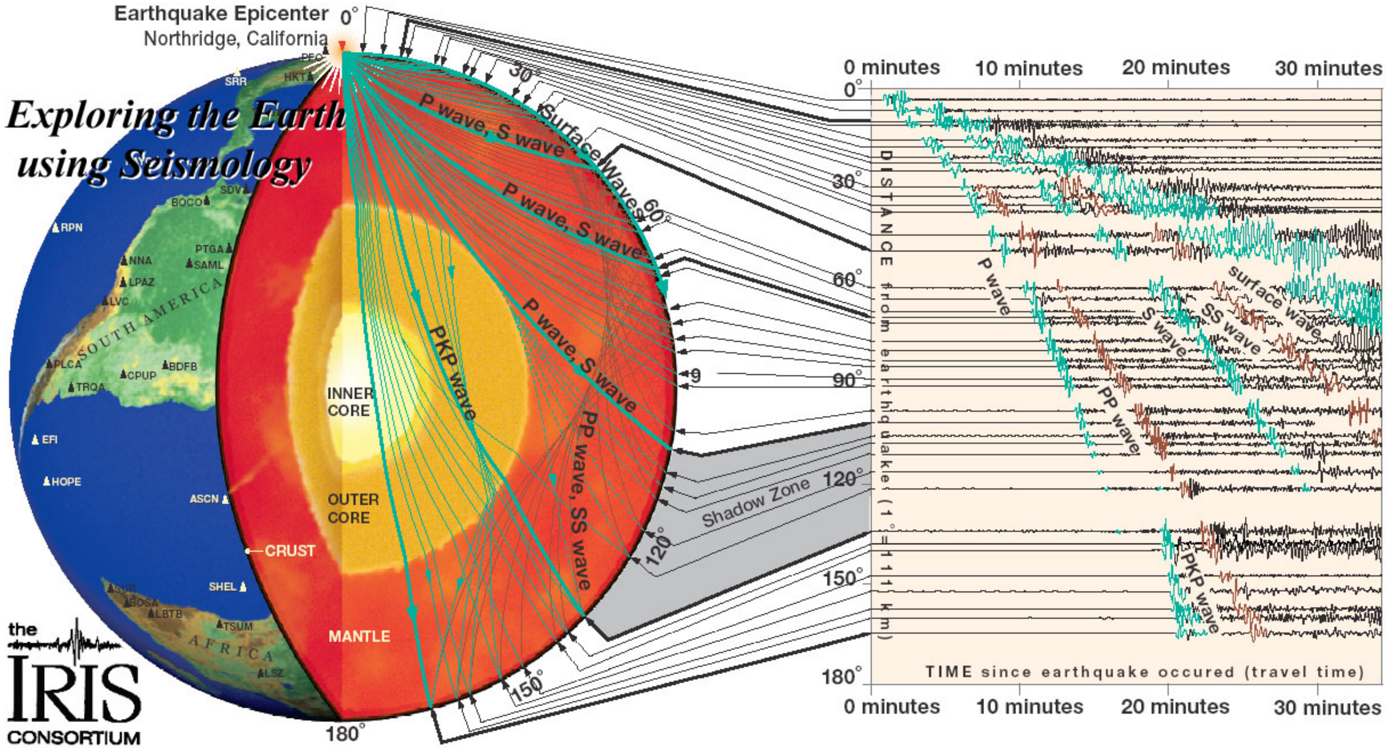
In addition…

- Specifically for HL-LHC project at CERN the civil engineering work of excavation for tunnels and two pits will be done during the LHC long shutdown exactly to avoid the negative impact of ground vibration
- Let's quantify the effects

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

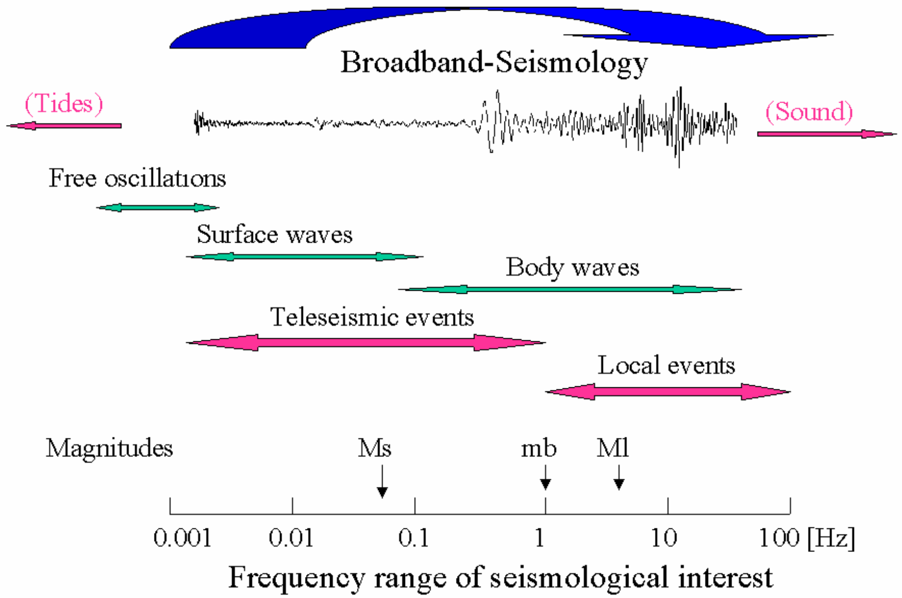
Slide from J. Wenninger

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 (teleseismic) are dominated by low frequencies < 1 Hz.

- Ground motion from local earthquakes extends to higher frequencies.



Slide from J. Wenninger

Observed Earthquakes at the LHC (a preliminary list)

Location	Date	Mag	LHC	DR (mm)	Int (10^{13} p/ beam)
Italy	20-05-12	6	4 TeV collisions	±60	14
Costa-Rica	05-09-12	7.6	4 TeV collisions	±80	19
Chile	16-09-15	8.3	Injection	±200	5
Chile	17-09-15	6.5	6.5 TeV collisions	±15	10
Italy	24-08-16	6.2	Injection (MD)	±60	0.3
Ascension Islands	29-08-16	7.1	6.5 TeV collisions	±20	20

Presented at Charmonix 2016

New events with available ground motion measurements in TT1.

