Status of vibration studies

D. Gamba, R. Corsini, L. Wroe

Many inputs from previous works of M. Guinchard, M. Schaumann, M. Fitterer, J. Wenninger, P. Fessia, D. Valuch, et al.

119th HiLumi WP2 Meeting – 17/04/2018

Outline

- Recap on effects we are looking for
- Comparison of LHC and HL-LHC using analytical formula
  - Impact on IP orbit separation
  - Impact on orbit at collimators
- A look at data collected from geophones
  - Estimate impact on beam quantities

Note:

- Most of the content summarised in IPAC2018 paper (THPAF040)
- Topic already presented a few times, e.g.:
  - M.Fitterer et al. – April 2015 link
  - D.Gamba et al. – Jul 2017 link
- Many other references available on my page

Frequency regimes

- $f < \approx 1$ Hz:
  - slow orbit drifts;
  - reduction of available orbit corrector strength;
  - frequent machine re-alignments;
- $\approx 1 < f <$ a few 100 Hz:
  - closed orbit jitter;
  - beam intensity and luminosity losses;
- $f >$ a few 100 Hz:
  - emittance growth;
  - increase in tail's population;
  - beam lifetime reduction.

Regime we are looking at

Particularly dangerous are the betatron motion sidebands:
$f_{rev} \approx 11.2$ kHz; $Q \approx .31$
=> first dangerous **f ≈ 3.5 kHz**

See also "What we know on the LHC limits ", M. Fitterer, et al., Apr 2015, link

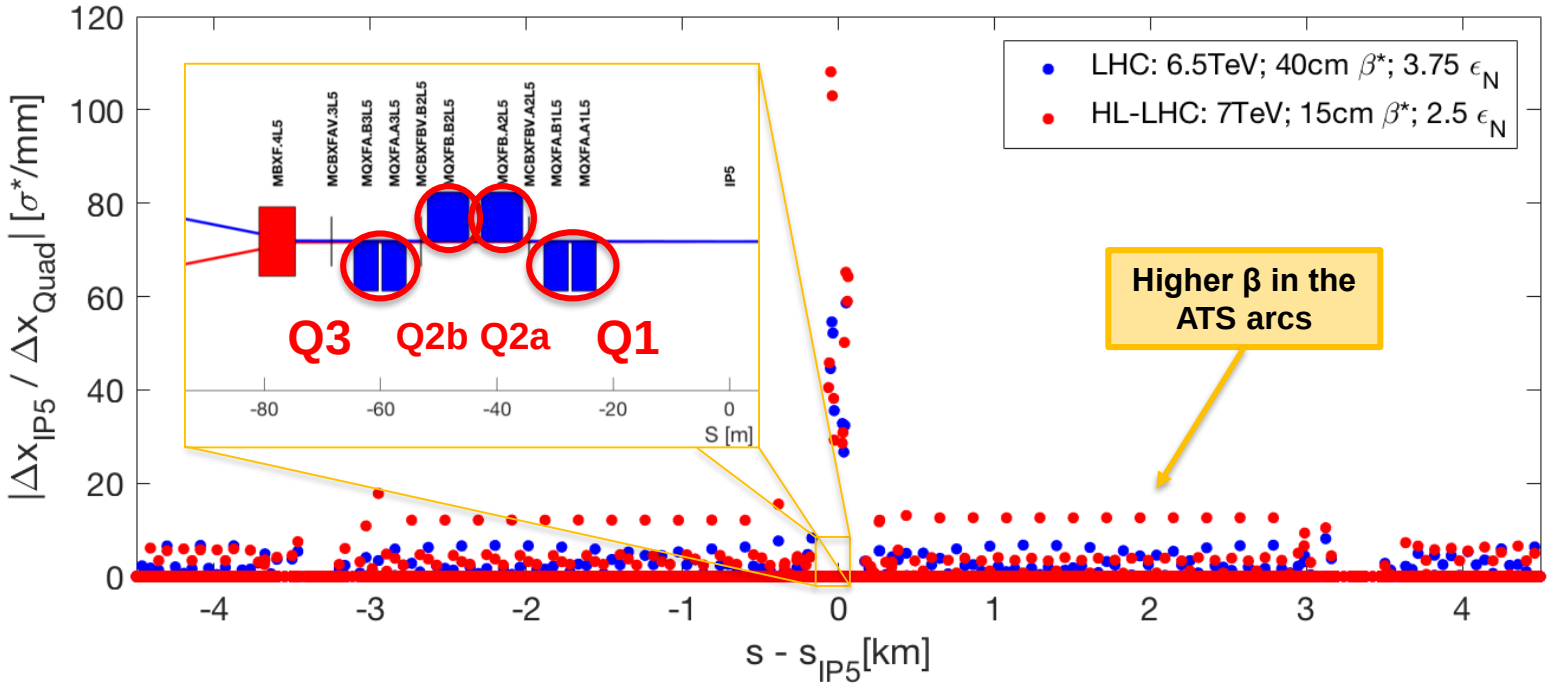
Questions (not covered here):

- Is it true that at low frequency we don't have emittance growth?
  - See M. Fitterer *et al.*, "MD1271: Effect of low frequency noise on the evolution of the emittance and halo population", Geneva, Switzerland, Rep. CERN-ACC-NOTE-2018-0006, Feb. 2018.
    - Some possible intensity loss and/or emittance growth.
    - Results difficult to interpret
      - Might require some further studies
- Can we estimate the impact of high frequency ground motion on emittance?
  - See 118th WP2 meeting – X. Buffat (link)
    - No spectrum available above 1000 Hz.
    - ATL law predicts $1/f^4$ decay -> impact should be small. TBC

Impact of quad misalignment on closed orbit

- Expected B1 closed orbit variation at IP5:

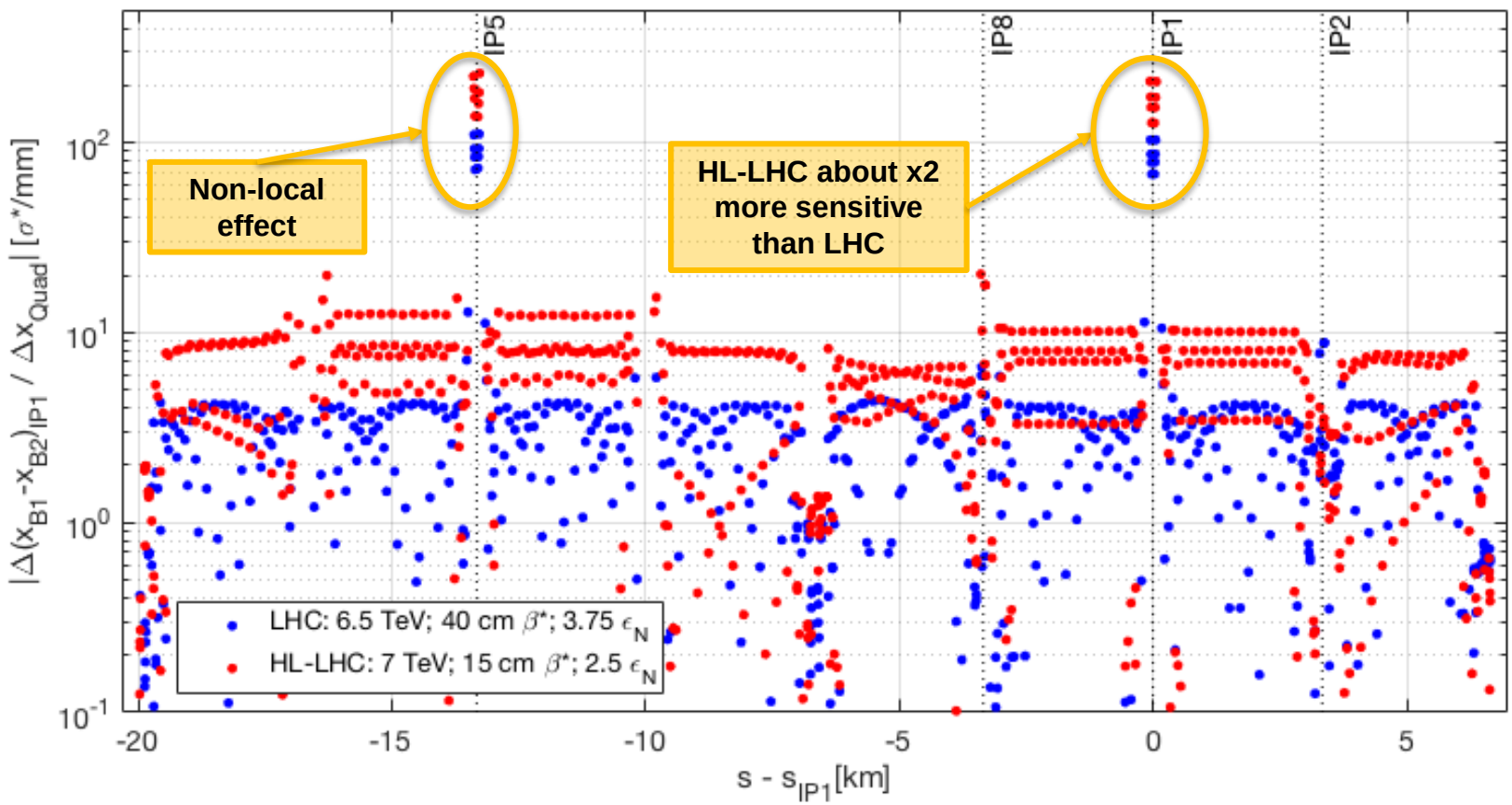
$$\frac{\Delta x_{IP}}{\sqrt{\beta^* \epsilon_g}\Delta x_q} = \frac{\sqrt{\beta_q}(K1L)_q}{\epsilon_g}\frac{\cos(2\pi\phi_{q*} - \pi Q_x)}{2\sin(\pi Q)}$$



