Effect of civil engineering work on LHC and implications for HL-LHC

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

132th HiLumi WP2 Meeting – 02/10/2018

Outline

- Disclaimer: work in progress…
- Optics sensitivity: LHC vs HL-LHC
  - Impact on orbit separation at IPs
  - Impact on orbit at collimators
  - Impact on orbit at pickups
- Ground motion observed in the LHC
  - 2017 and 2018
  - Trying to get some numbers out of observations

Note:

- Follow up of topic presented a few times, e.g.:
  - M. Schaumann – Aug 2018 link
  - D. Gamba et al. – Apr 2018 link
  - D. Gamba et al. – IPAC2018 link
  - D. Gamba et al. – Jul 2017 link
  - M. Fitterer et al. – Apr 2015 link
- Many other references available on my page

Optics sensitivity: assumptions

- Equal **uncorrelated** ground motion distributed along the whole machine with same amplitude
  - Main players are triplets in IP1/5
- Assuming all perturbations induce simply a **closed orbit** variation ($f << f_{rev}$).
- Beam/optics parameters
  - LHC: ε_N **2 (~~3.75~~)** µm; 6.5 TeV; β* **30 (4~~0~~)** cm
  - HL-LHC: ε_N 2.5 µm; 7 TeV; 15 cm β*

HiLumi HL-LHC PROJECT CERN

Optics sensitivity: summary tables

- Amplification factors from magnet motion to IP orbit separation
  - New LHC values assuming ε_N = 2 μm and ATS optics β* = 30 cm
  - ~~Old~~ LHC values assuming ε_N = 3.75 μm and ATS optics β* = 40 cm

	IP1 [σ^*_{beam}/μm]		IP5 [σ^*_{beam}/μm]		IP2 [σ^*_{beam}/μm]		IP8 [σ^*_{beam}/μm]	
	Δx	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**
LHC all quads	**0.536** ~~0.360~~	0.440 ~~0.274~~	0.527 ~~0.360~~	0.443 ~~0.375~~	0.231 ~~0.175~~	0.252 ~~0.177~~	0.290 ~~0.176~~	0.368 ~~0.185~~
LHC IR1/5 only	0.516 ~~0.353~~	0.419 ~~0.264~~	0.516 ~~0.354~~	0.419 ~~0.294~~	0.120 ~~0.082~~	0.131 ~~0.075~~	0.172 ~~0.049~~	0.288 ~~0.072~~
HL-LHC all quads	0.721	**0.758**	0.719	0.755	0.269	0.367	0.341	0.592
HL-LHC IR1/5 only	0.703	0.736	0.704	0.735	0.211	0.331	0.235	0.550

- **Meaning:** if all quadrupoles in LHC oscillate randomly uncorrelated by **1 μm rms**, then the B1-B2 orbit separation at IP1 is **0.536 σ_{beam}** in H and **0.44 σ_{beam}** in V

Partially from 119th WP2 meeting (link)

Optics sensitivity: summary tables

- Impact at primary collimators (max rms orbit excursion at any TCP)
  - New LHC values assuming ε_N = 2 μm and ATS optics β* = 30 cm
  - ~~Old~~ LHC values assuming ε_N = 3.75 μm and ATS optics β* = 40 cm

	B1				B2			
	[σ_{beam}/μm]		[μm/μm]		[σ_{beam}/μm]		[μm/μm]	
	Δx	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**
LHC all quads	0.316 ~~0.205~~	0.273 ~~0.207~~	**99**	63	**0.337** ~~0.212~~	0.268 ~~0.169~~	71	57
LHC IR1/5 only	0.294 ~~0.179~~	0.245 ~~0.187~~	92	52	0.316 ~~0.189~~	0.231 ~~0.146~~	67	49
HL-LHC all quads	0.393	**0.454**	**133**	130	0.418	0.227	95	50
HL-LHC IR1/5 only	0.367	0.425	123	120	0.394	0.195	90	43

- **Meaning:** if all quadrupoles in LHC oscillate randomly uncorrelated by **1 μm rms**, then the rms orbit at the **most sensitive TCP** is **0.316 σ_{beam}** in H and **0.273 σ_{beam}** in V
- **Note:** σ_{beam} given without considering dispersion.

Partially from 119th WP2 meeting (link)

Optics sensitivity: summary tables

- Impact at pickups (max orbit excursion at any pickup, e.g. as for TCP)

	ADT pickup				Q1 BPM IP1/5			
	B1 [μm/μm]		B2 [μm/μm]		B1 [μm/μm]		B2 [μm/μm]	
	Δx	Δy	Δx	Δy	Δx	Δy	Δx	Δy
LHC all quads	57	55	56	**66**	125	**204**	180	179
LHC IR1/5 only	52	49	50	61	102	182	159	156
HL-LHC all quads	96	**130**	92	126	208	257	**280**	217
HL-LHC IR1/5 only	84	115	82	118	178	224	248	184

	"ARC" BPMs			
	B1 [μm/μm]		B2 [μm/μm]	
	Δx (Quad)	Δy (Quad)	Δx (Quad)	Δy (Quad)
LHC all quads	84 (6L7)	86 (11R5)	87 (6R7)	**92** (11L5)
LHC IR1/5 only	76 (6L7)	80 (11R5)	82 (6R7)	86 (11L5)
HL-LHC all quads	123 (6L1)	130 (9R4)	**162** (6R5)	130 (8R2)
HL-LHC IR1/5 only	108 (6L1)	115 (9R4)	146 (6R5)	121 (8R2)

Indicates which is the most sensitive pickup

Main observations

- HL-LHC (15cm β*) will be about 2 times more sensitive to quadrupoles vibrations than LHC (40cm β*; 3.75).
  - but if we consider present LHC performance (30cm β*; 2.00), the difference is clearly reduced.
- Dominant quadrupoles are the triplets in IP1/5
- Oscillations of the order of 1 µm should show up very easily in our instrumentation.

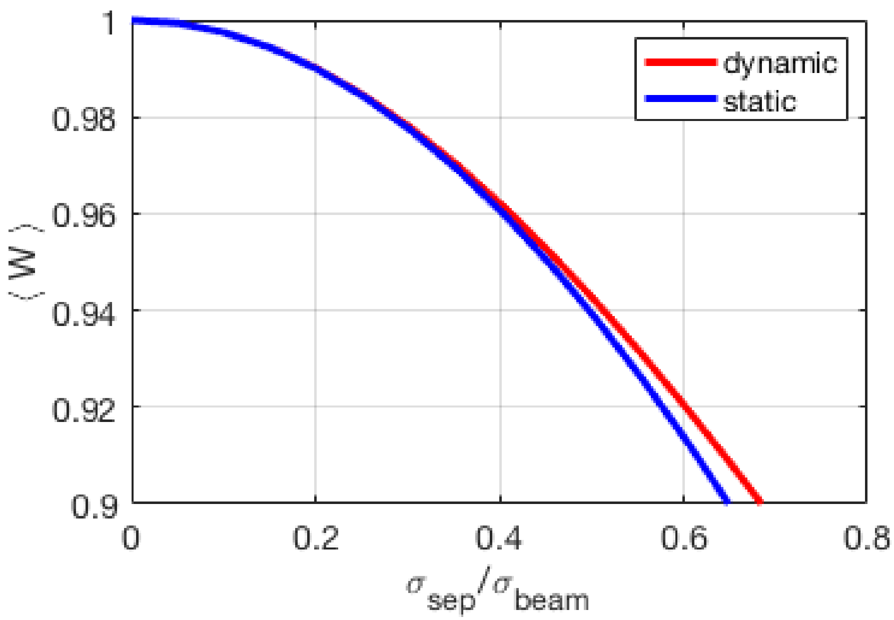
Instantaneous* Luminosity reduction [1]

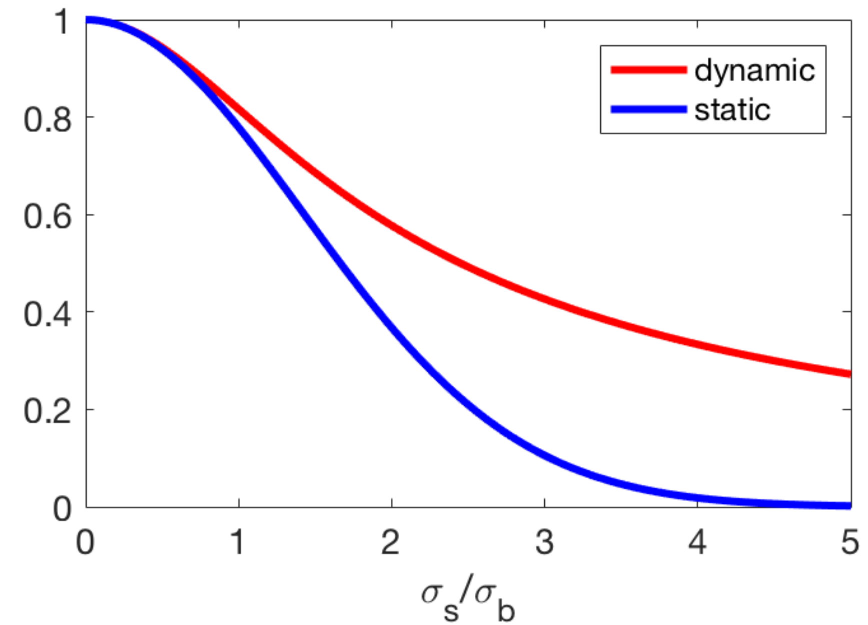
$$W = e^{-\frac{1}{4\sigma_x^2}(d_2 - d_1)^2}$$

Factor due to "static" orbit separation (d_2-d_1)

$$\langle W \rangle = \frac{\sqrt{2}}{\sqrt{\sigma_s^2/\sigma_b^2 + 2}}$$

Factor due to "dynamic" orbit separation σ_s i.e. assuming beam separation is oscillating around zero.