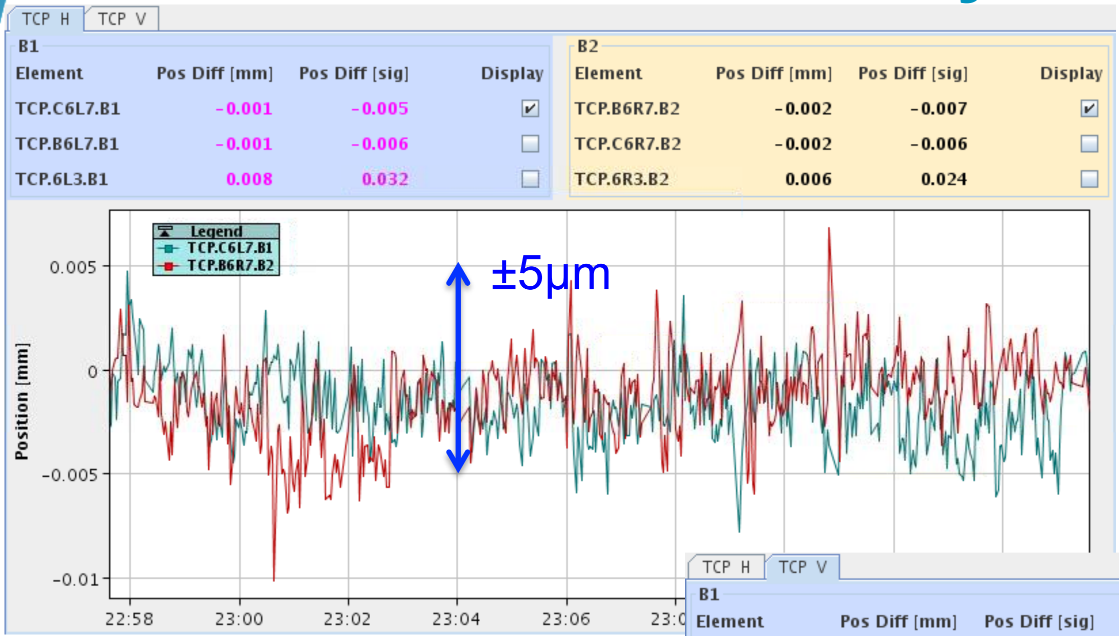
Qualitative estimate of RMS orbit distortion impact (LHC):

50µm (≈0.25σ@TCP) beam dumps unlikely
>~100µm (≈0.5σ@TCP) beam dumps probable
>~200µm (≈1σ@TCP) beam dumps definitive

If beams would be dumped for a certain orbit movement, strongly depends on tail population, wave properties …

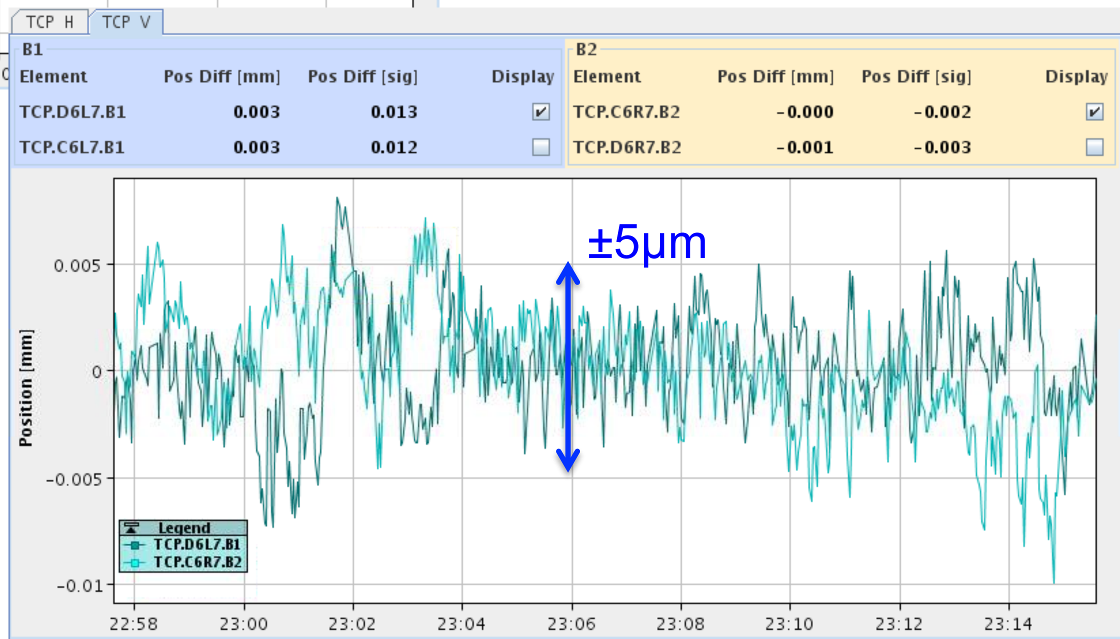
Scaling the loss pattern at TCP, the first Italy event could have dumped under HL-LHC conditions.

Orbit Stability at TCP



B1 Element	Pos Diff [mm]	Pos Diff [sig]	Display	B2 Element	Pos Diff [mm]	Pos Diff [sig]	Display
TCP.C6L7.B1	-0.001	-0.005	☑	TCP.B6R7.B2	-0.002	-0.007	☑
TCP.B6L7.B1	-0.001	-0.006	☐	TCP.C6R7.B2	-0.002	-0.006	☐
TCP.6L3.B1	0.008	0.032	☐	TCP.6R3.B2	0.006	0.024	☐

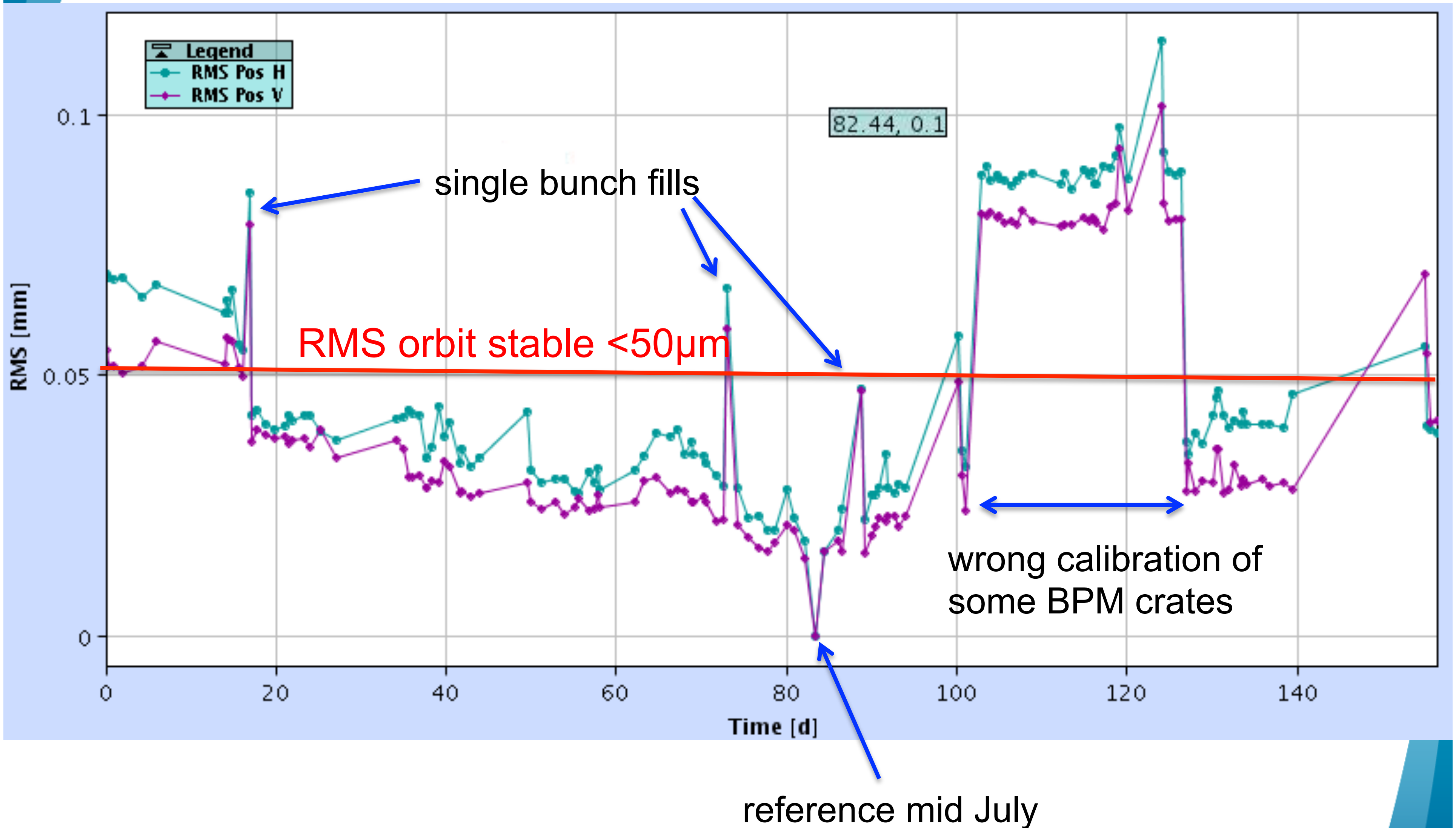
The orbit at the TCP during stable collisions is controlled to ±5µm.