- HL-LHC up to **x2 more sensitivity** to errors than LHC to be expected

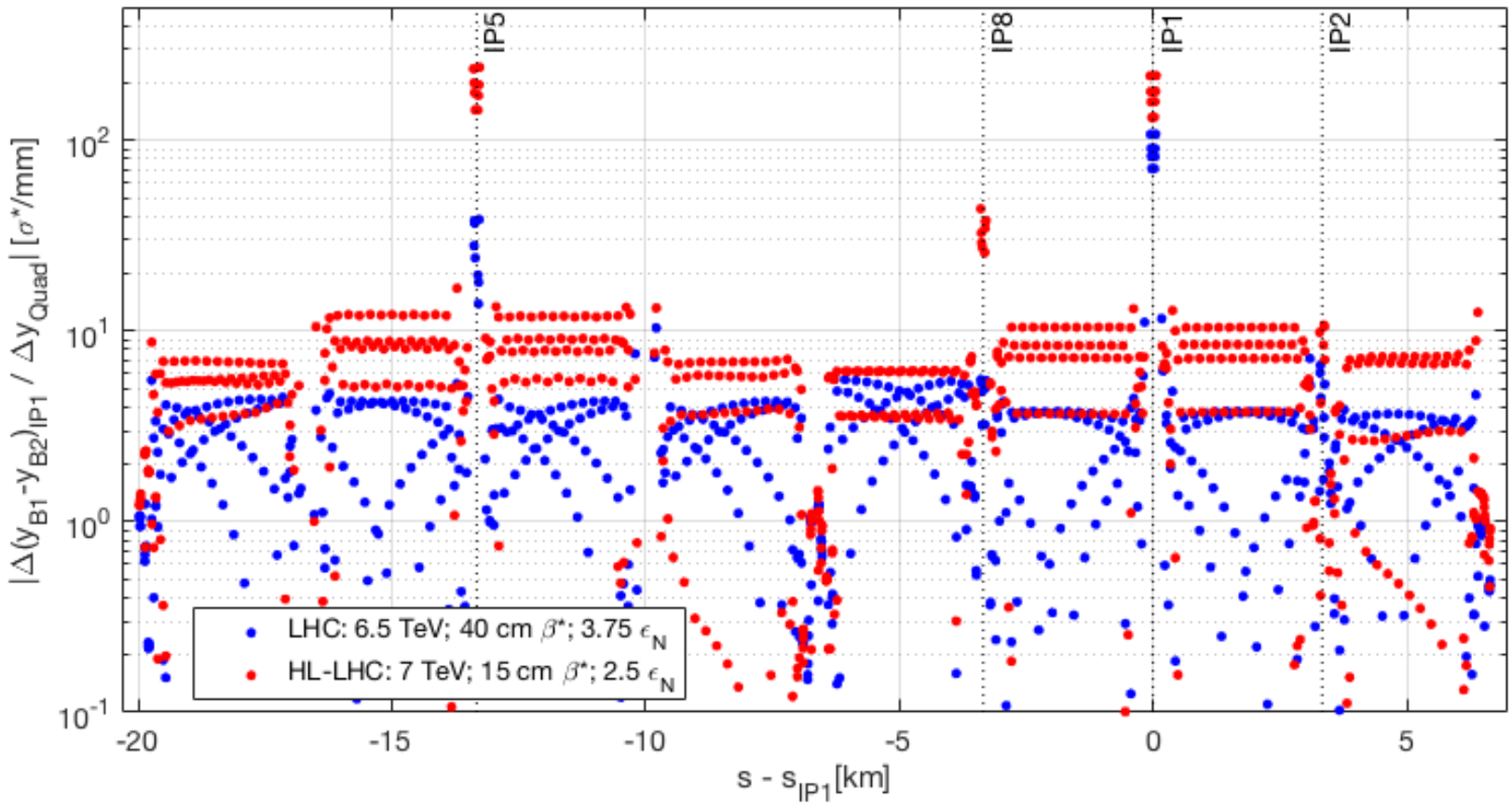
Looking at the whole machine: impact on IP1

- Horizontal B1-B2 separation at IP1



Looking at the whole machine: impact on IP1

- Vertical B1-B2 separation at IP1



Looking at the whole machine: impact on IP

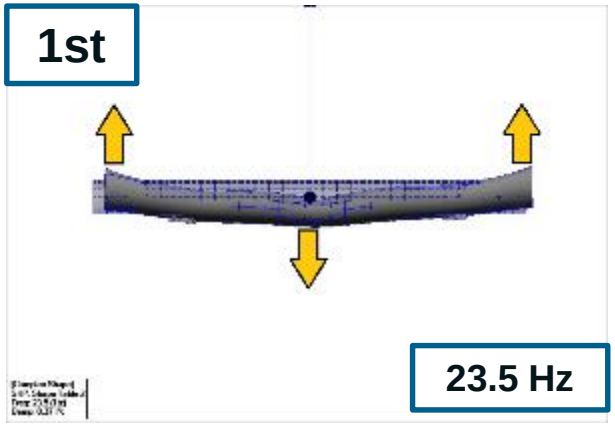
- Summing up **in quadrature** all contributions
  - Assuming each element is moving **independently**, **randomly**, **same amplitude**

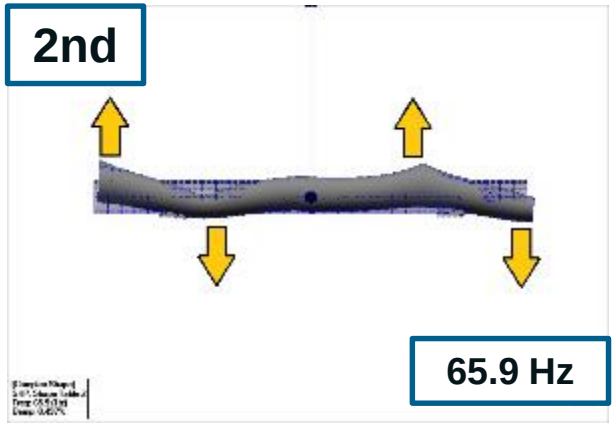
	IP1 [σ^*_{beam}/mm]		IP5 [σ^*_{beam}/mm]		IP2 [σ^*_{beam}/mm]		IP8 [σ^*_{beam}/mm]	
	Δx	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**
LHC all quads	360	274	360	375	175	177	176	185
LHC IR1/5 only	353	264	354	294	82	75	49	72
HL-LHC all quads	721	758	719	755	269	367	341	592
HL-LHC IR1/5 only	703	736	704	735	211	331	235	550

- Résumé:
  - HL-LHC about a factor 2 more sensitive than LHC.
  - Impact of IR1/5 is dominant
    - They might also become dominant for IP2/8
  - Biggest degradation (w.r.t. LHC) is in IP8 Vertical

Note1: cold mass modal shapes mode

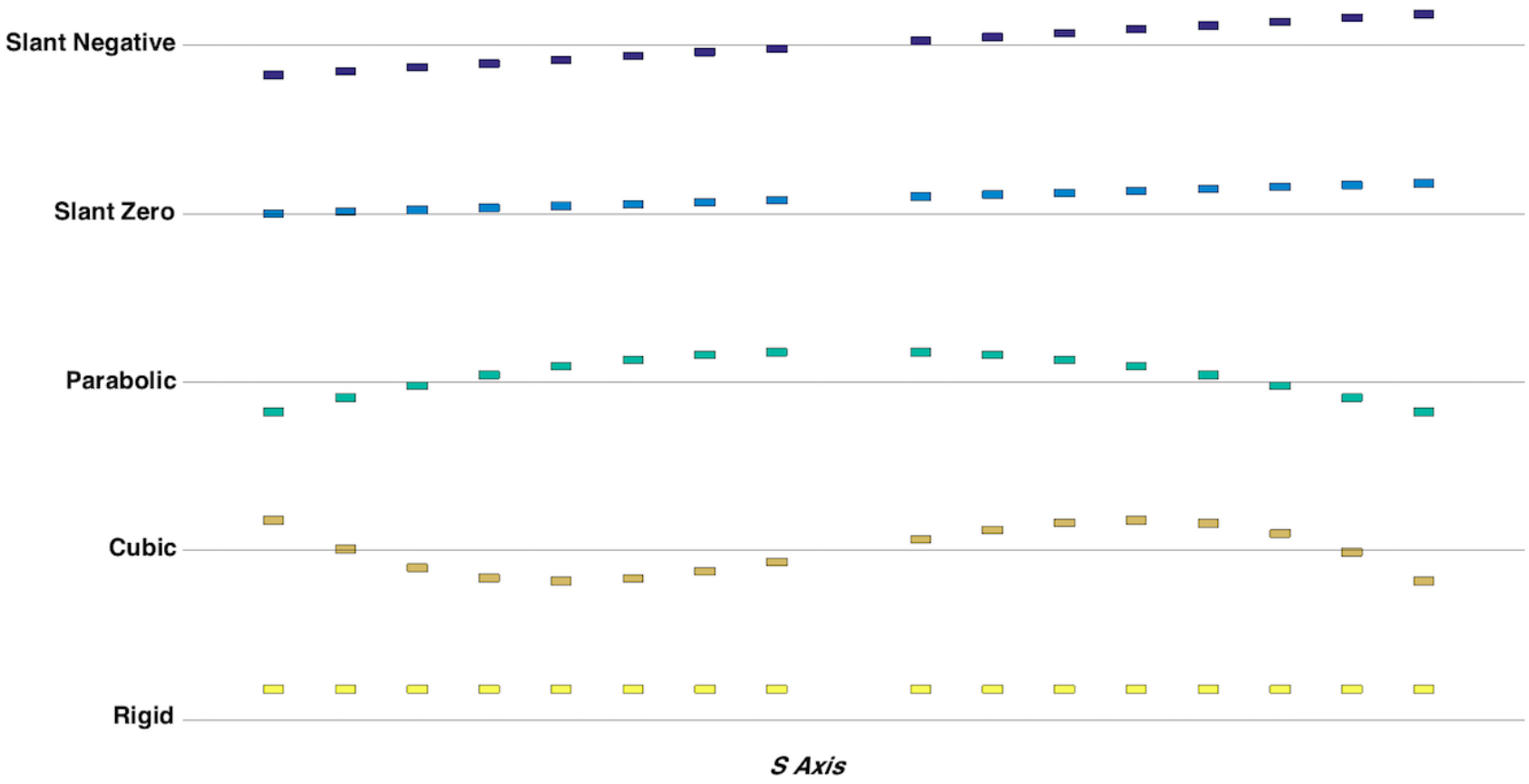
- Previous values obtained assuming rigid, lateral displacement of each quadrupole.
- Ground motion is more likely to excite proper oscillation mode of the cold mass. e.g. Vertical Modes (**See: M. Guinchard, 29/05/2017 link**)