* **Instantaneous** compared to LHC fill, **integrated** compared to revolution frequency

[1] Concept of Luminosity, W. Herr and B. Muratori, (CERN-2006-002)

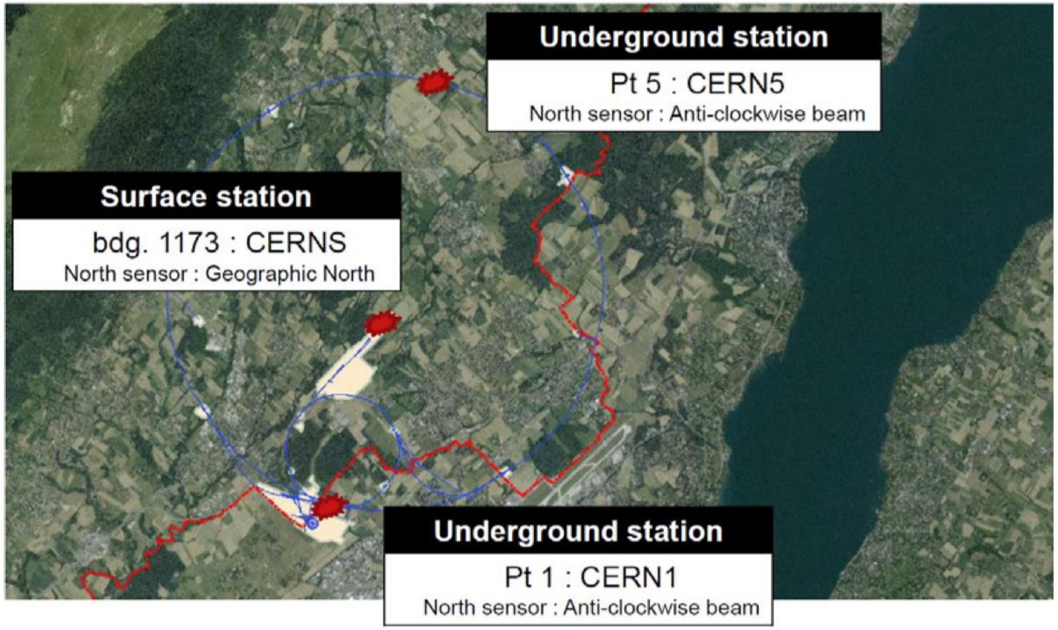
Partially from 99th WP2 meeting (link)

Summary: impact on observables

Luminosity loss [%] $W = e^{-\frac{1}{4\sigma_x^2}(d_2-d_1)^2}$	1		10		~2
	LHC	HL-LHC	LHC	HL-LHC	HL-LHC
Orbit sep. IP1/5 [σ_{beam}]	0.2		0.68		0.29
Necessary quad. motion rms [μm]	**0.39**	**0.27**	**1.33**	**0.93**	**0.39**
rms orbit @TCP [σ_{beam}]	0.12	0.12	0.42	0.40	0.17
rms orbit @TCP [μm]	36	34	122	114	48
rms orbit @ADT pickups [μm]	24	32	81	110	46
rms orbit @Q1 BPMs [μm]	71	68	242	231	97
rms orbit @11L5 BPM [μm]	34	40	114	136	57

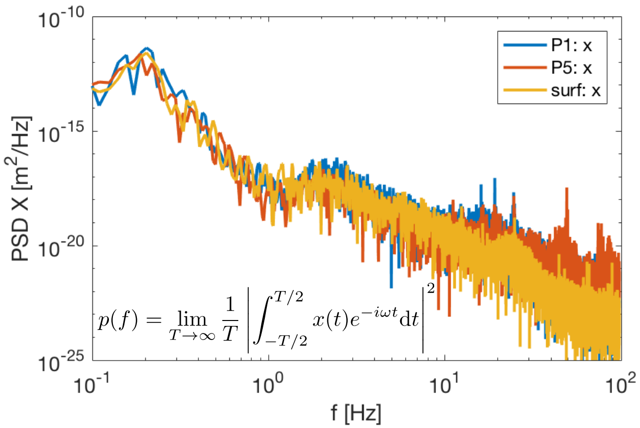
- Numbers computed assuming IP1/5 triplet only source of perturbation.
  - **Assuming both IP triplets oscillate by the same rms amplitude in one plane only.**
  - **If only one triplet oscillates => sqrt(2) more quadrupole motion needed to give same effect.**
- A reasonable threshold is **1% instantaneous luminosity loss**, which correspond to about **0.4 (LHC) or 0.3 (HL-LHC) μm triplet motion**.
- An event causing **1%** instantaneous luminosity loss in **LHC** would cause a **2%** luminosity loss in **HL-LHC**

Ground motion observations in LHC



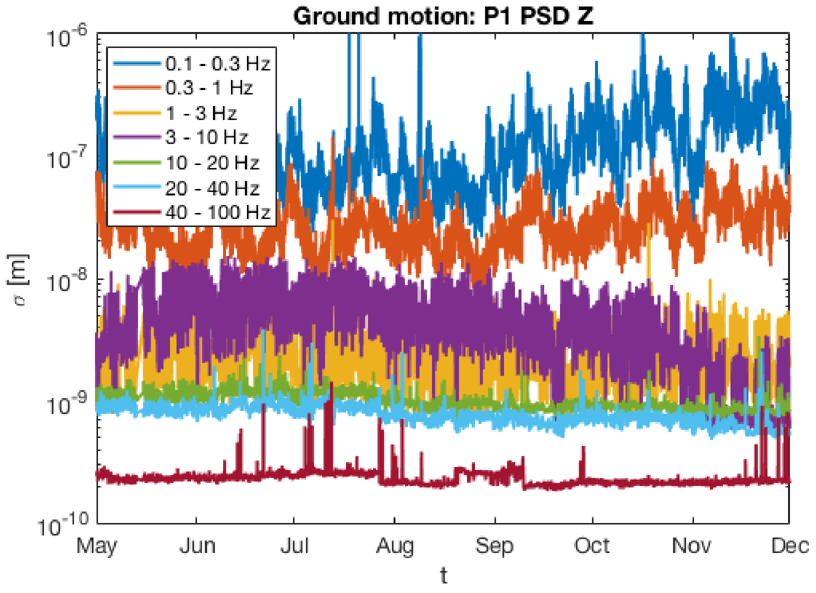
M. Guinchard, Oct. 2017 link

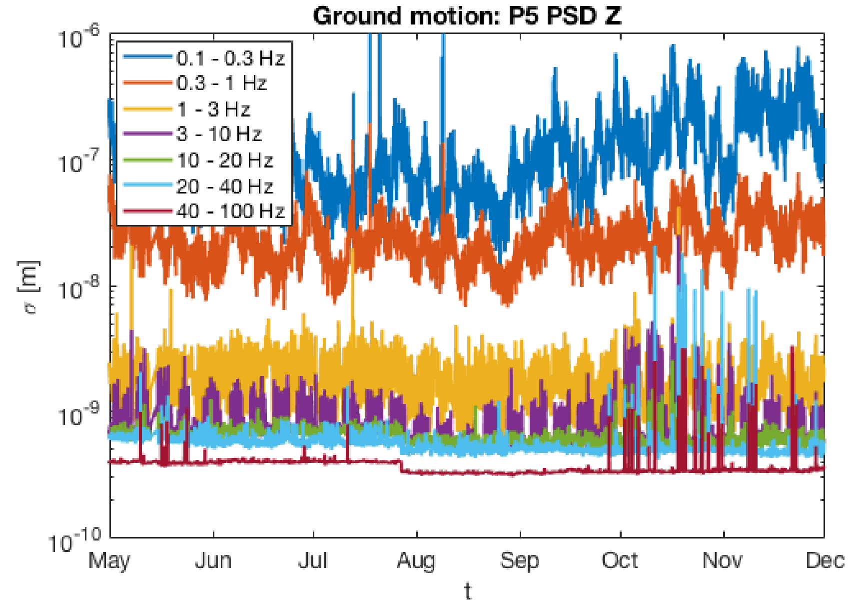
- Geophones are logging data since 2017
- Data logged into Timber in the form of PSD

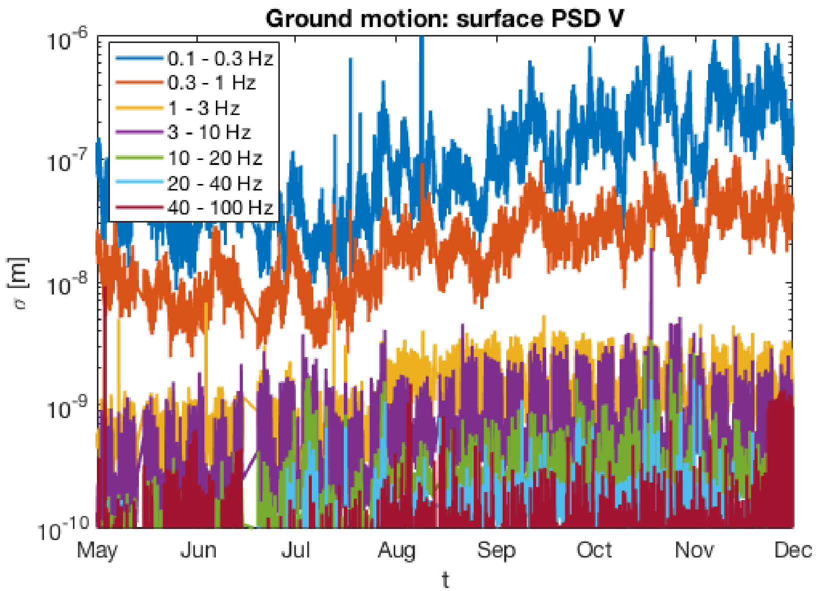


- 15 May 2018: Official start of HL-LHC excavation works.
  - 2018 run is the occasion to see perturbation on the beam due to ground motion
  - It could allow us to see if our expectations for HL-LHC are correct.