B1 Element	Pos Diff [mm]	Pos Diff [sig]	Display	B2 Element	Pos Diff [mm]	Pos Diff [sig]	Display
TCP.D6L7.B1	0.003	0.013	☑	TCP.C6R7.B2	-0.000	-0.002	☑
TCP.C6L7.B1	0.003	0.012	☐	TCP.D6R7.B2	-0.001	-0.003	☐

J. Wenninger

RMS Orbit over the year



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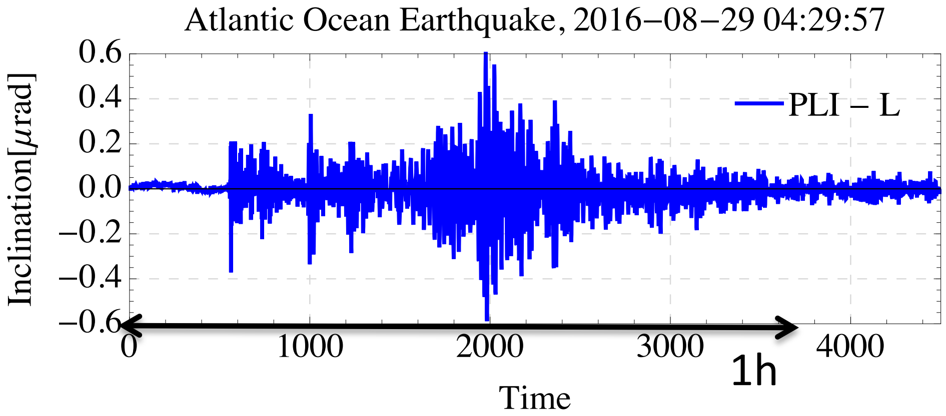
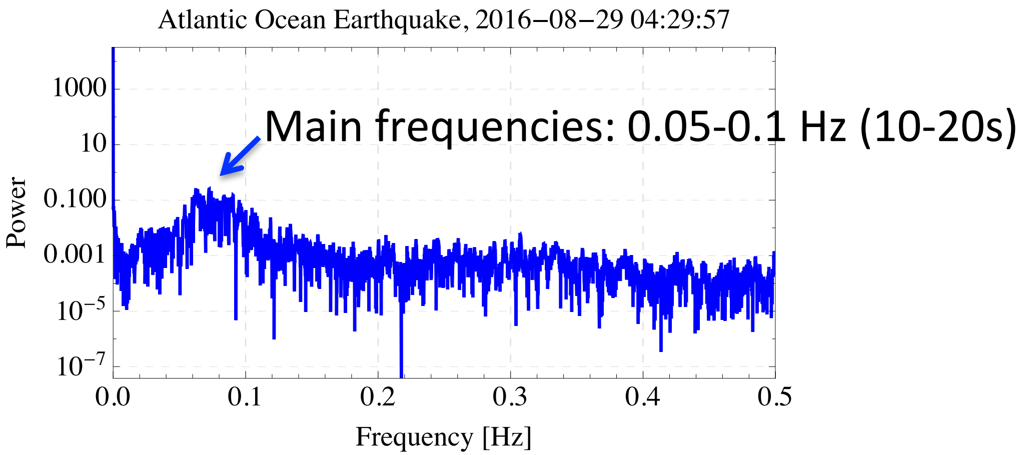
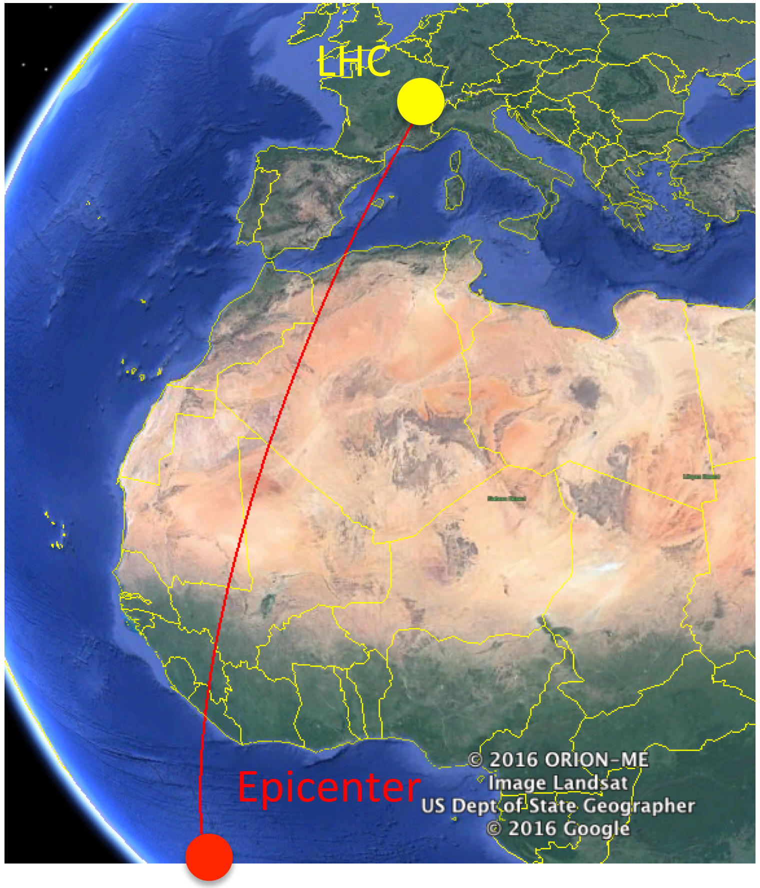
Ascension Islands Earthquake, 29th Aug. 2016