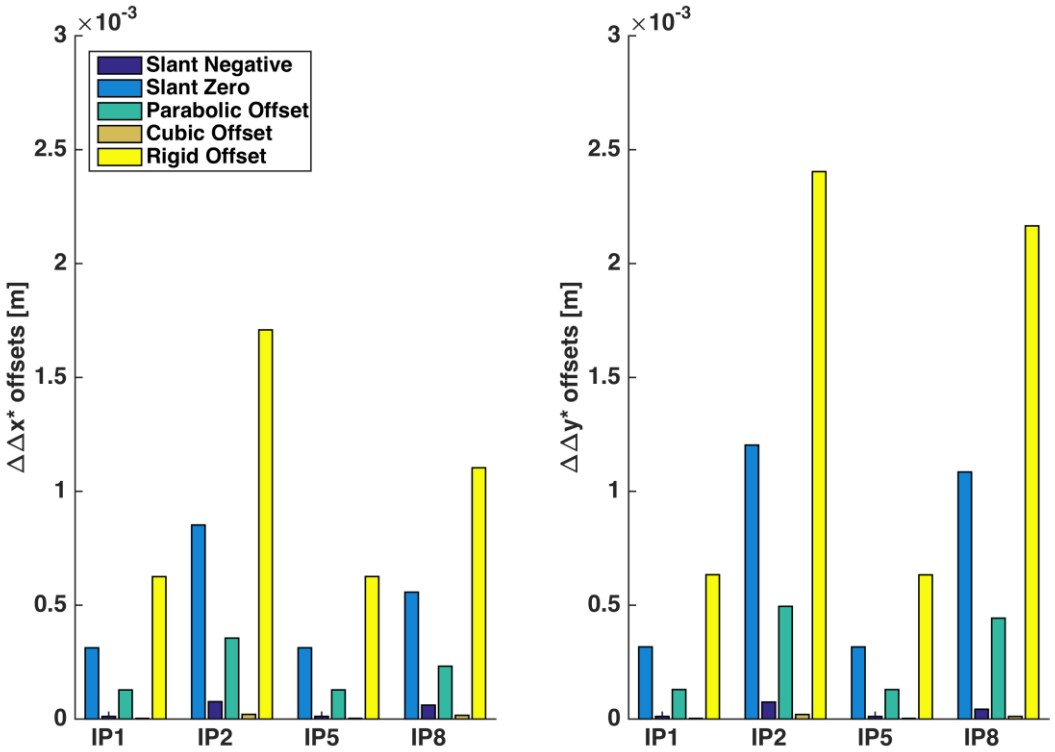
Note1: Simulated quadrupole modes

By Laurence Wroe
summer student 2017



Note1: Comparison different modes

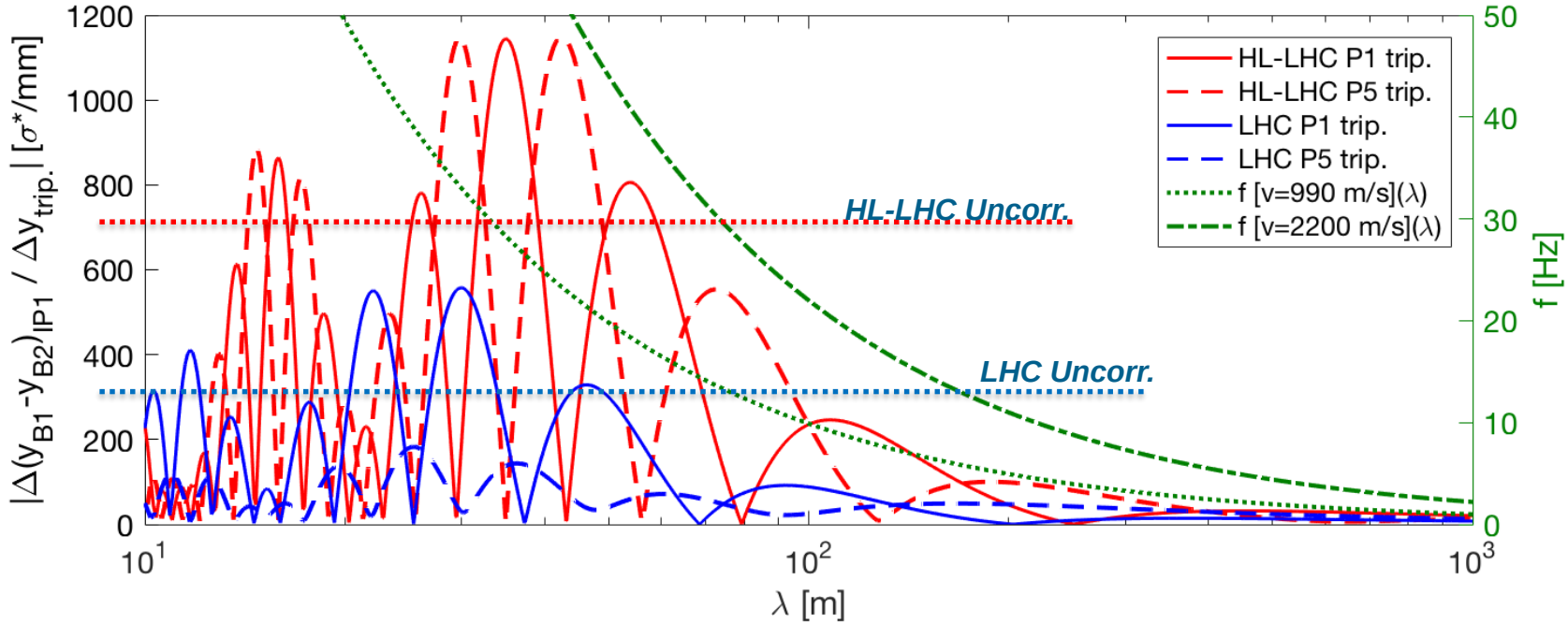
By Laurence Wroe
summer student 2017



- 0.1mm maximum offset of the quadrupole in all triplets
- Lower order oscillations that with large antisymmetry over the central axis have dominant effect