Integrated PSD along 2017 (1/5/17 – 1/12/17)







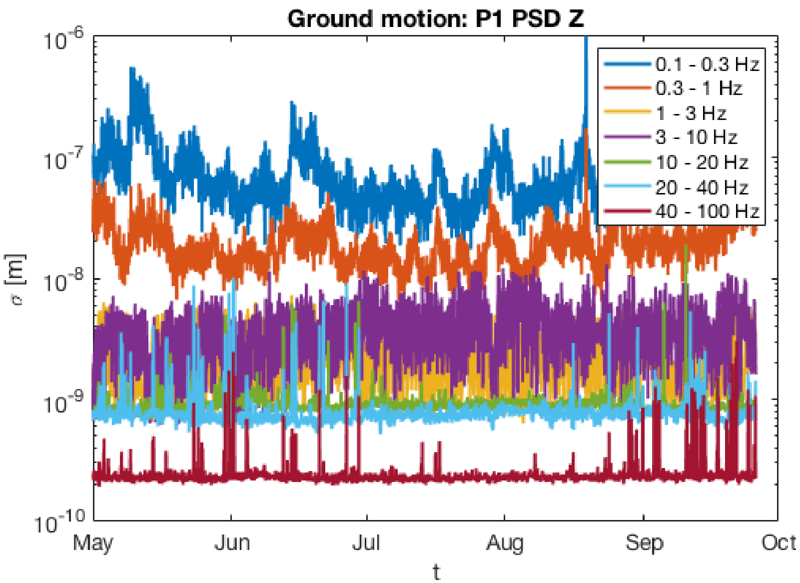
- PSDs integrated over range of frequencies:

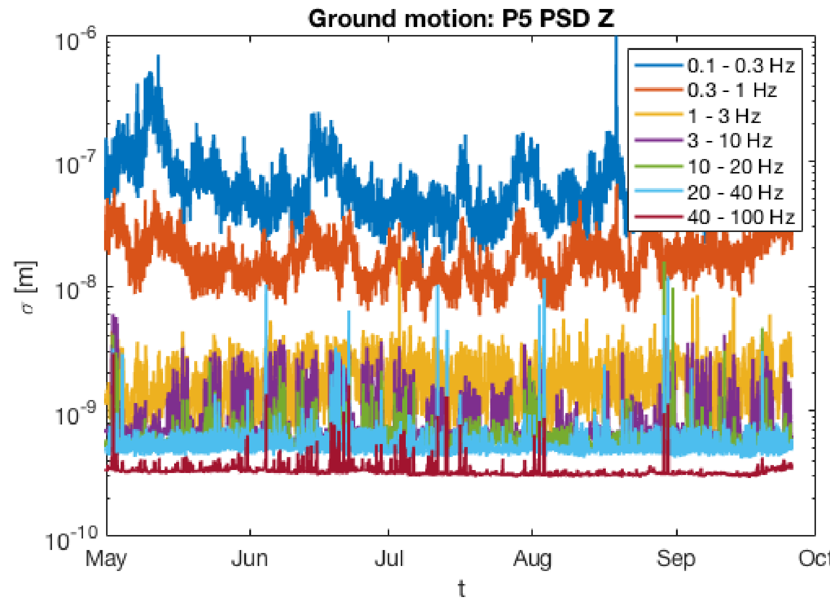
$$\sigma^2(f_0 < f < f_1) = \int_{f_0}^{f_1} p(f)\mathrm{d}f$$

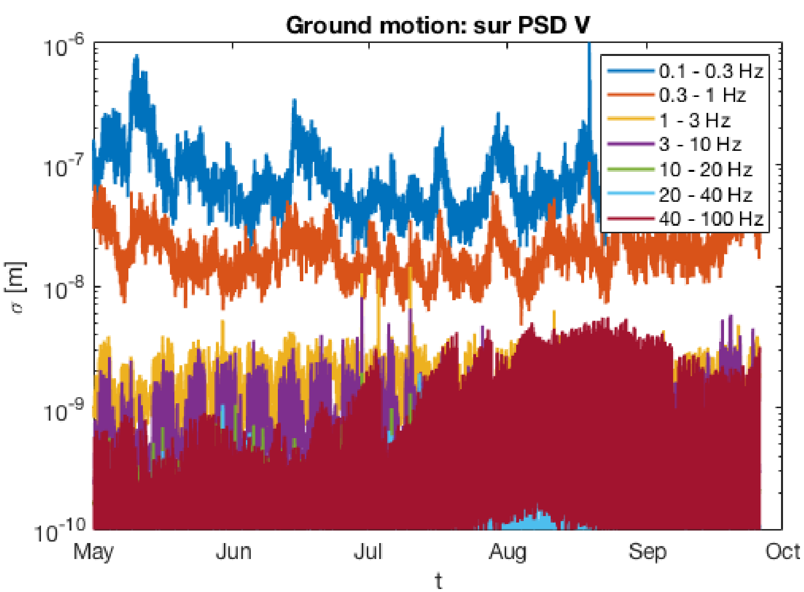
- Low frequency (f < 1 Hz) levels very correlated between P1/5 and surface
- Some more activity in Oct./Nov. in P5

From 99th WP2 meeting (link)

Integrated PSD along 2018 (1/5/18 – 26/09/18)



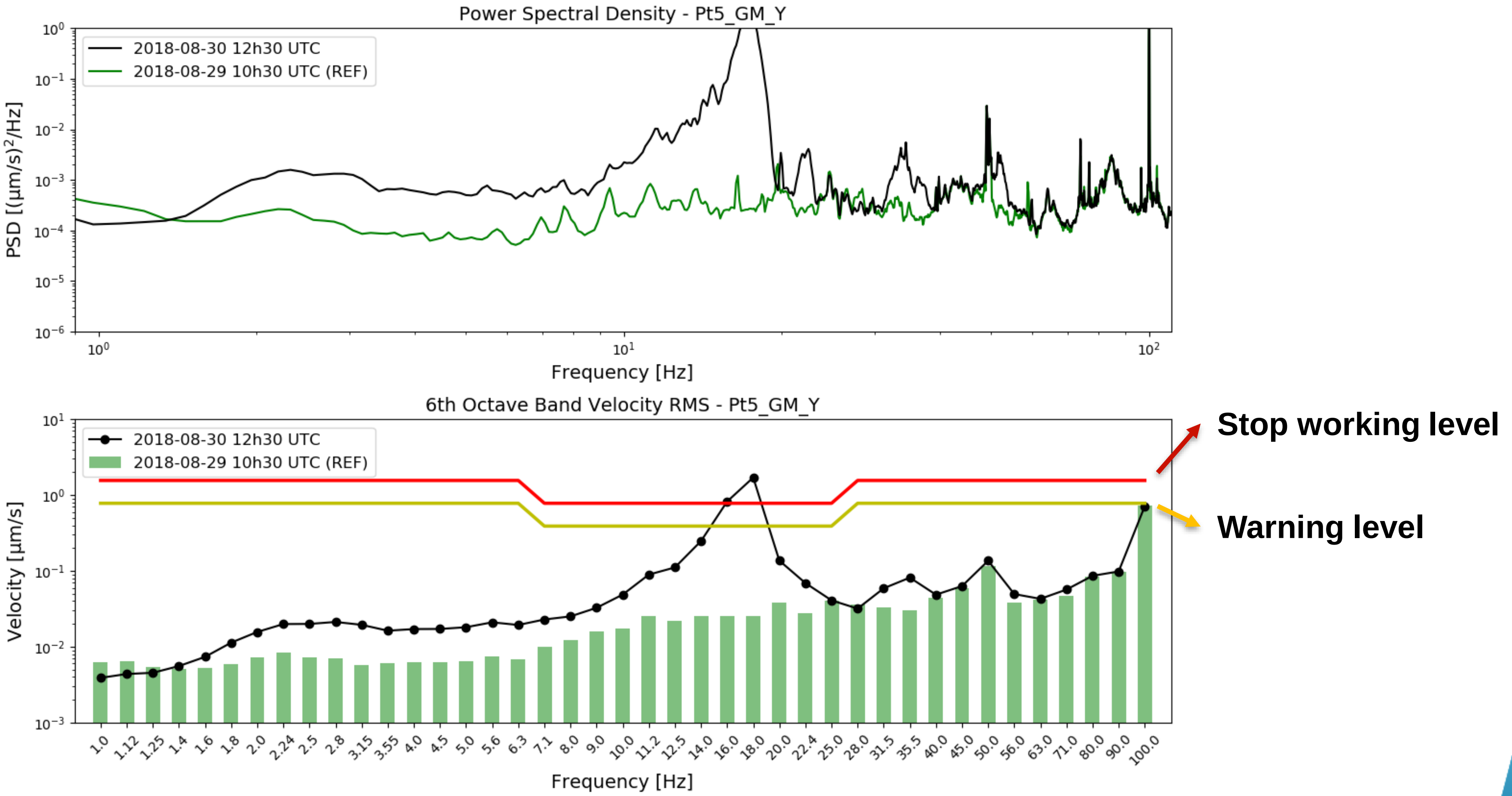




- Overall, similar levels as in 2017.
- More noise in the 40-100 Hz range on surface.
- More spikes along the year in both P1 and P5 at f > 20 Hz, but not necessary linked with HL-LHC works
  - (official start wasMay 15th)