Magnitude 7.1 in Ascension Islands
Monday, August 29, 2016 at 04:29:57 UTC

LHC was in stable collisions

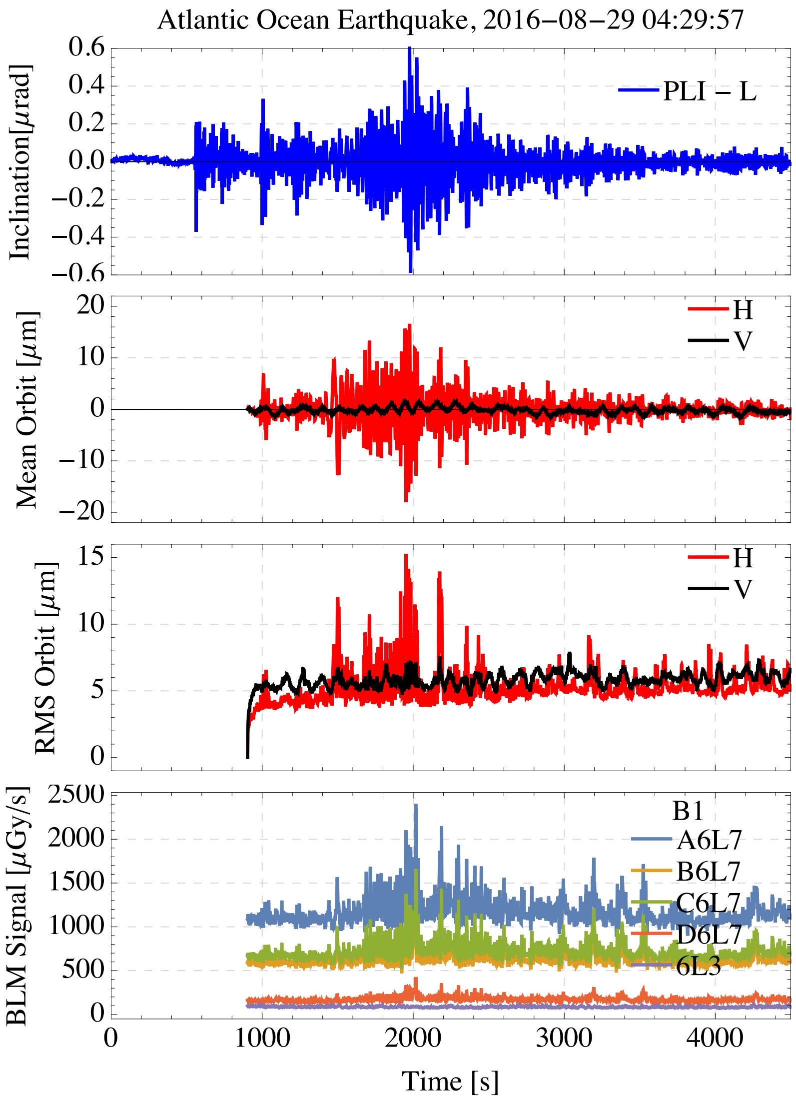


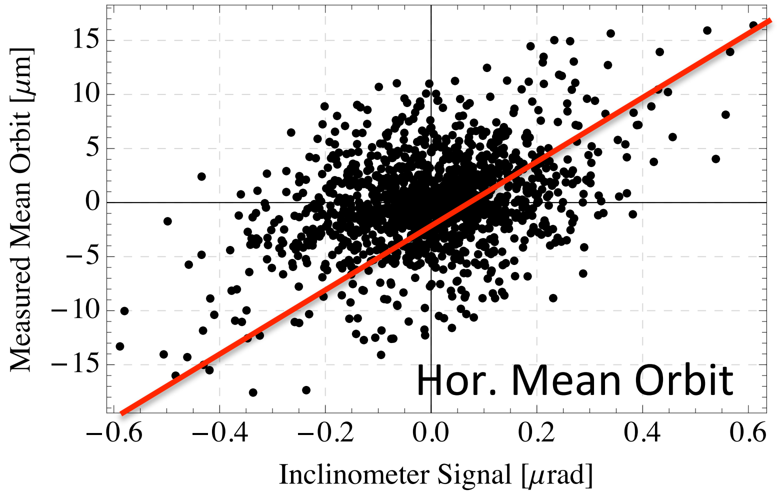


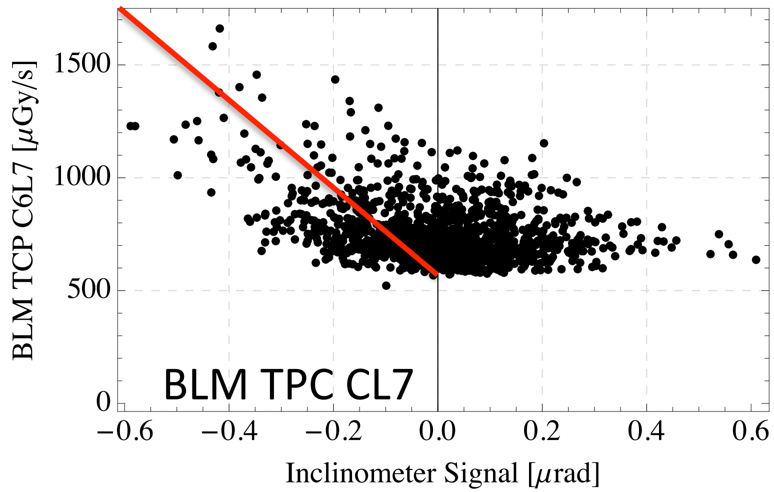


Observations on the LHC Beam

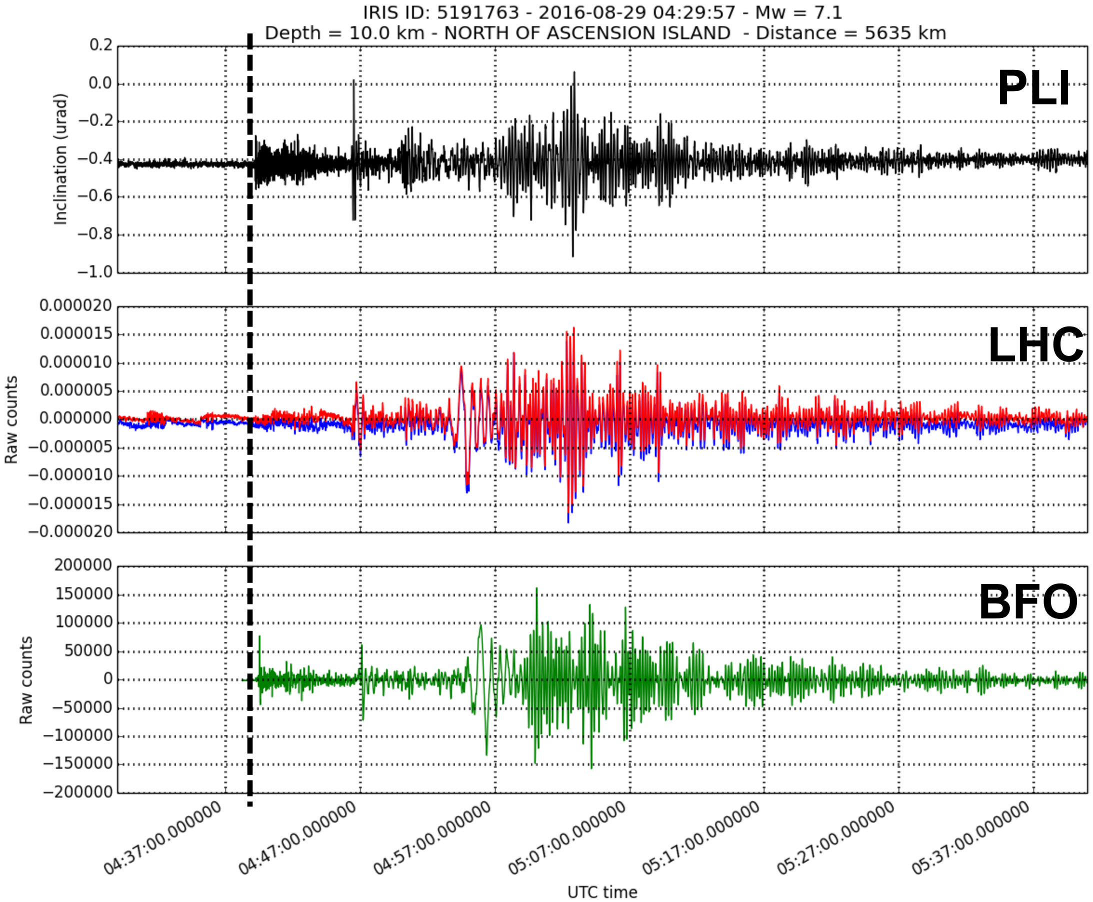
Clear correlations between ground motion in TT1, orbit and losses in IP7.