Note2: correlated IR motion

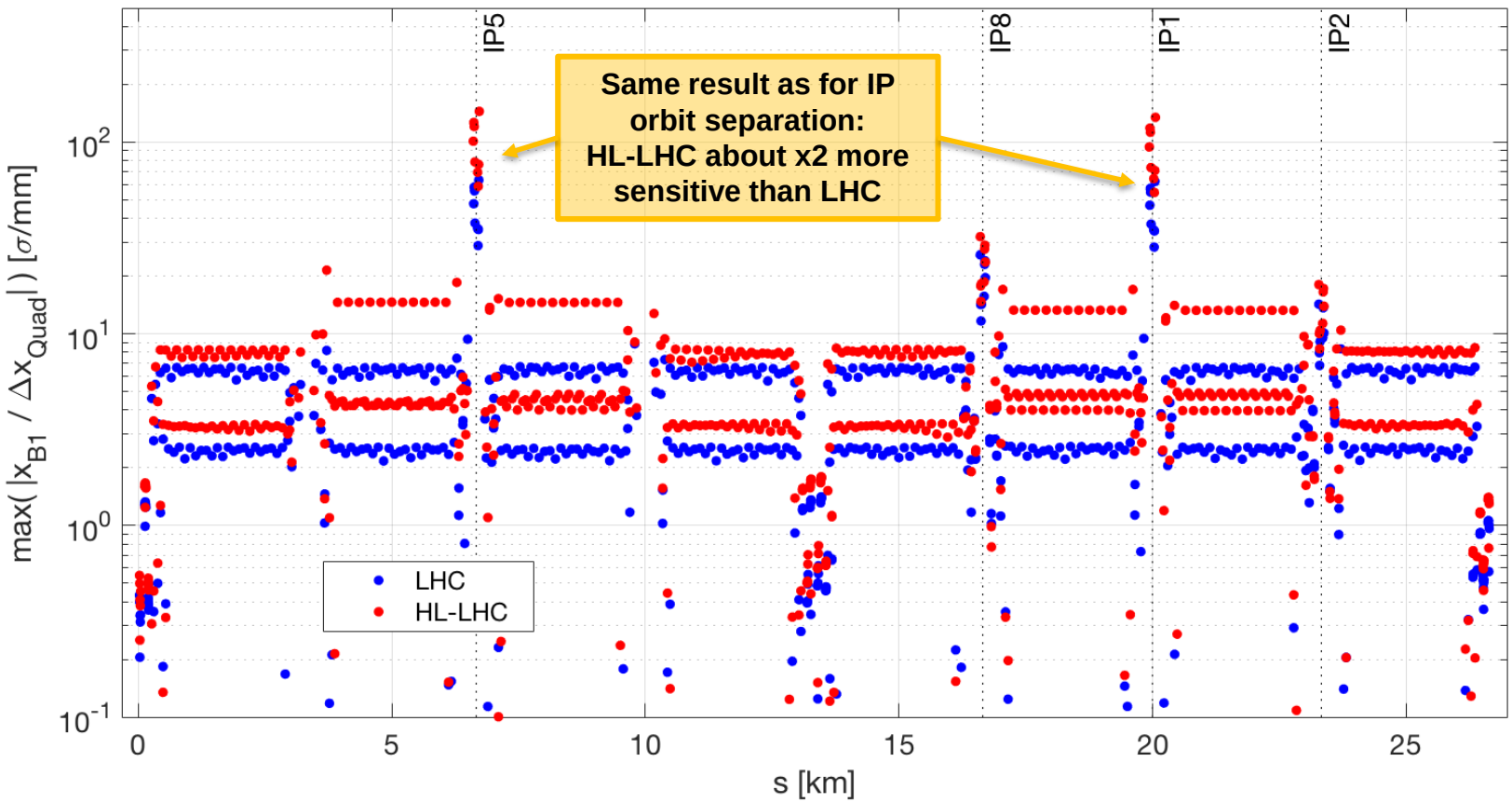
- Impact of a wave propagating along the local IR1 or remote IR5 on IP1 orbit separation: amplification factor as a function of λ



- Typical wave speed measured in the CERN tunnels:
  - 990 m/s (shear); 2200 m/s (pressure)
- ***f* below a few Hz** (most likely *f* to be correlated) **have "small" amplification factor w.r.t. fully uncorrelated case.**

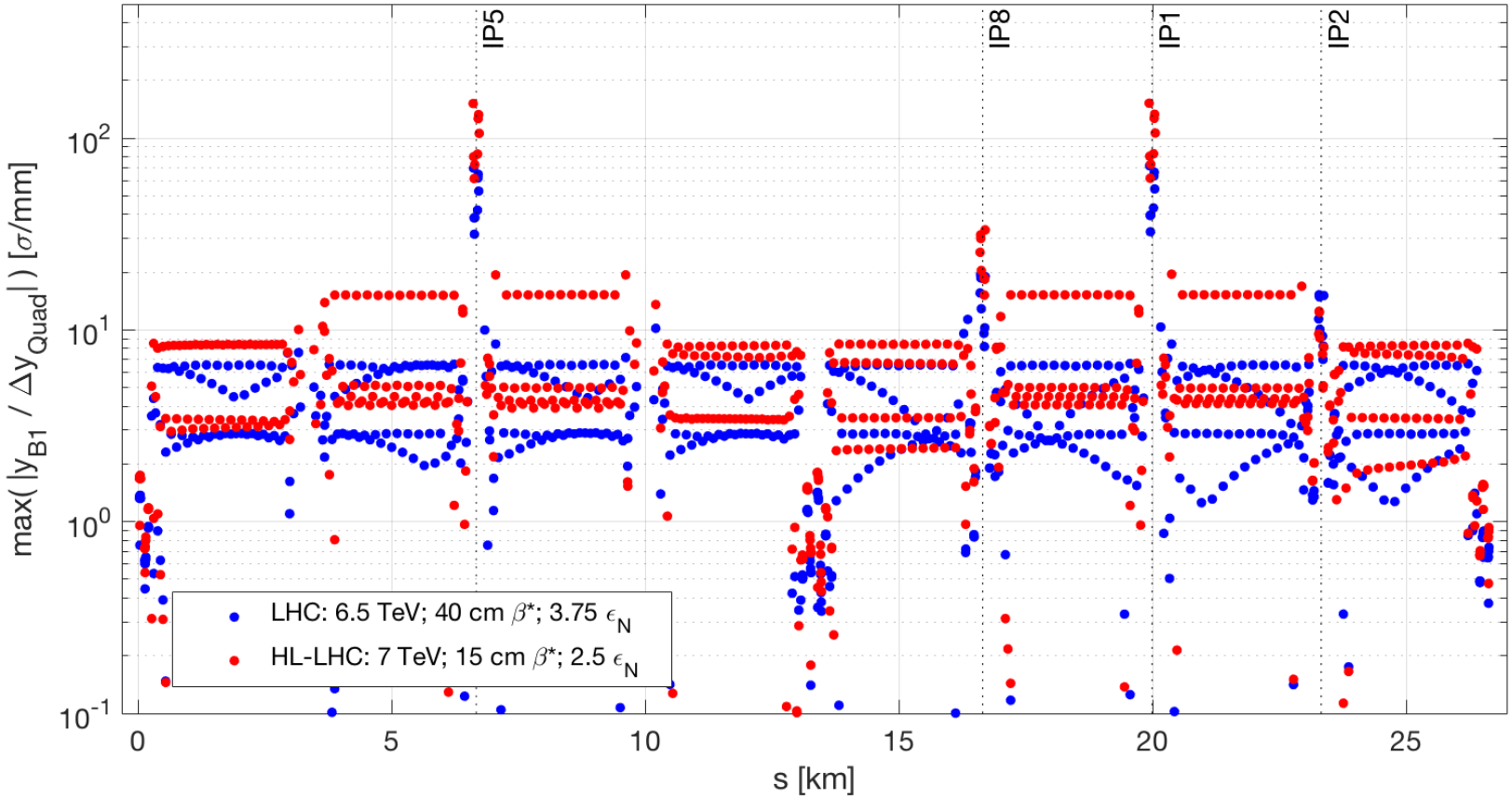
Looking at the whole machine: @ collimators

- **Max** B1 horizontal orbit **at any primary collimator**



Looking at the whole machine: @ collimators

- **Max** B1 vertical orbit at **any primary collimator**



Looking at the whole machine: @ collimators

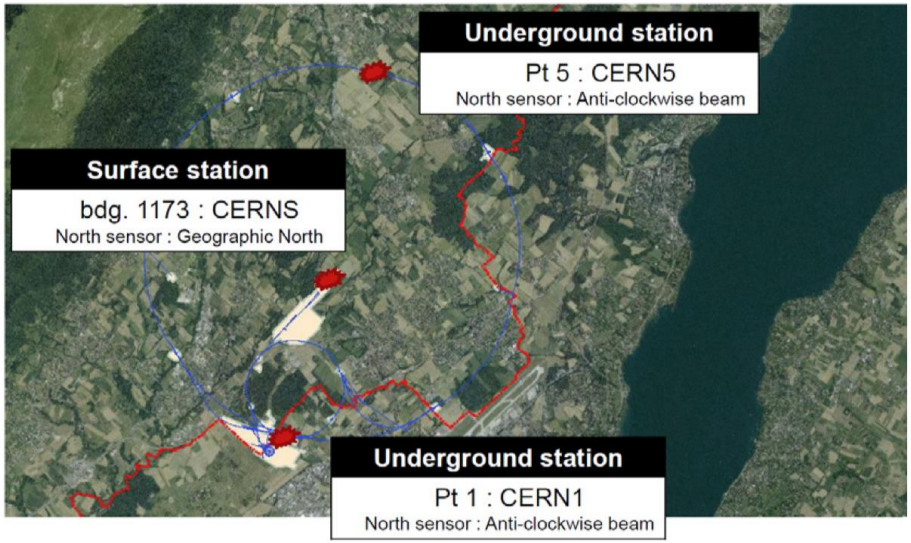
- Summing up **in quadrature** all contributions
  - Assuming each element is moving **independently**, **randomly**, **same amplitude**

	B1 [σ_{beam}/mm]		B2 [σ_{beam}/mm]	
	Δx	**Δy**	**Δx**	**Δy**
LHC all quads	205	207	212	169
LHC IR1/5 only	179	187	189	146
HL-LHC all quads	393	454	418	227
HL-LHC IR1/5 only	367	425	394	195

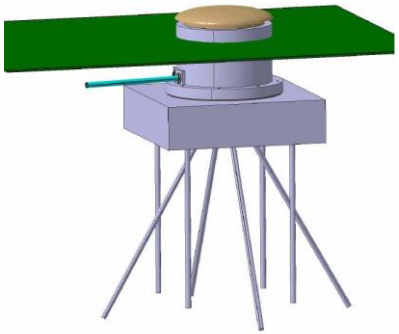
- Résumé (same result as for IP orbit separation)
  - HL-LHC about a factor 2 more sensitive than LHC also at collimators.