Warning from EN-MME, e.g. 30/08/2018

- Alarm system set up by M.Guinchard and L.G.Scislo (EN-MME) to eventually stop the excavation works if ground motion exceeds safety level (see also M.Fitterer – link)

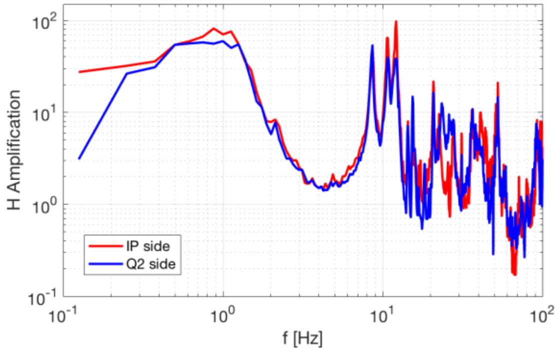


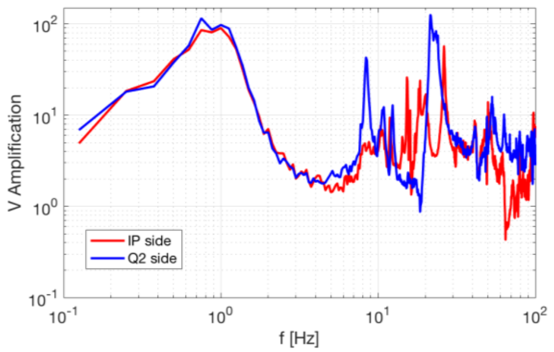
Courtesy L. G. Scislo

Warnings fired by EN-MME

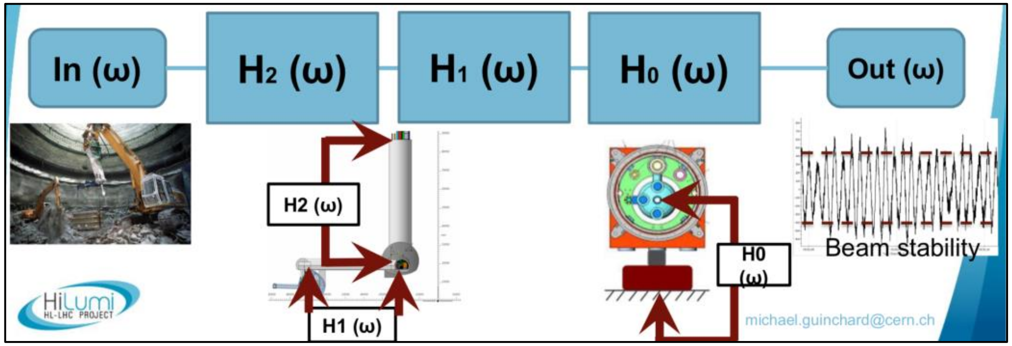
- Point 1
  - 30/08/18: 5:40 - 7:00 -> No Beam at this time
  - **10/09/18**: 6:30 - 7:00 -> **Stable Beam** (Fill 7145)
    - To be looked at!
  - 11/09/18: 5:50 - late morning -> No Beam
- Point 5
  - **04/06/18**: around 08:11 -> **Stable Beam** (Fill 6757)
    - Analyzed by Michaela
  - 22/06/18: 08:00 and 11am -> No Beam
  - **13/07/18**: Day -> **Stable Beam** (no ATLAS lumi) (Fill 6919)
    - Analyzed by Michaela
  - **30/08/18**: 5:50-8:00 and 12:30-13:20 -> **Stable Beam** (Fill 7105)
    - Seen by Michaela
  - **03/09/18**: 7:00 - 7:25 -> **Stable Beam** (Fill 7122)
    - To be looked at!
  - **04/09/18**: 6:43 - 7:10 -> **Stable Beam** (Fill 7124)
    - To be looked at!

Digression: amplification of Q1 assembly

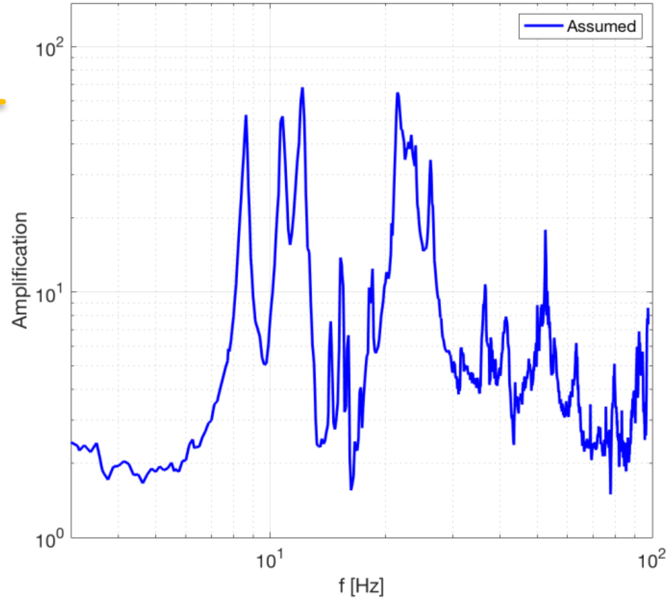




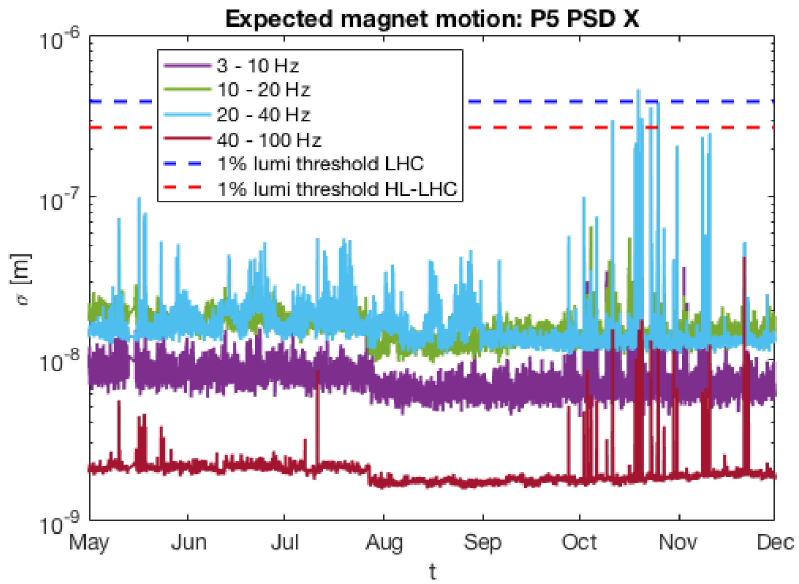
- Measured on Q1 spare assembly in SM18
  - See for example M. Guinchard, Oct 2017, link
- Only "valid" for f > 3 Hz
  - Response below 3 Hz is unknown

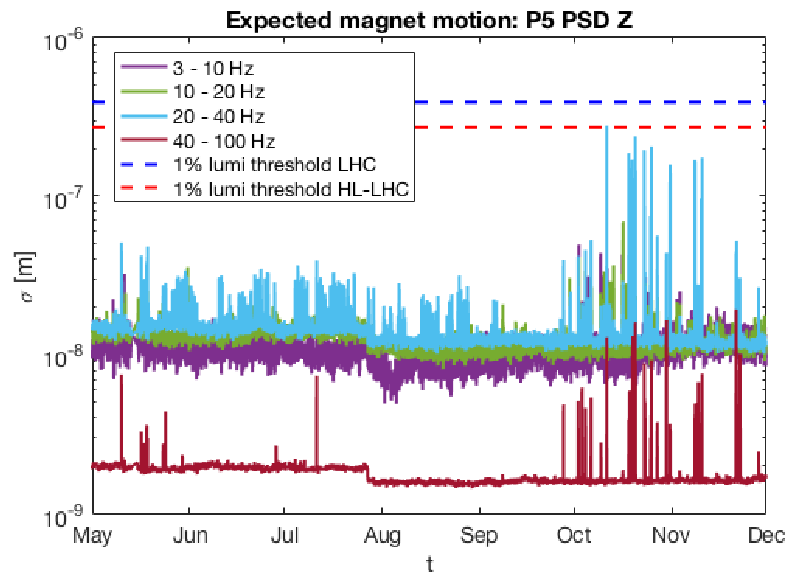


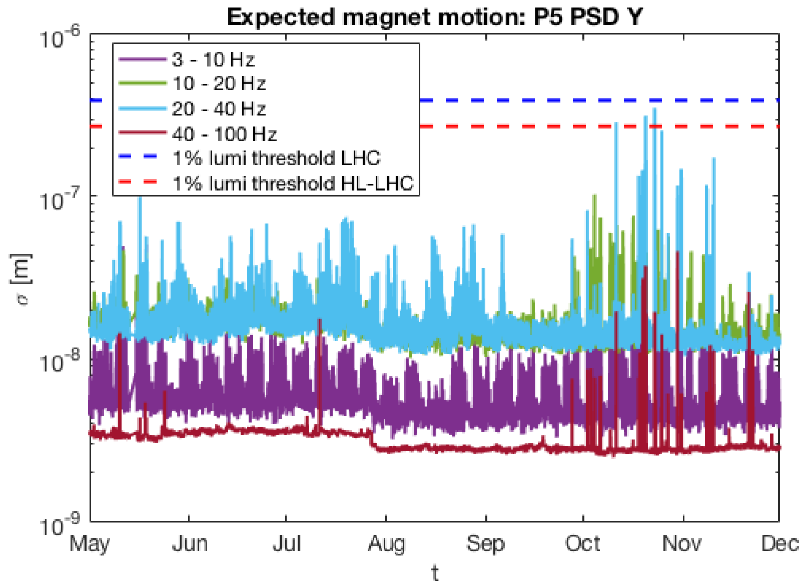
- Considering **mean** between "IP side" and "Q2 side".
- Considering the **max** between vertical and horizontal amplifications.
- Only f > 3 Hz:



Integrated PSD along 2017 – P5 (1/5/17 – 1/12/17)

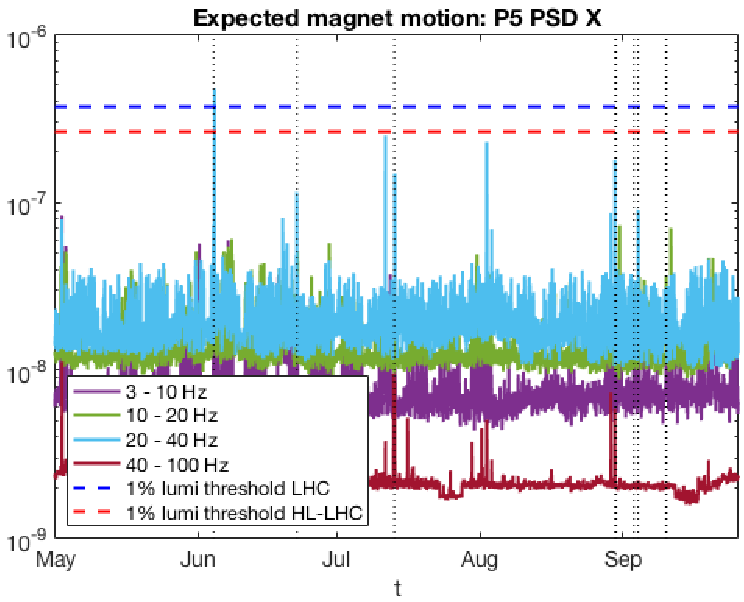


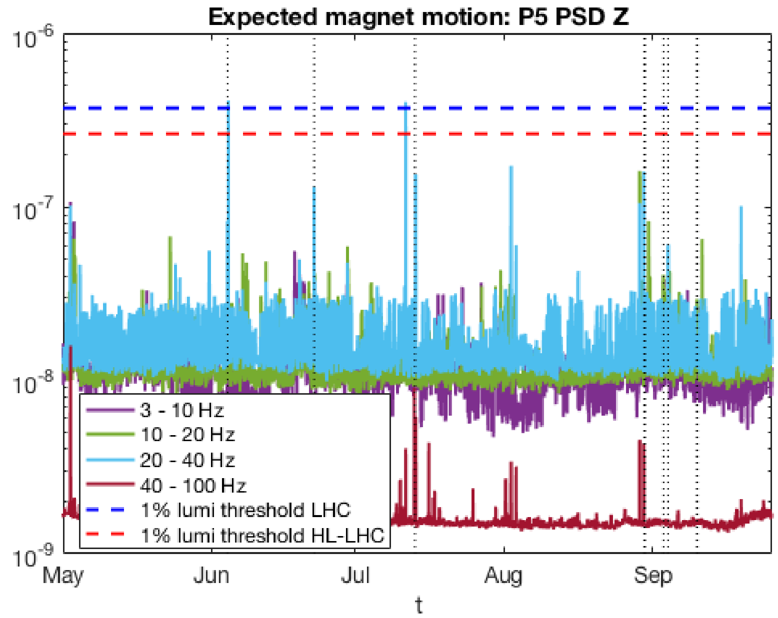


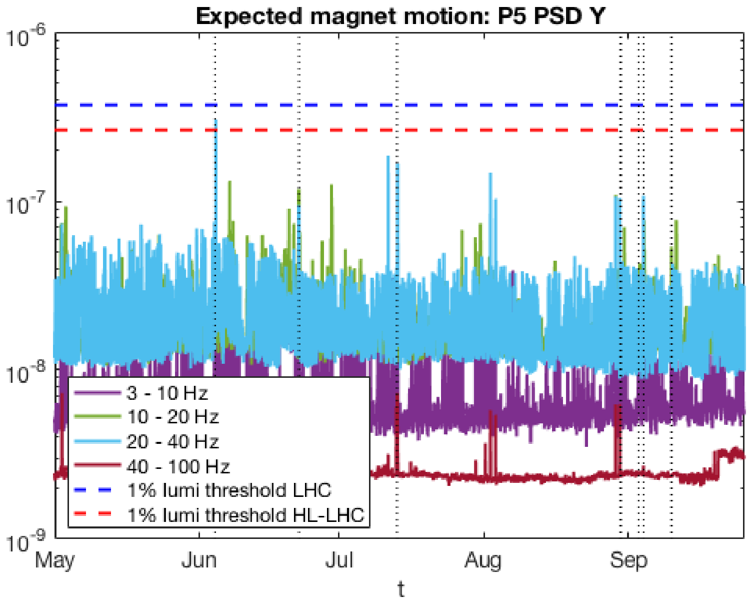


- geophone in **P5, all directions**
- Integrated spectra amplified by measured Q1 “max” transfer function
- Some activity getting close to “1% luminosity threshold” in Oct-Nov 2017.
  - **Did not observed any luminosity losses**, but maybe not careful enough analysis.

Integrated PSD along 2018 – P5 (1/5/18 – 26/09/18)

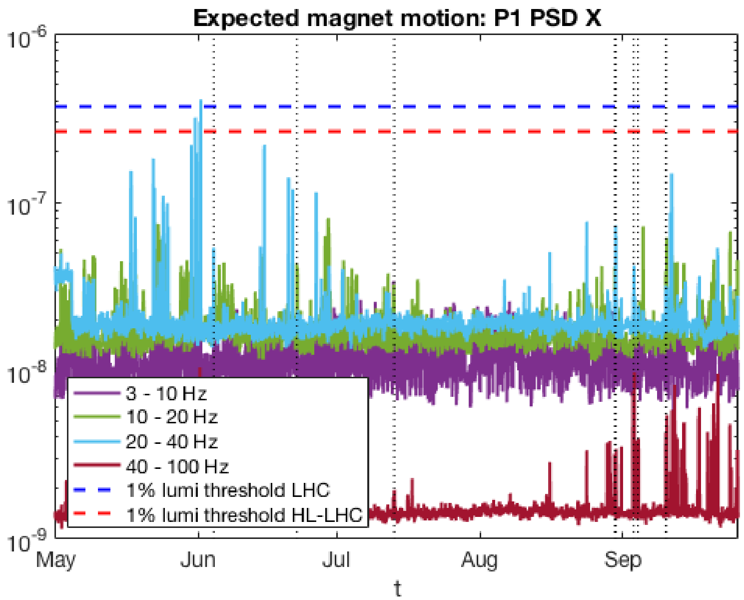


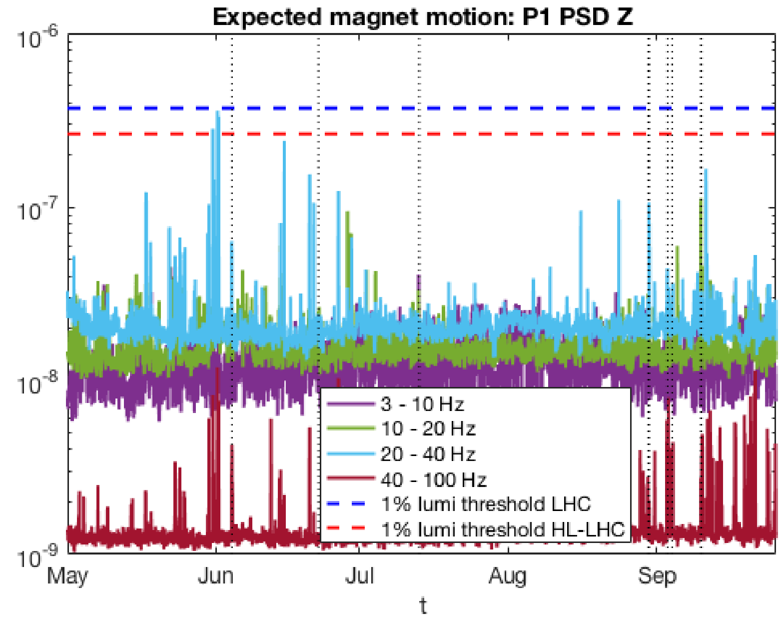


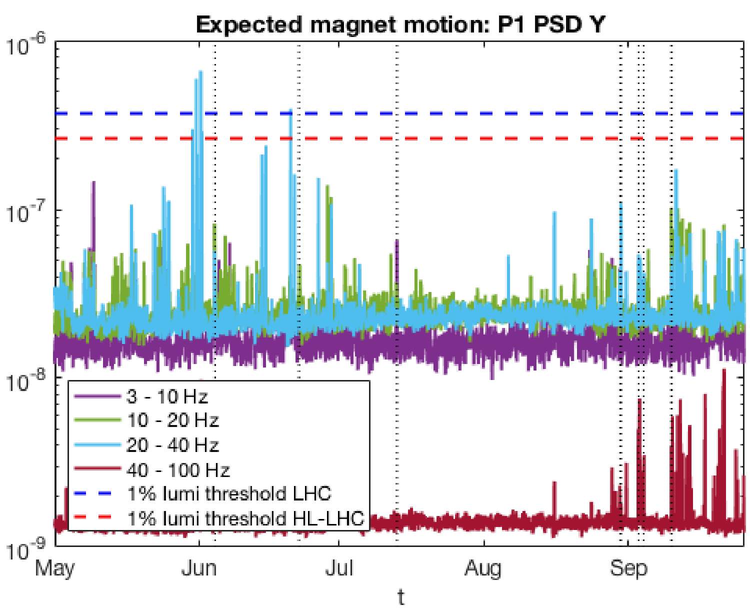


- geophone in **P5**, **all directions**
- Highlight of "warnings" by EN-MME
  - Vertical dashed lines
  - The correspond to spikes in the 20-40 Hz frequency range.
    - **Not a surprise! It should be the same "data"**