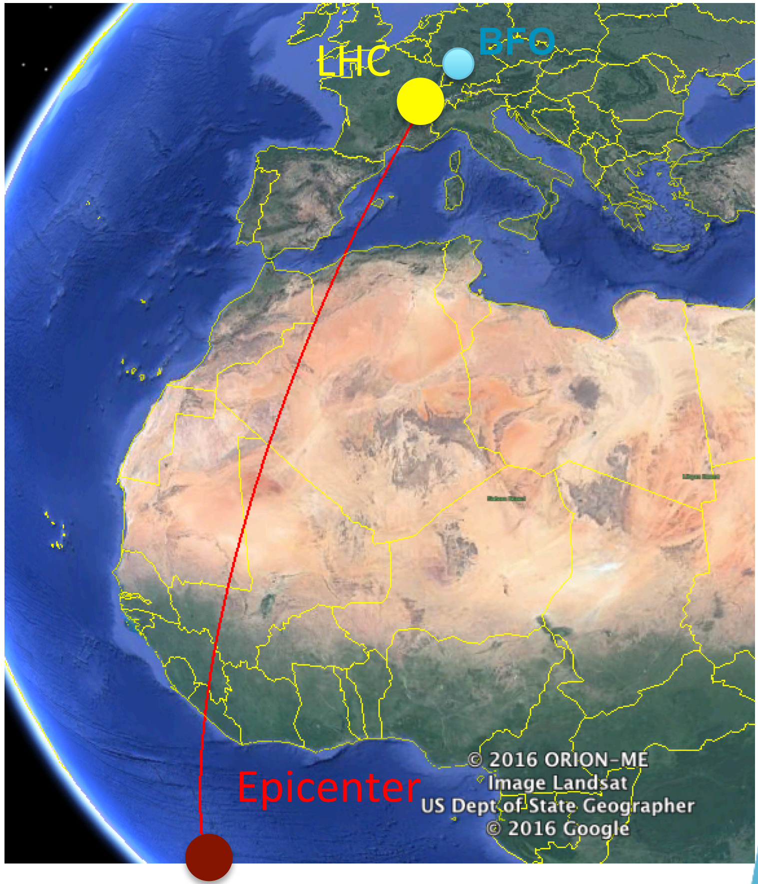






Additional information: the delay of detection



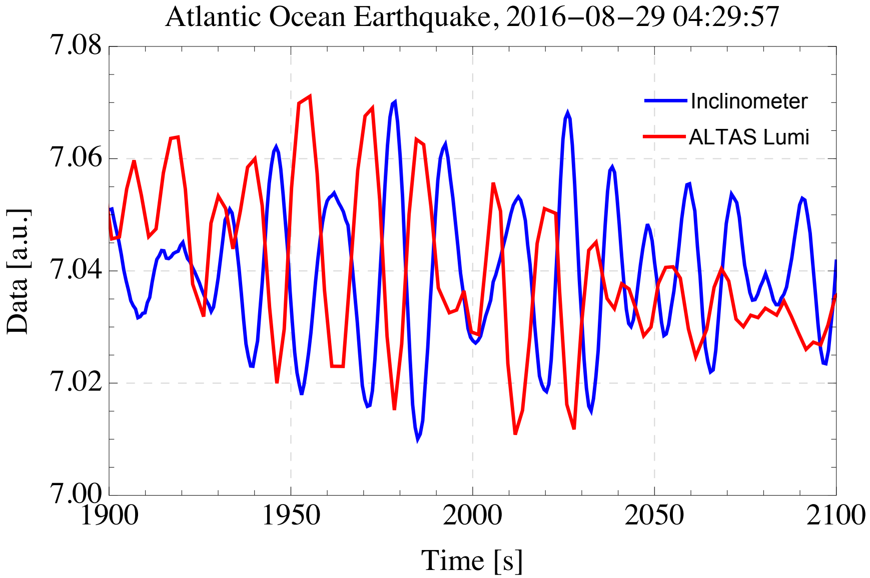


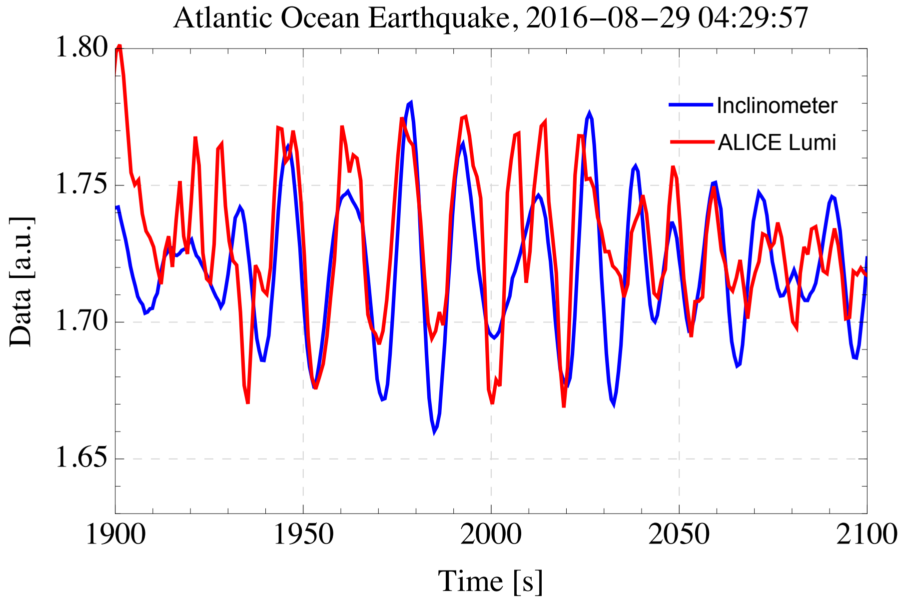
The PLI detects a big ground motion earlier than LHC orbit. As confirmation also the seismogram from the Black Forrest Observatory (which receives it later as expected)

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.