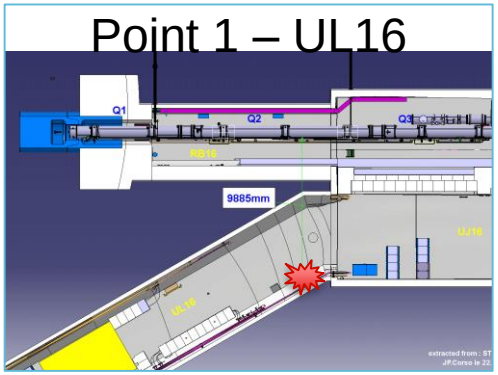
Ground motion measurements

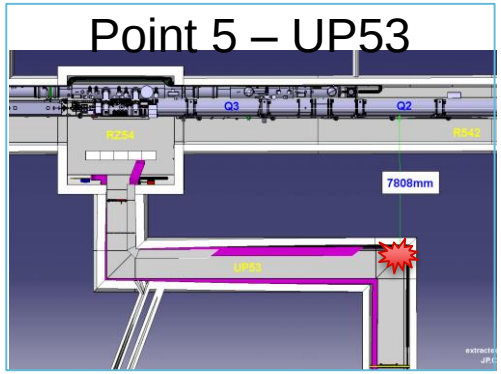
- Sensors are logging data since last year



M. Guinchard, Oct. 2017 link

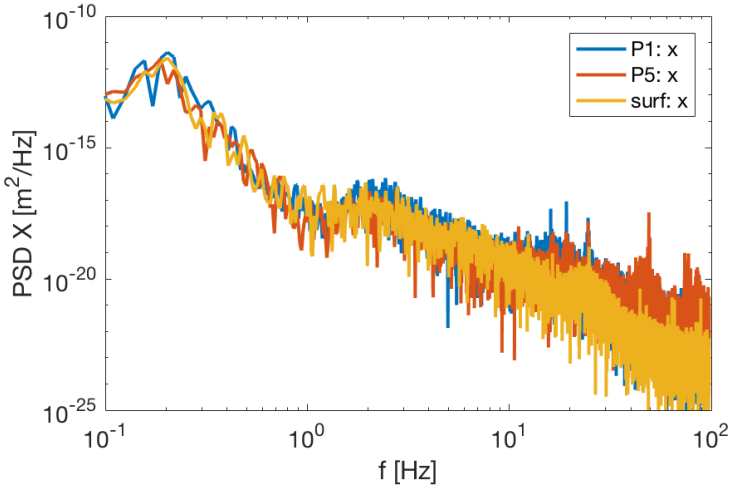


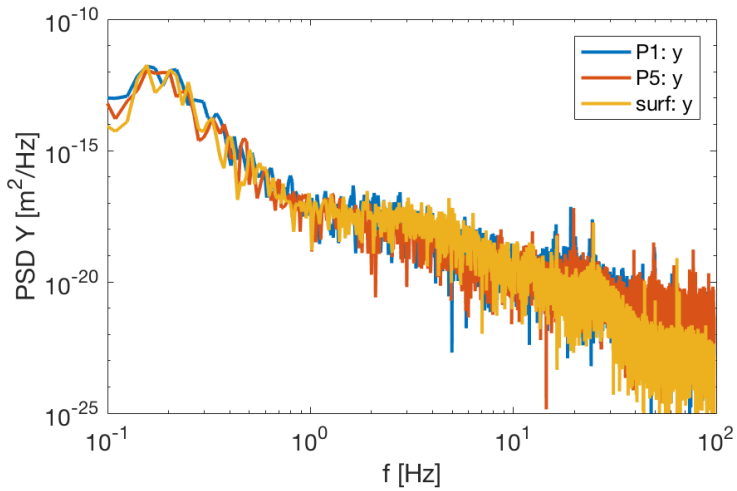


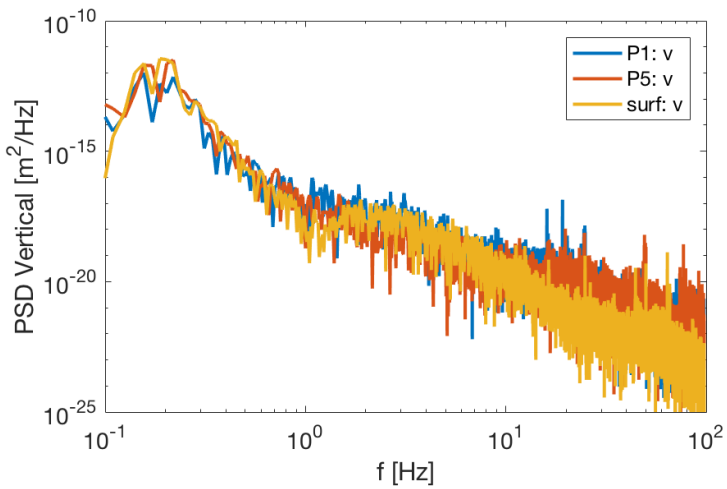


"Ground vibration monitoring at CERN as part of the international seismic network", C. Charrondiere, et al., 2018, link

Typical PSD logged in Timber



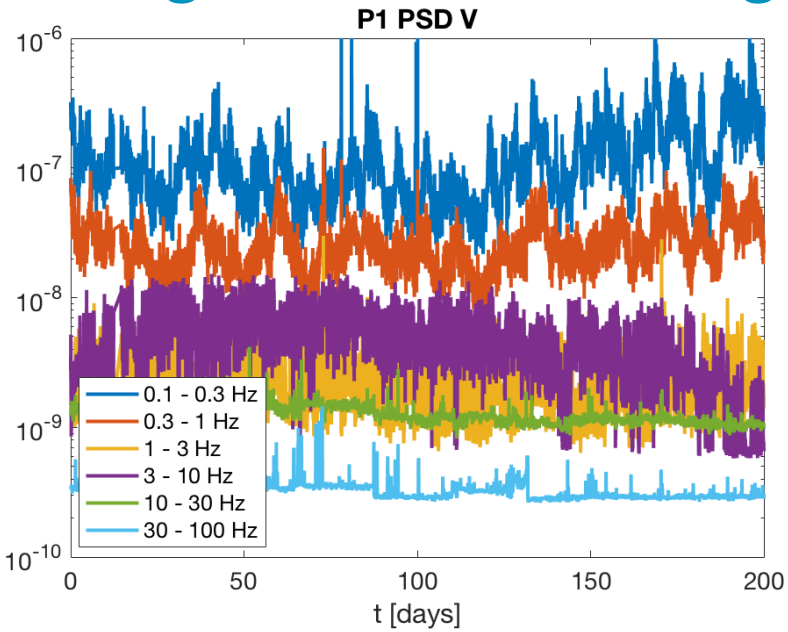


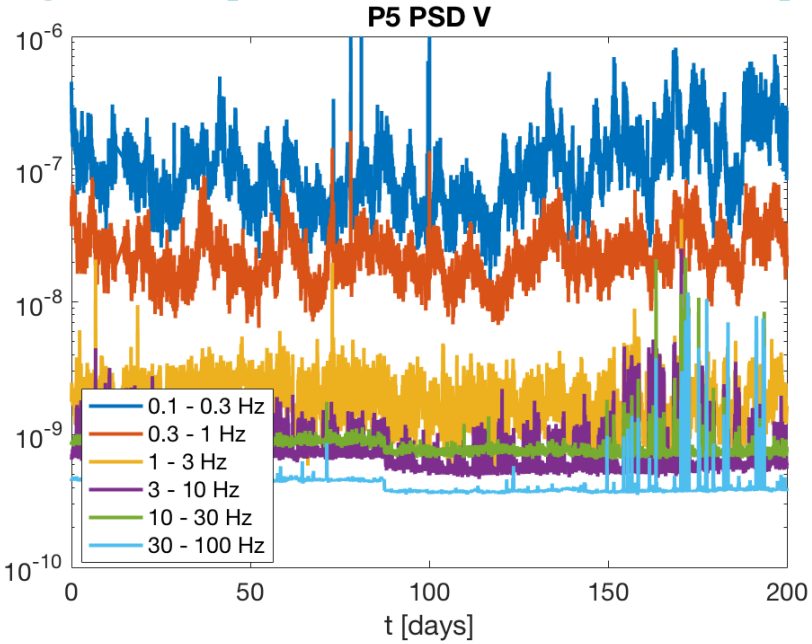


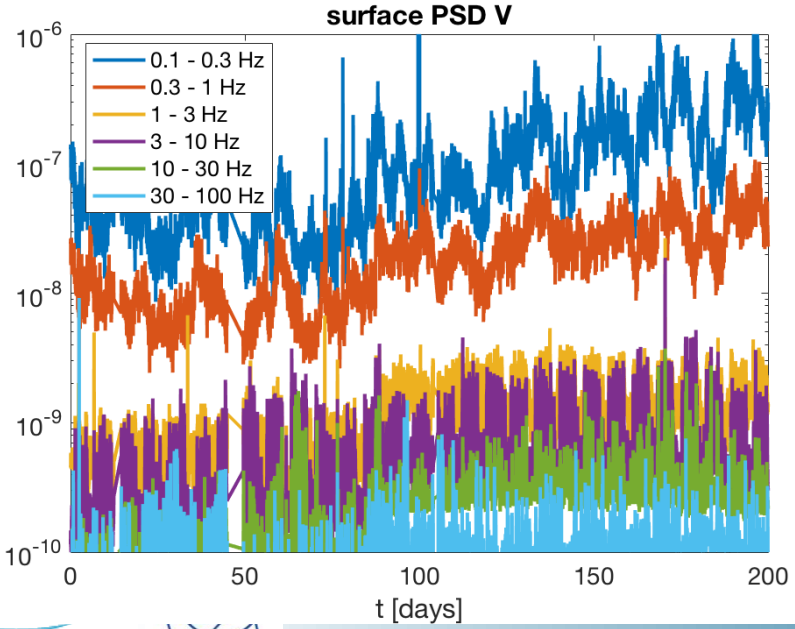
$$p(f) = \lim_{T\to\infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} x(t) e^{-i\omega t} \mathrm{d}t \right|^2$$

- From a first view, very similar spectra in all places, directions.