Integrated PSD along 2018 – P1 (1/5/18 – 26/09/18)







- geophone in **P1**, **all directions**
- “high” activity in the 10-20 Hz and 20-40 Hz band at different times.
  - Not sure if they did/didn’t trigger an EN-MME alarm.
- Generally quieter 20-40 Hz band

Additional warnings from previous plots

- Point 1
  - **30/05/18: around 13:00-> Beam (no lumi drops) fill 6741**
  - **31/05/18: around 9:00 -> No beam**
  - **31/05/18: around 14:00 -> No beam**
  - **01/06/18: around 08:00 -> Beam fill 6749**
  - **01/06/18: around 13:00 -> Beam fill 6749**
  - 15/06/18: around 7:00 -> no interesting beam (fill 6799)
  - 11/09/18; around 14:00 -> some noise, no interesting beam -> fill 7147
- Point 5
  - **11/10/17: around 8:00 Beam fill 6291**
  - **19/10/17: around 8:00 -> Beam fill 6308**
  - **20/10/17: around 9:00 -> Beam fill 6311**
  - 23/10/17: around 9:00 -> no beam
  - 25/10/17: around 12:00 -> no beam
  - 31/10/17: around 11:00 -> no beam
  - 11/07/18: around 13:00 -> no beam
  - 02/08/18: around 12:00 -> no beam

Summary of possibly interesting fills

- Point 1
  - 30/05/18: 13:00 -> fill **6741**
  - 01/06/18: 08:00-13:00 -> fill **6749**
  - 10/09/18: 6:30-7:00 -> fill **7145**
- Point 5
  - 11/10/17: around 8:00 Beam fill **6291**
  - 19/10/17: around 8:00 -> Beam fill **6308**
  - 20/10/17: around 9:00 -> Beam fill **6311**
  - 04/06/18: 08:11 -> Fill **6757**
    - Already presented by Michaela
  - 13/07/18: Day -> Fill **6919**
    - Already presented by Michaela
  - 30/08/18: 5:50-13:20 -> Fill **7105**
  - 03/09/18: 7:00 - 7:25 -> Fill **7122**
  - 04/09/18: 6:43 - 7:10 -> Fill **7124**

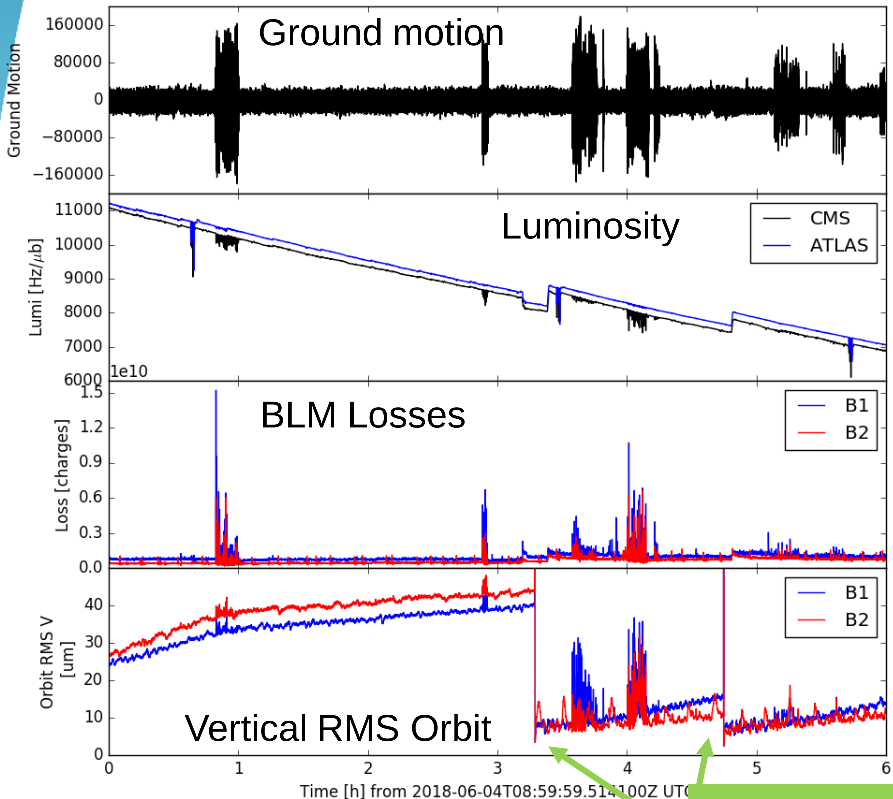
I will also consider those fills for the time being.

Possible beam observables

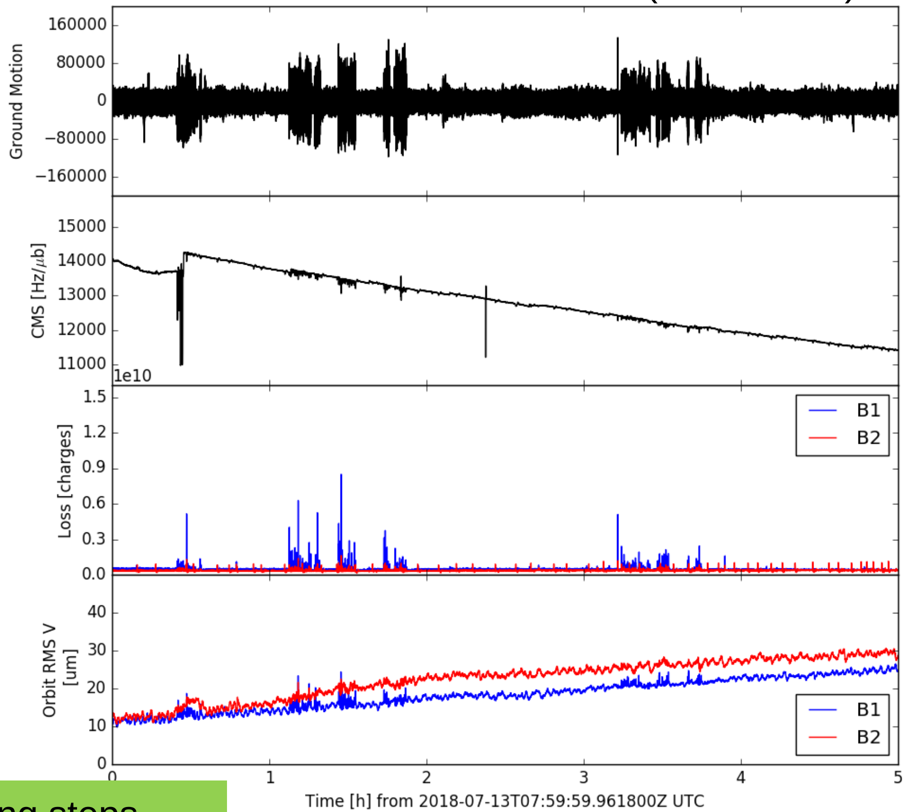
- **Luminosity** (e.g. 'ATLAS:LUMI_TOT_INST')
  - Probably the most sensitive observable.
- Beam **intensity** (e.g. 'LHC.BCTDC.A6R4.B1:BEAM_INTENSITY_ADC24BIT')
  - Very high dynamic range due to intensity variation along fill.
- BLM **integrated losses** (e.g. 'LHC.BLM.LIFETIME:B1_CALIBRATED_LOSS')
  - Very sensitive signal, with beam intensity one can have ratio of losses.
- **ARC BPMs** (e.g. 'LHC.BOFSU:POSITIONS_H')
  - Position acquired at 25 Hz, but available only as **mean over 1 s**
- **DOROS BPMs** (e.g. 'LHC.BPM.1L1.B1_DOROS:POS_H')
  - Could acquire at much higher frequency, but also normally logging **average over 1 s**.
  - **Logging of spectra requested by Michaela, will happen soon.**
- **BBQ** (e.g. 'LHC.BQBBQ.CONTINUOUS.B1:ACQ_DATA_H')
  - A lot of spectra, not amplitude calibrated.
  - Maybe interesting the logged Eigen-modes (e.g. ':EIGEN_AMPL_1') to detect jumps.
- **ADT** (e.g. 'ADTH.SR4.B1:SPECTRUM_HB1')
  - A lot of spectra, **might be possible to get an amplitude calibration**.
  - Maybe interesting the transverse activity (e.g. ':TRANSVERSEACTIVITY_HB1'), but it contains only the "high-frequency" activity.