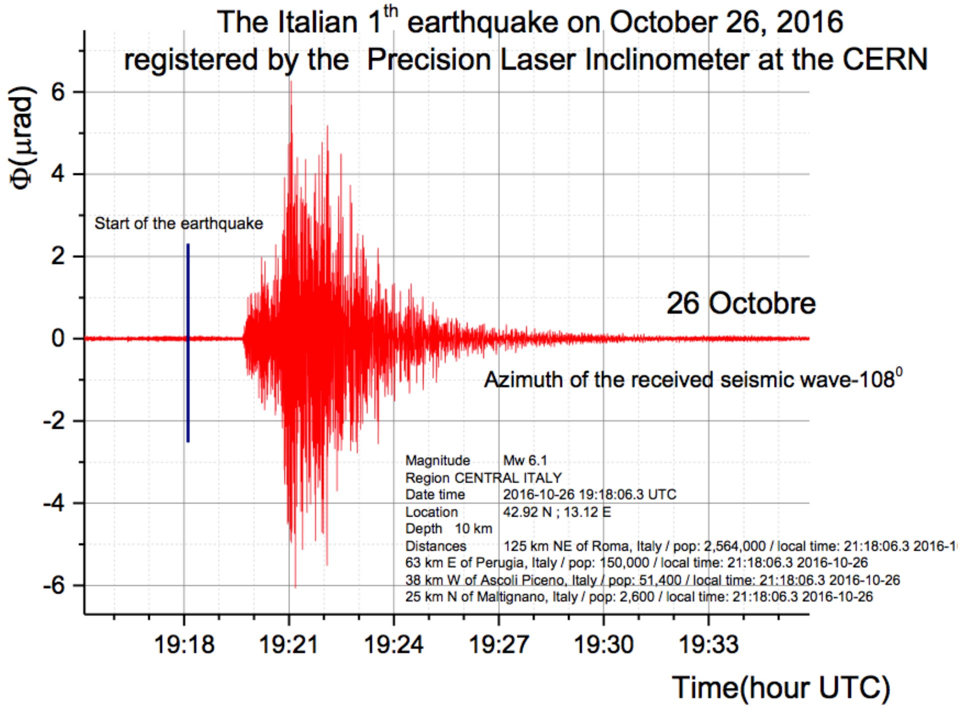




Italy Earthquakes, 26th Oct. 2016

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

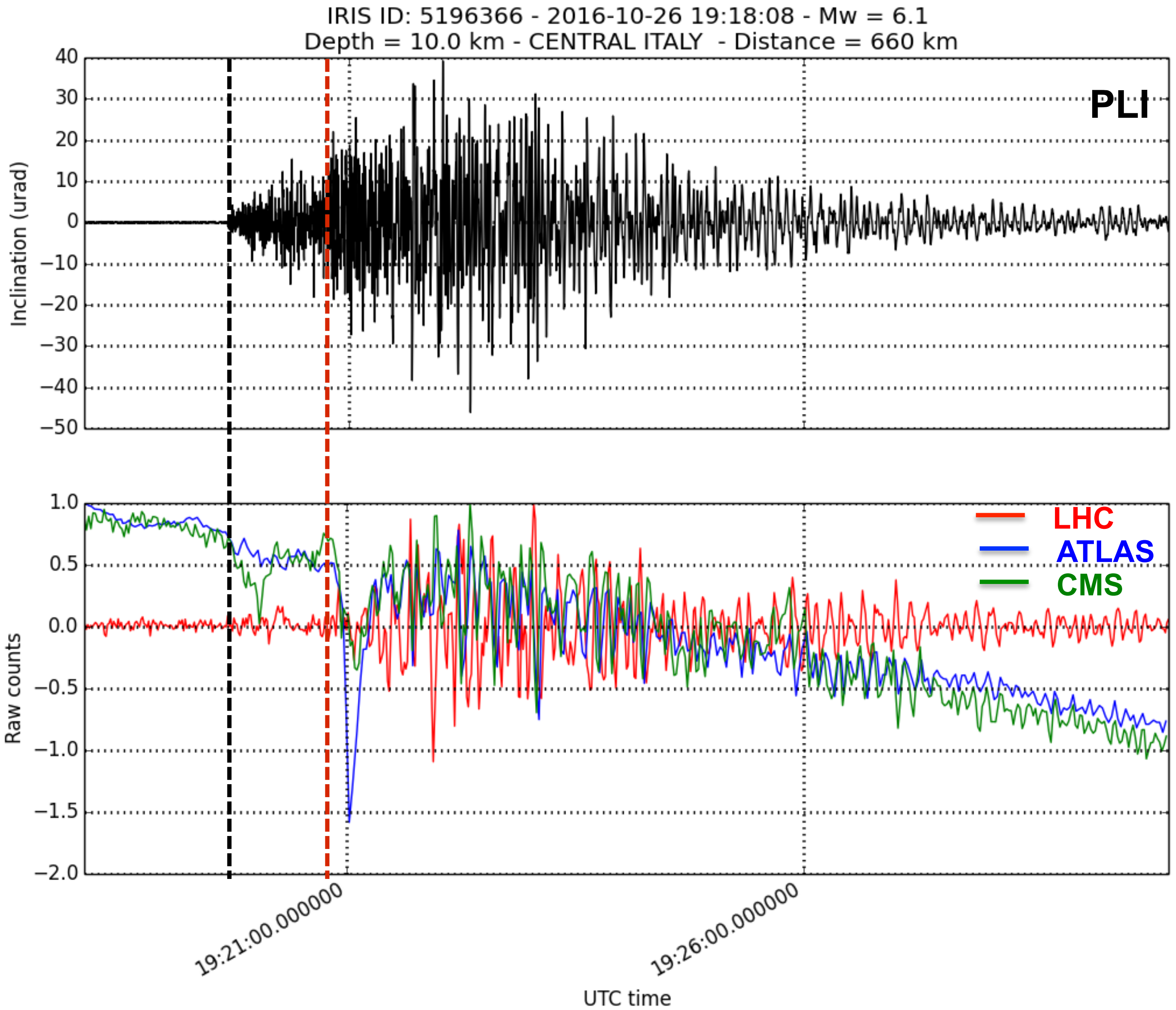
Recording of the event by the PLI.
The record provide the slop in two dimensions, it is therefore possible to **calculate the slope and the azimuth to determine the direction of the wave w.r.t. LHC**