Integrated PSD along the year (1/5/17 – 1/12/17)



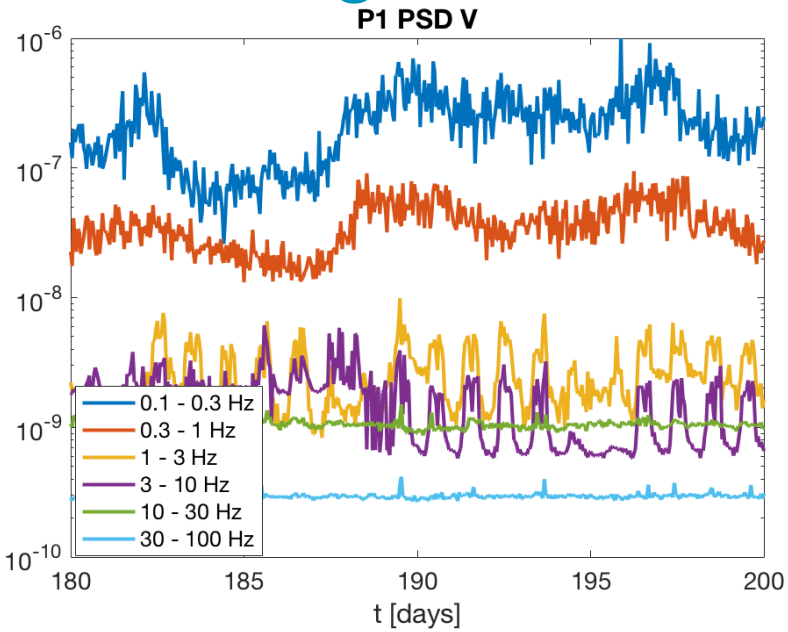


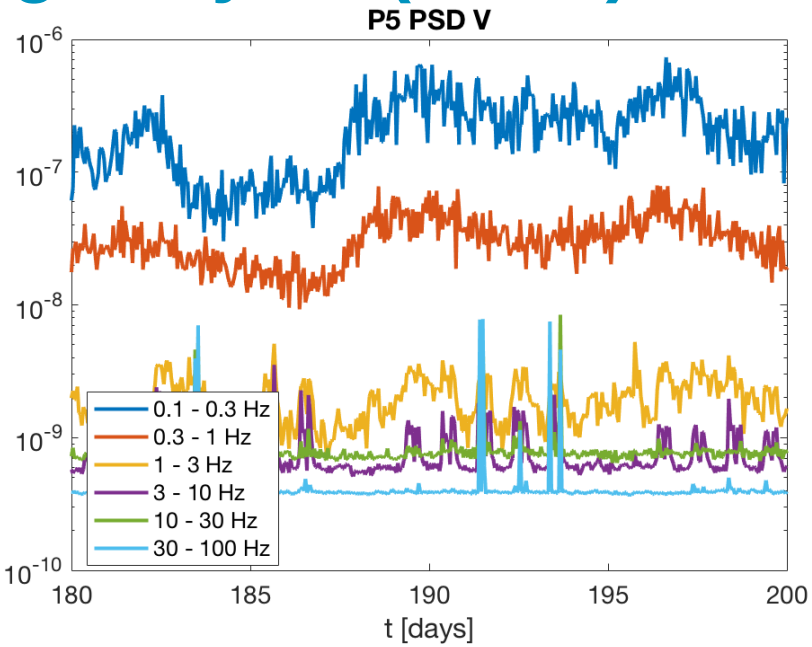


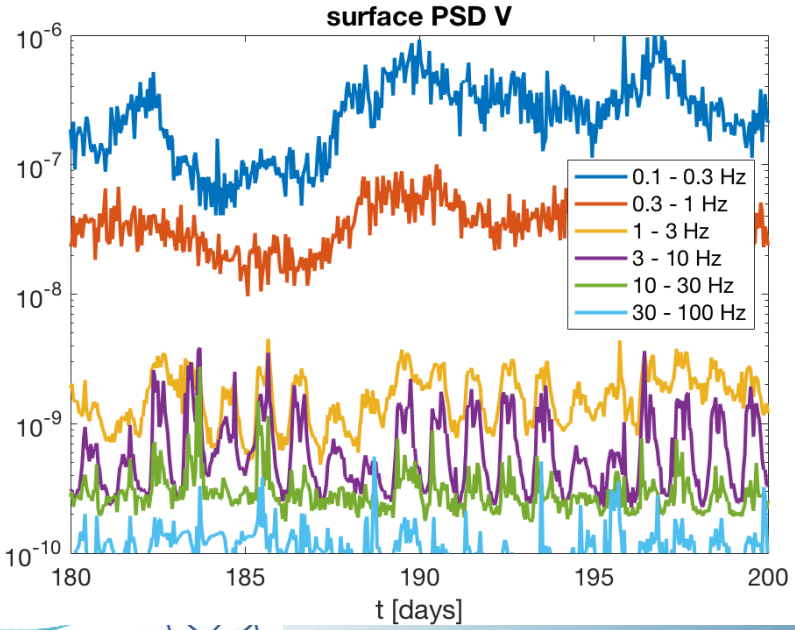
$$\sigma^2(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f)\mathrm{d}f$$

- Surface less noisy @high f
- Most of the noise “energy” at low frequency (f< ~1 Hz)
  - Assumed to be correctable by orbit feedback.

Integrated PSD along the year (zoom)

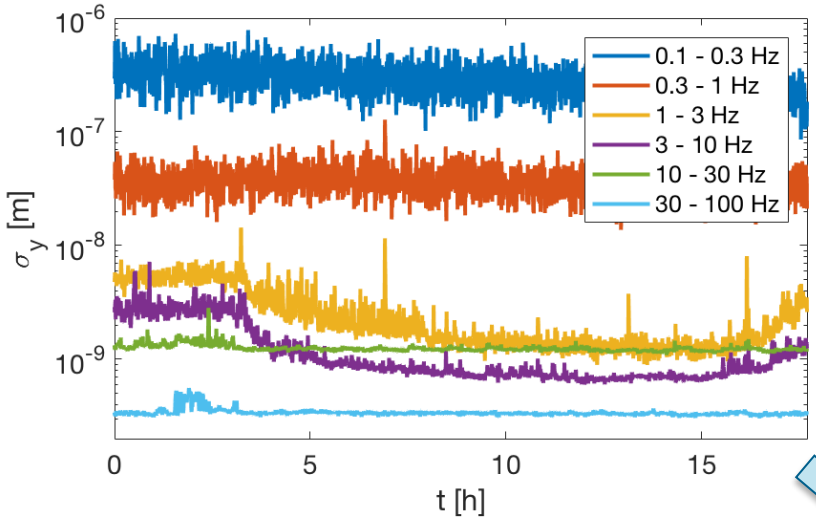






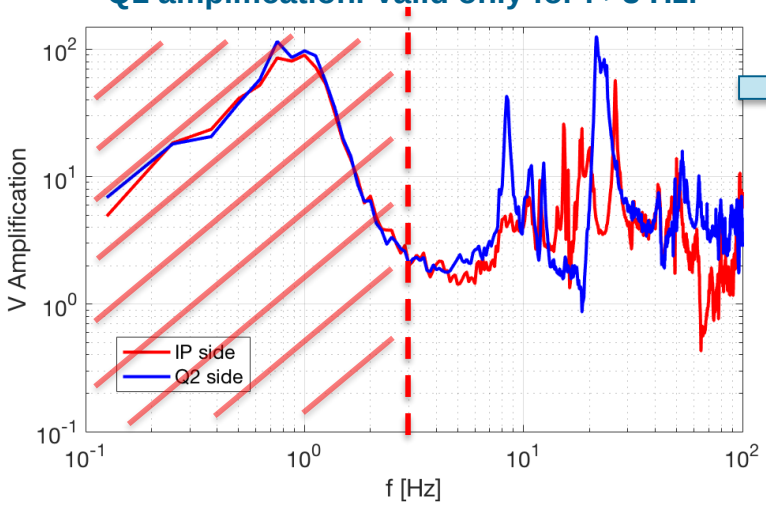
- Low frequency part “correlated” between different points.
  - **If** “really” correlated motion, amplification factor optics -> beam much lower than uncorrelated estimate.
- High frequency part shows **day/night/weekend** beating
  - Note that different type of sensors are used on surface and in the tunnel [link]

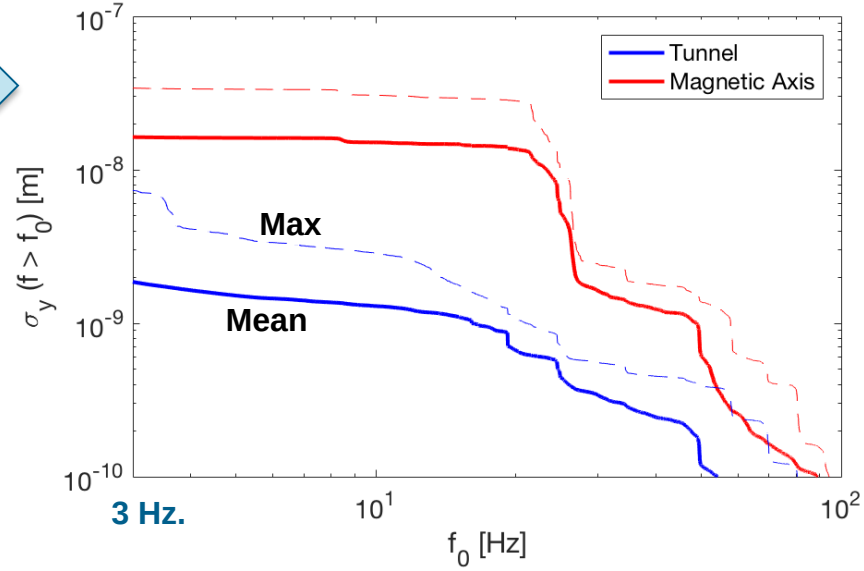
Integrated PSD during a fill (6399 – 20/11/2017)



- Considering typical a whole fill PSD at P1
- Considering amplification factor of cold mass (See link)
  - Direct multiplication on PSD
    - **conservative estimate**!
  - Integration of PSD for $f>f_0$

Q1 amplification. Valid only for f >3 Hz.