Main Events Overview presented by M. Schaumann

Fill 6757 (4/06/2018)



Fill 6919 (13/07/2018)

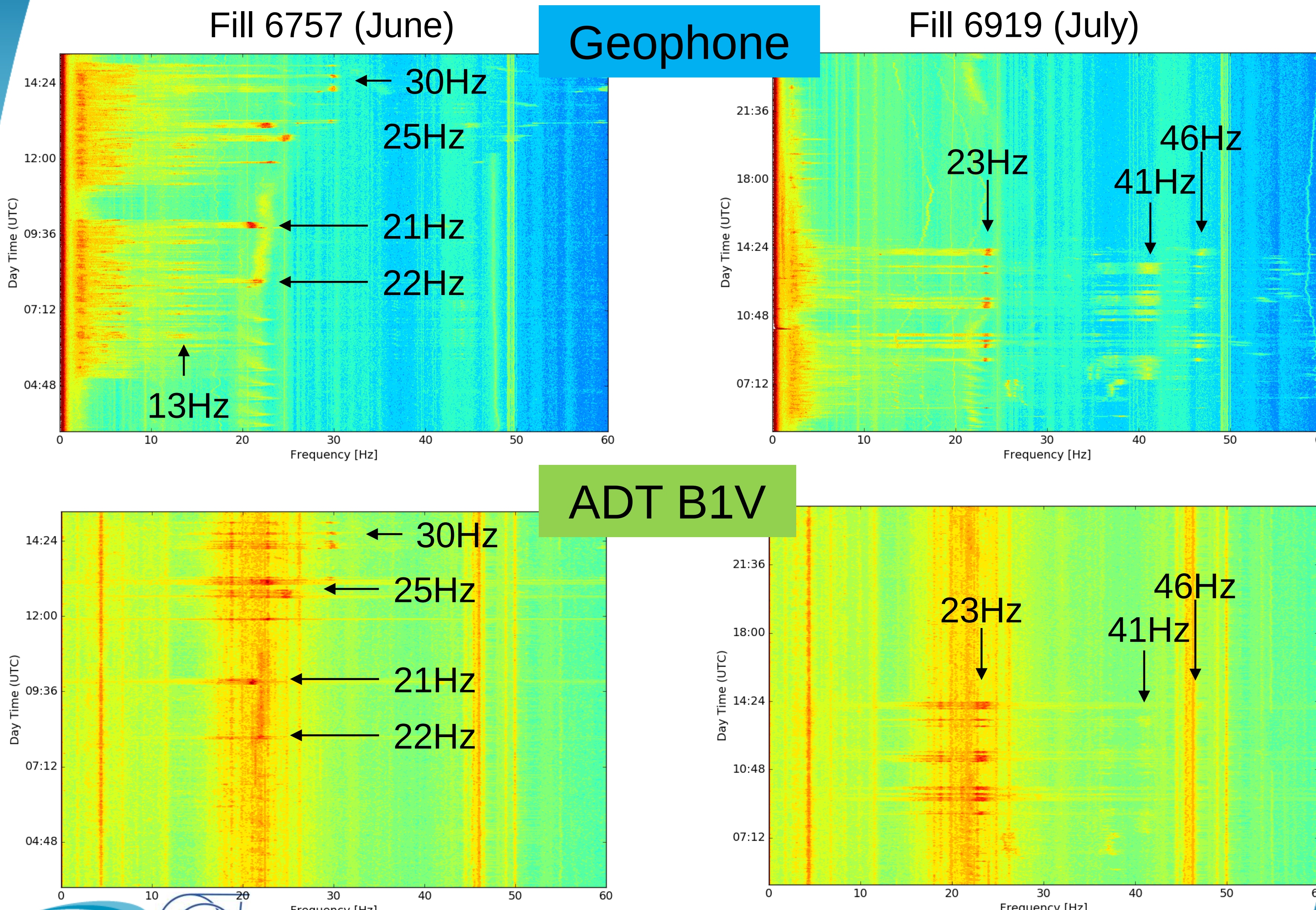


Beta* levelling steps and new orbit reference

- Same scales on all plots
- Fill 6757 higher excitation amplitude
  - → stronger effect on beams
  - → higher losses, deeper luminosity dips, higher vertical RMS orbit

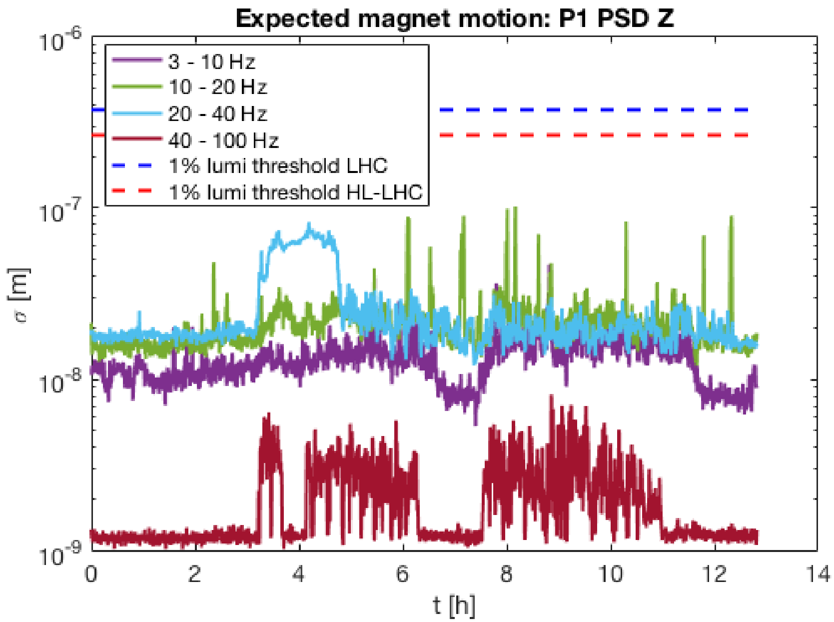
From: *Observation on HL-LHC CE vibration on the beam*, M. Schaumann (link)

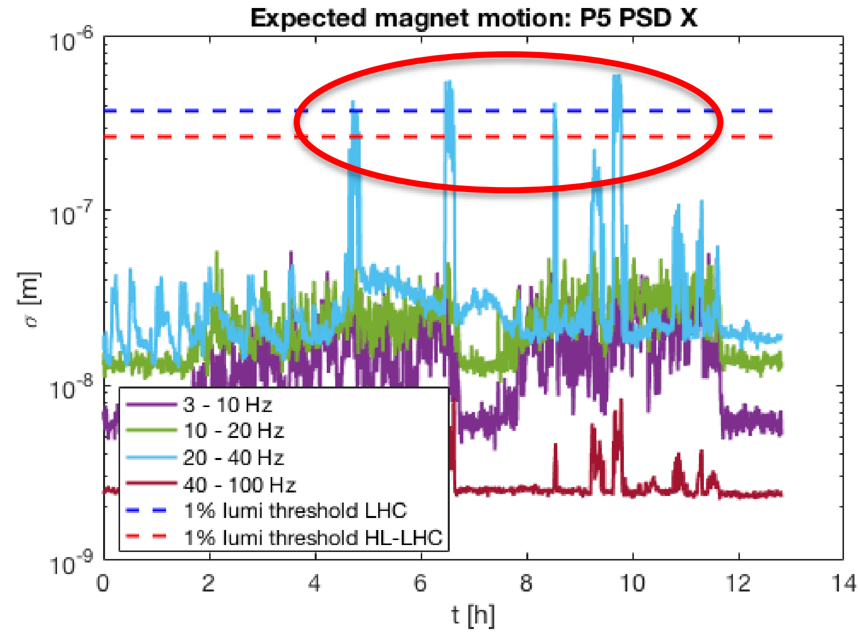
GM and Beam Spectrum Evolution



From: *Observation on HL-LHC CE vibration on the beam*, M. Schaumann ([link])

Fill 6757 (June)