Additional information from the Italy earthquake

- It was an earthquake quite near (~600 km)
- We observe still a late detection by LHC for the orbit, but
  - a clear dip in the luminosity in CMS at the beginning of the oscillations
  - Another decrease for both ATLAS and CMS luminosities when the orbit starts to oscillate heavily

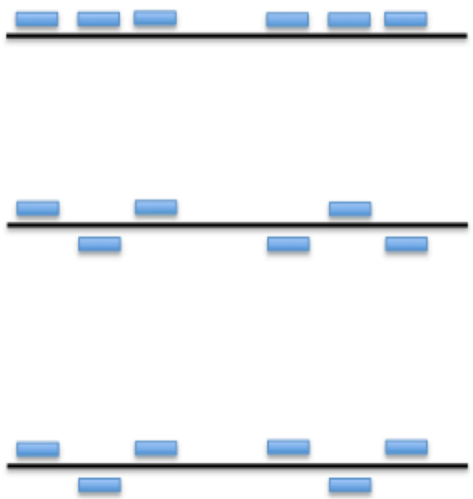
See next slide


IRIS ID: 5196366 - 2016-10-26 19:18:08 - Mw = 6.1
Depth = 10.0 km - CENTRAL ITALY - Distance = 660 km
PLI
Inclination (urad)
40
30
20
10
0
−10
−20
−30
−40
−50
LHC
ATLAS
CMS
Raw counts
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
19:21:00.000000
19:26:00.000000
UTC time

Simulation of Ring Response

- Simulation tool under development
- It takes into account the **measured displacement and the travel direction of the wave** w.r.t. LHC (the PLI provides both)
  - The travel direction determines the expected move of the different magnets

$$x_{co}(s) = \frac{\sqrt{\beta(s)}}{2\sin\pi\nu}\int_{s}^{s+C}\boxed{\Delta x(\bar{s})kl\sqrt{\beta(\bar{s})}}\cos\left(\pi\nu+\psi(s)-\psi(\bar{s})\right)$$