3 Hz.

Impact on measurable beam parameters

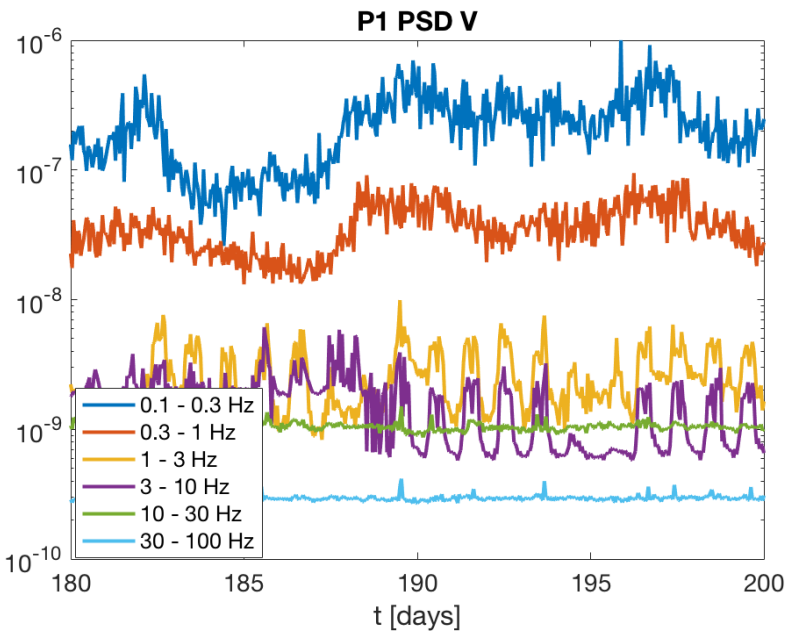
- Considering all ground motion for f > 3 Hz, with Q1 amplification applied to all magnets => 0.04 μm r.m.s.
- Assuming limit value imposed for HL-LHC excavation work during 2018 LHC operation (< 1 μm r.m.s. M. Fitterer, M. guinchard)

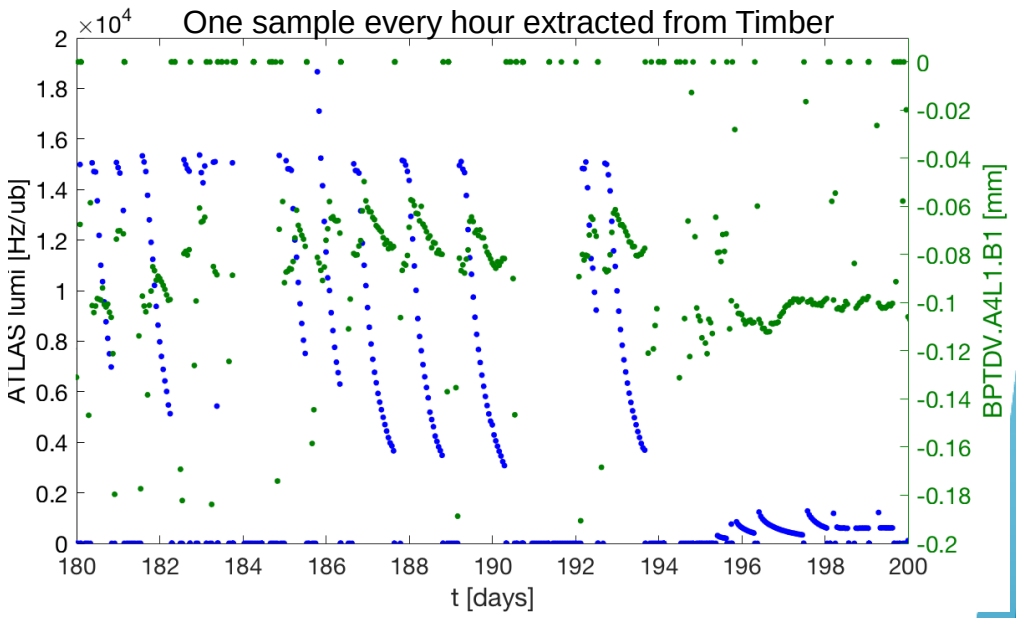
$\sigma_{magnetic\ axis}$ [μm]	0.04		1	
	LHC	HL-LHC	LHC	HL-LHC
Orbit sep. IP1/5 [σ_{beam}]	0.01	0.03	0.35	0.75
Luminosity loss [%] $W = e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2}$	<0.1	<0.1	3.0	13.1
Max orbit @TCP [σ_{beam}]	0.01	0.02	0.2	0.45

- No visible effect on LHC today, but **it might be possible to see something during HL-LHC excavation works**
  - **Motion of the order of 1 μm would be unacceptable for HL-LHC!**

Looking at some other signal

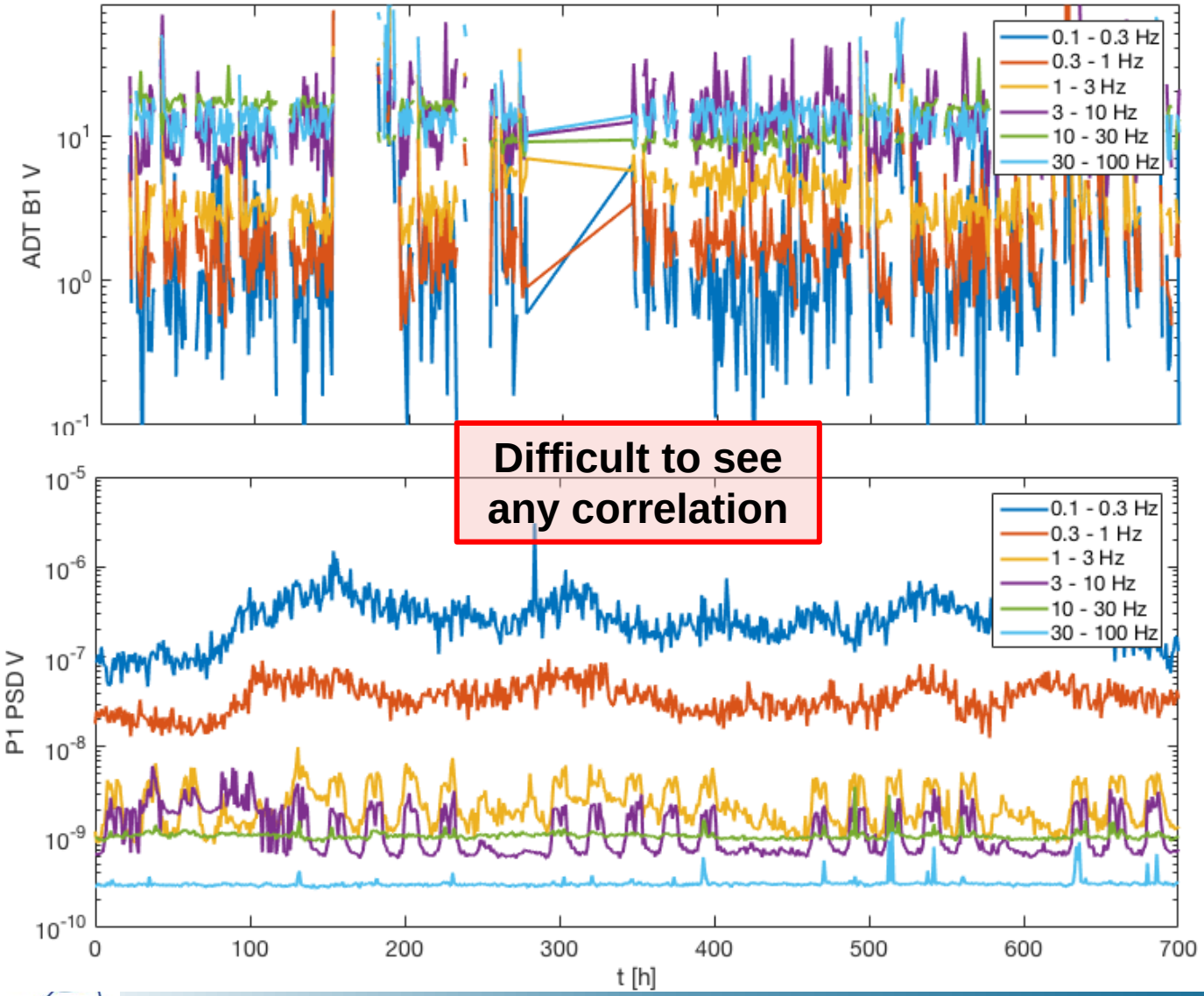
- Most signal are logged at low frequency (about every 1 s)
  - E.g. Luminosity or orbit at standard pickup (e.g. collimators)
- Orbit variation at collimators during a fill up to 20 μm (0.03 σ_{beam})





Looking at some other signal

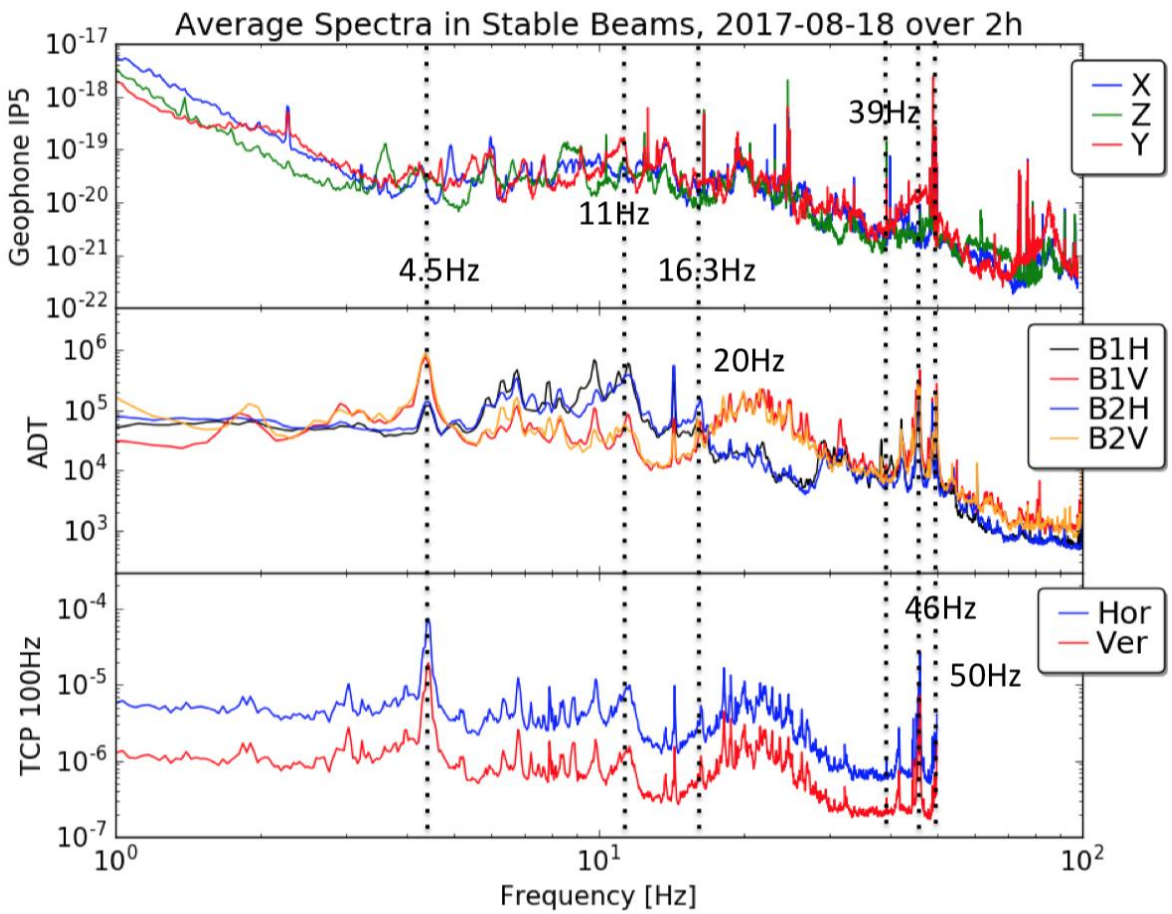
- Looking at ADT data (once every hour since 1st November)



Comparing spectra during stable beams

- Work ongoing by M. Schaumann (link) – also interested in earthquakes

Average Spectra in Stable Beams (2017-08-18)



2017/09/20 M. Schaumann, LMC 18

Conclusions

- Analytical formula applied on whole ring confirms previous results:
  - **IR1/5 triplet** misalignments are the **main sources** of orbit perturbation
  - **HL-LHC about x2 more sensitive than LHC**
- **Uncorrelated motion** seems a good approximation
  - **Correlated** motion would be "**dangerous**" at **high frequencies**
    - in contrast with observation where motion more likely to be correlated at low frequencies.
  - **Below a few Hz** the correlation would lead to **local compensation** of orbit kicks.
- **No observable effect** on the beam **today** (in normal conditions)
  - Compatible with a (still) conservative estimate starting from geophone observation
  - A **signal might come up during excavation works** for HL-LHC
- **HL-LHC estimation** are based on the assumption that
  - **HL-LHC** triplet **quadrupoles** will **behave similarly** to the **LHC Q1**
    - *See next presentation*
  - **ground motion amplitude will not change in HL-LHC era**
- **TODO:** *keep an eye on 2018 geophone and beam data.*

--- Thanks for your comments ---

Modes EDMS #347269

Table 1 – Lateral modes of SSS5, with and without transport restraints

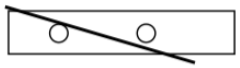
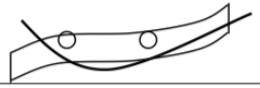
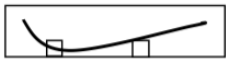
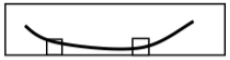
Mode	Modal shape	Frequency (Hz)	
		Without restraints	**With** restraints
Lateral 1		**7**	**7**
Lateral 2		**12**	**14**
Lateral 3		**14**	**15**
Lateral 4		**29**	**29**
Lateral 5		**40**	**40**
Lateral 6		**46**	/
Lateral 7		**54**	**55**

Table 2 - Vertical modes of SSS5, with and without transport restraints

Mode	Modal shape	Frequency (Hz)	
		Without restraints	**With** restraints
Vertical 1		**22**	**22-23**
Vertical 2		**27**	**28**
Vertical 3		**42**	**42**
Vertical 4		/	**44**
Vertical 5		**53**	**53**
Vertical 6		/	**57**

Definitions

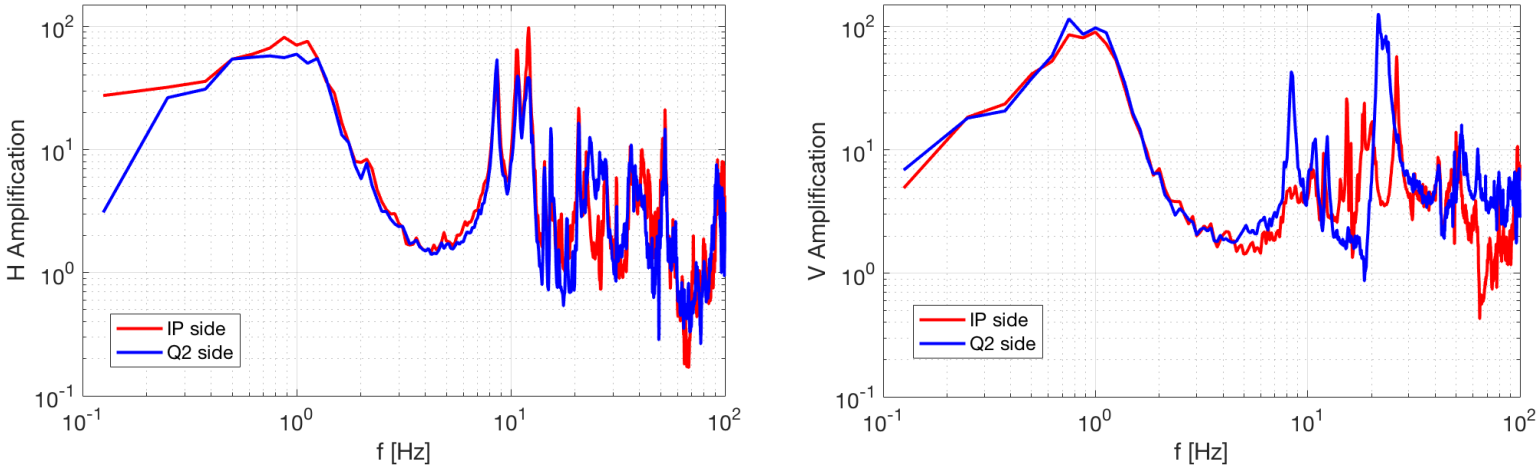
- PSD: $$p(f) = \lim_{T\to\infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} x(t) e^{-i\omega t} \mathrm{d}t \right|^2$$
  - Can be integrated to obtain variance of the signal:

$$\sigma^2 = \int_{-\infty}^{+\infty} p(f)\mathrm{d}f \qquad \sigma^2(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f)\mathrm{d}f$$

- FFT: $$\hat{x}(f) = \int_{-\infty}^{+\infty} x(t) e^{-i\omega t} \mathrm{d}t$$
  - If computed on a small sample of n points on period T:

$$c_n = \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t)\, e^{-2\pi i \left(\frac{n}{T}\right) x}\, \mathrm{d}t$$

Amplification of Q1 assembly



- Measured on Q1 spare assembly in SM18
  - See for example M. Guinchard, Oct 2017, link
- Only “valid” for f > 3 Hz
  - Response below 3 Hz is unknown