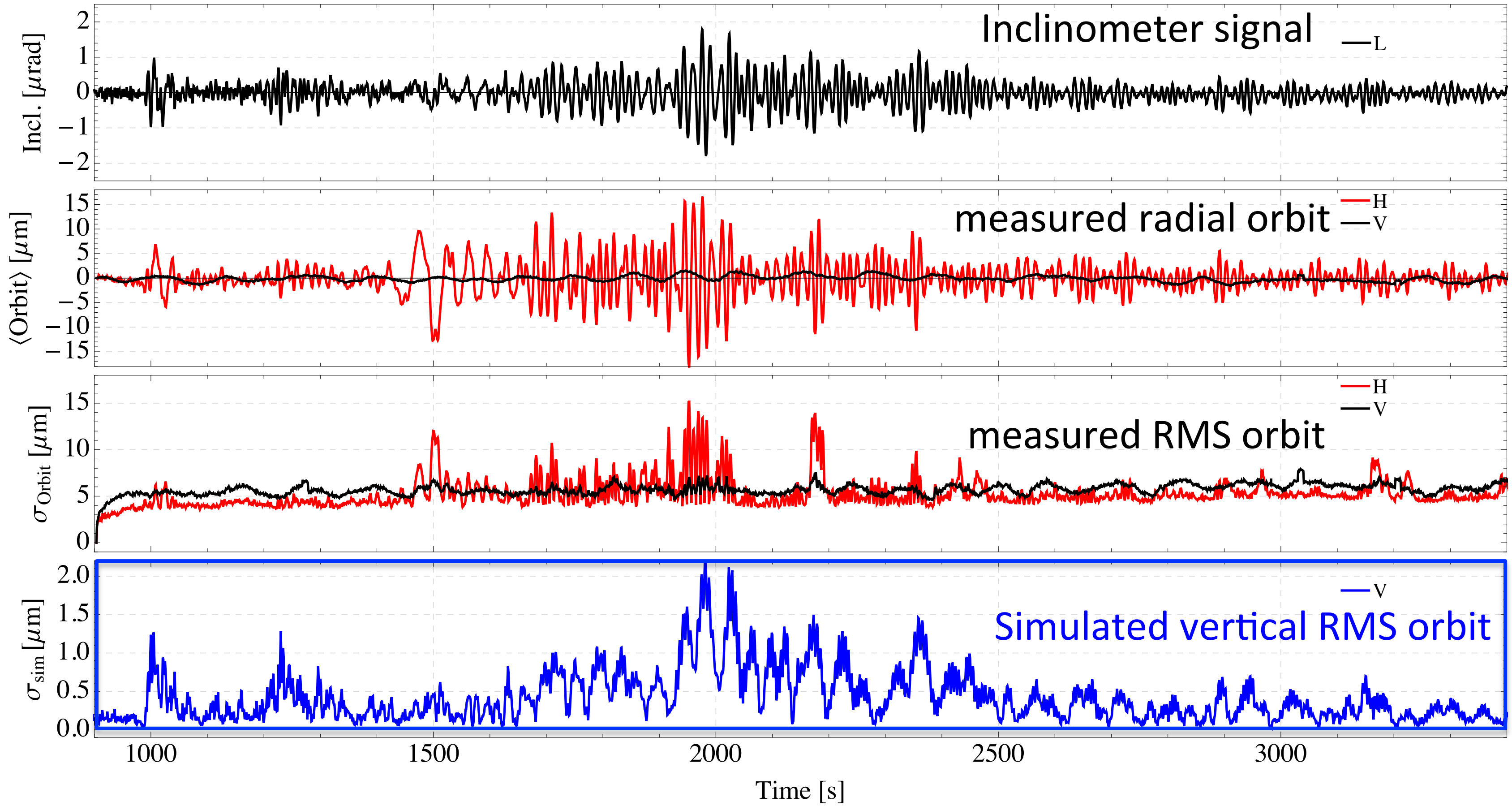


The main effect comes from quadrupole misalignment, where β function is higher

Simulation of Orbit Responce

Simulation with Inclinometer data

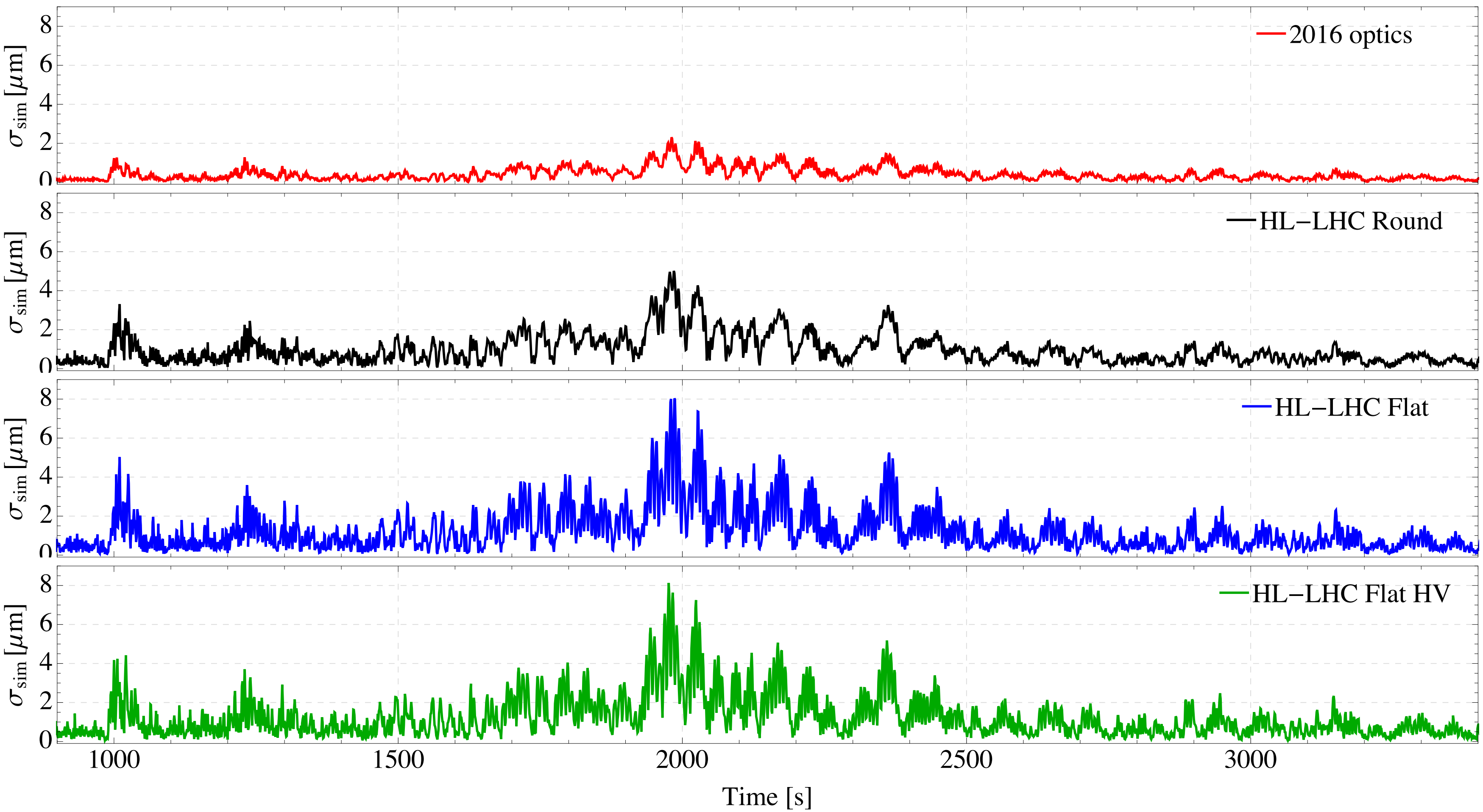
- No proper calibration to units of meter (as required for the simulation).
  → ***Amplitude of simulated RMS orbit distortion not reliable.***
- Assumed same signal for longitudinal and vertical offsets.
  → ***Some frequencies and amplitudes may not be covered in simulation.***
  → ***Where orbit and inclinometer show equivalent peaks the simulation follows.***



Simulations with HL-LHC Optics

Compared to the 2016 LHC optics the sim. RMS orbit response increases by a factor

- **~2 for round HL-LHC optics**
- **~3 for flat HL-LHC optics**



Observations

- The PLI is capable of monitoring ground vibrations with high precision
- The comparison with LHC orbit oscillations shows:
  - The PLI detects the earthquakes earlier than the LHC orbit starts oscillating
  - The PLI detection is correlated with losses at the collimators and luminosity oscillations
  - Earthquakes might dump the beam of HL-LHC
  - If HL-LHC would be more sensitive to micro-seismic activity solutions need to be anticipated

How the PLI can help

- The monitoring activity can be enlarged with the installation of PLI devices in the LHC tunnel at least in proximity of the 4 experiments
- Once fully commissioned and calibrated the PLI can supply an active feedback and signal to the LHC operators that a large Earthquake is arriving preventing unforeseen dumps
- Being the PLI a mechanical-based device can be used for active stabilization by networking of multiple devices

Monitoring

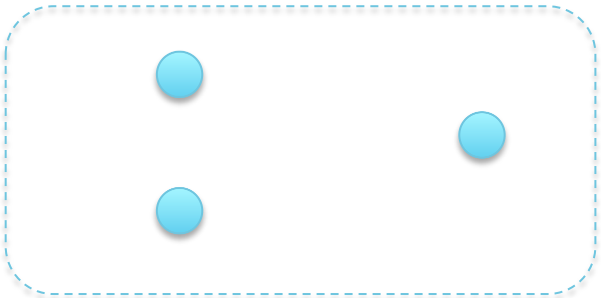
- The PLI has undergone a detailed systematic set of technical specifications
- It is being built according to the specifications to pave the way to industrialization
- Identical devices can be installed in the LHC tunnel
  - To provide monitoring
  - For the device calibration with other known devices (geophones) being installed in the LHC tunnel
  - Accumulating experience and statistics in the monitoring of LHC tunnel for several years

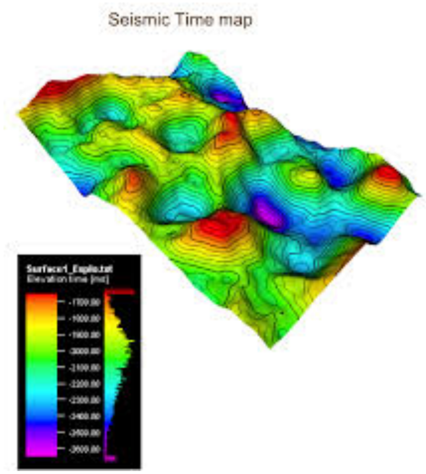
Active feedback

- The LHC is the most instrumented accelerator we know
- The PLI maximum frequency is, at the moment 4 Hz
- The electronic detection of orbit displacement is faster than the PLI, however
  - The PLI detects severe ground oscillations with higher sensitivity and earlier than the start of perturbation for the LHC orbit
  - Far and near earthquakes are earlier detected by PLI

Active stabilization

- The PLI devices will work in network
- Installing a PLI on each Inner Triplet jack at the HL-LHC would allow to correct for any ground oscillation upon online real-time mapping of the ground movements provided by a PLI network





Other considerations

- Earthquakes are rare events. Some near events might induce a dump of the beam
- But what would happen if HL-LHC or future ee, ep, pp colliders would be more sensitive to tinier sources of oscillations?

Next steps

- The PLI setup is being consolidated with an industrialization approach
- The readout can be easily simplified while maintaining the high level of detection precision
  - Lower sensitivity might also be useful for different types of applications to reduce costs and complexity
- The sensitivity is being further improved as well as the extension of the frequency range of operations
- The networking of PLI devices will allow extended regions/objects mapping

Conclusions

- A novel instrument has been developed in collaboration by JINR, ATLAS and CERN
- Among other applications, the monitoring and possible active input to high energy colliders is being investigated
- It is a baby now, growing step by step to a brilliant future
- Большое спасибо!