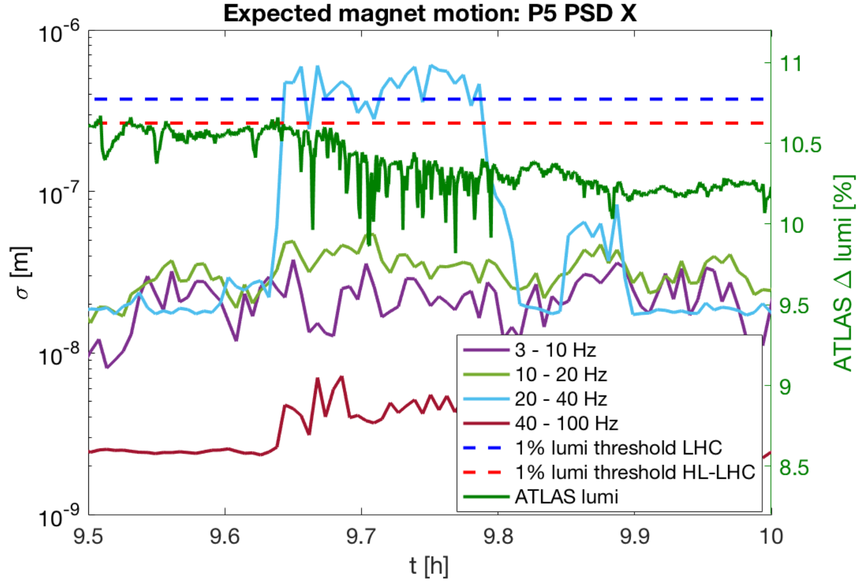


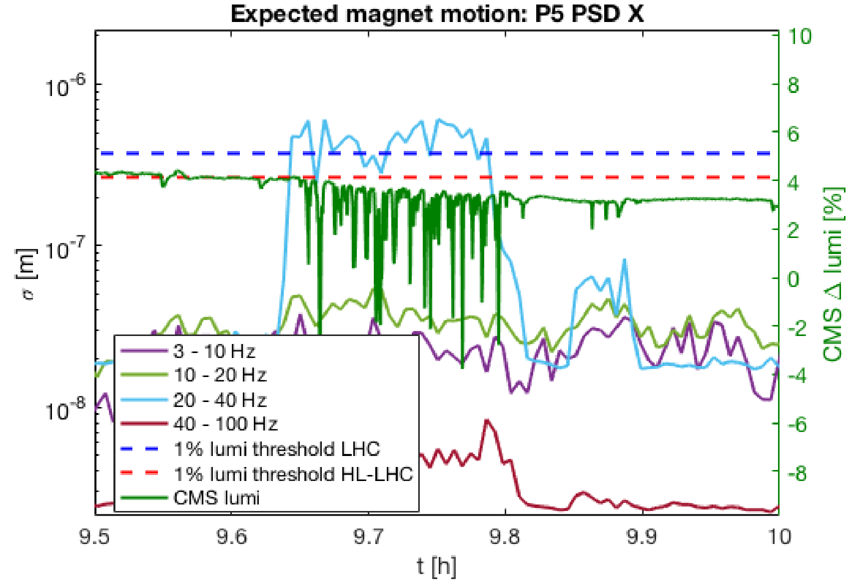


Looking at PSDs amplified and integrated during STABLE beams

- No relevant ground motion measured in P1
- Sizable ground motion in P5 above “1% luminosity loss threshold”

Fill 6757 (June)



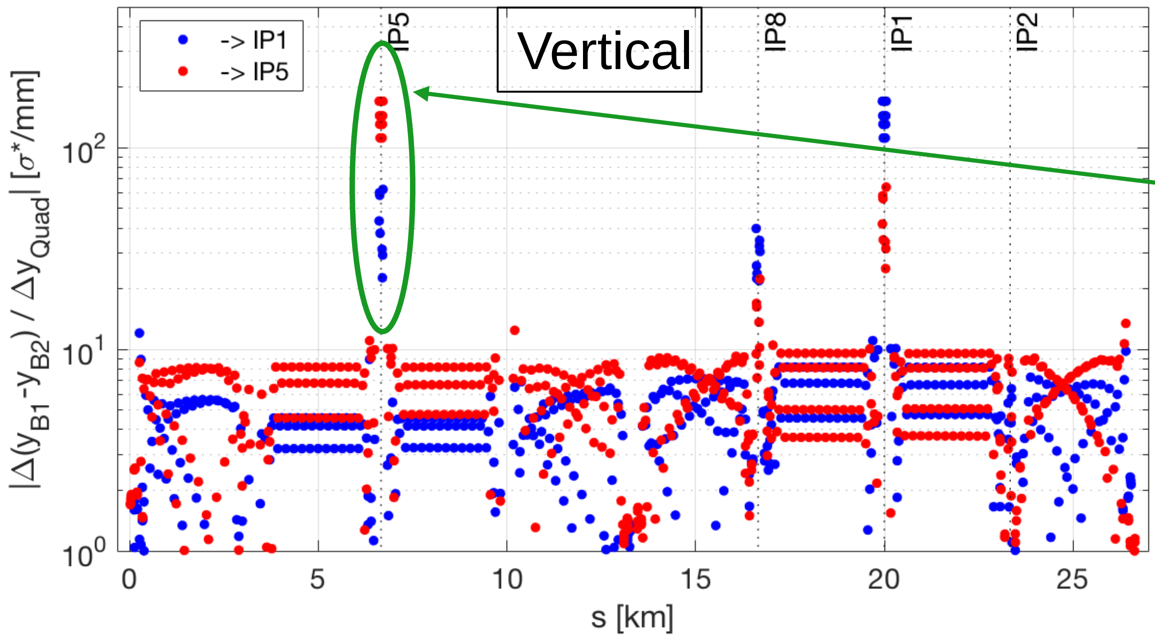


Zoom over a certain time. Comparison of ground motion (left scale) and luminosity variation (right scale).

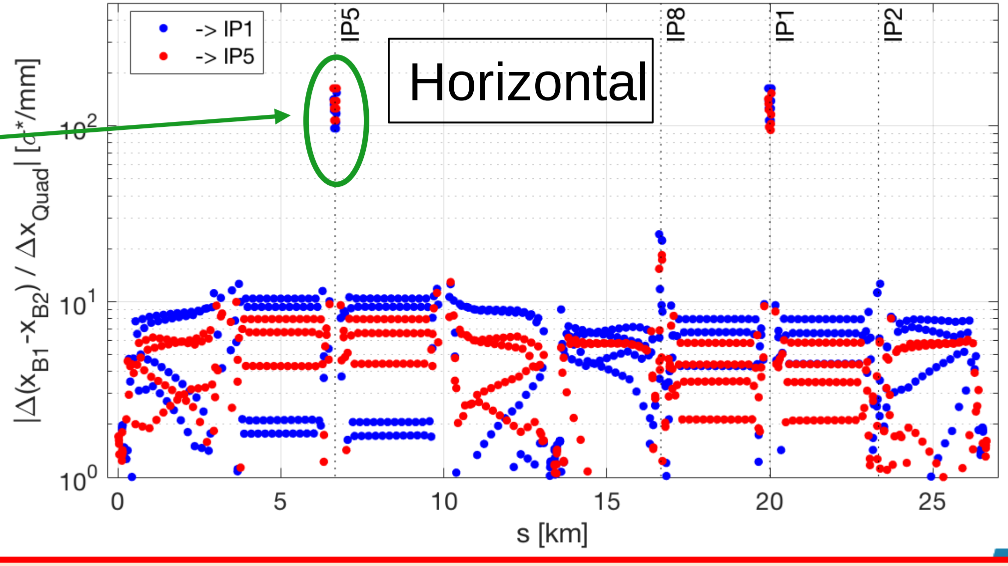
- Variation w.r.t. fitted exponential decay along fill.
- Both **CMS** and **ATLAS** luminosities seems to be **affected**.
  - **CMS** much **more sensitive** (a few % peaks compared to < 1%)
  - Could be possible if only vertical plane is mainly affected…

Beam Separation at IP1/5 due to Quadrupole Offset

Assumption:
30cm optics, 2um emittance



Vertical offset of triplet in IP5 introduces a larger orbit effect in the IP5 compared to IP1 and vice versa



Horizontal offset of triplet in IP1/5 introduces a similar orbit effect in the both IPs.

From: *Observation on HL-LHC CE vibration on the beam*, M. Schaumann (link)

Back to optics sensitivity tables

- Amplification factors from magnet motion to IP orbit separation

	IP1 [σ^*_{beam}/µm]		IP5 [σ^*_{beam}/µm]		IP2 [σ^*_{beam}/µm]		IP8 [σ^*_{beam}/µm]	
	Δx	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**	**Δx**	**Δy**
LHC all quads	**0.536**	0.440	0.527	0.443	0.231	0.252	0.290	0.368
LHC IR1/5 only	0.516	0.419	0.516	0.419	0.120	0.131	0.172	0.288
LHC IR5 only	**0.346**	**0.128**	0.383	0.399	0.028	0.099	0.100	0.126
HL-LHC all quads	0.721	**0.758**	0.719	0.755	0.269	0.367	0.341	0.592
HL-LHC IR1/5 only	0.703	0.736	0.704	0.735	0.211	0.331	0.235	0.550
HL-LHC IR5 only	0.517	0.544	0.477	0.497	0.189	0.268	0.175	0.375

- If we consider only one triplet we should get a sqrt(2) smaller impact, with the exception of the vertical plane in LHC where the “remote” impact is smaller.

Partially from 119th WP2 meeting (link)

Back to optics sensitivity tables

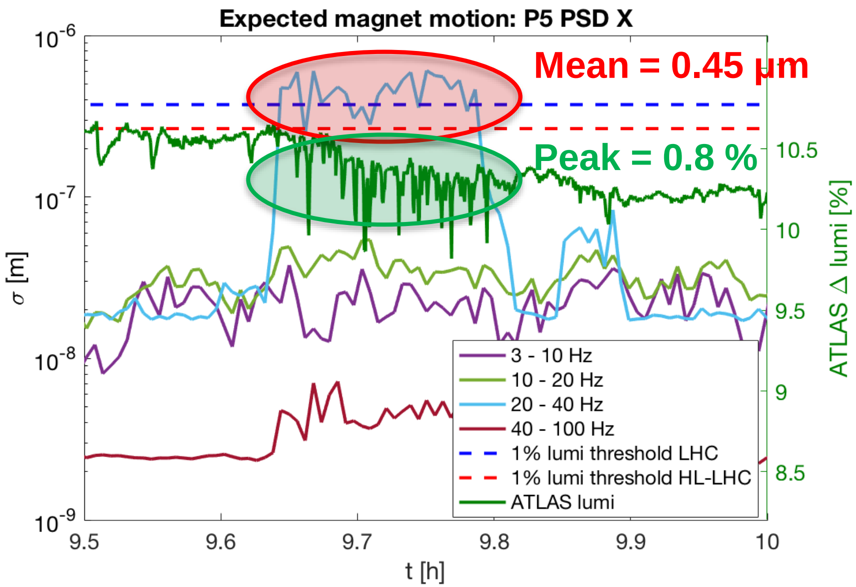
- Impact at primary collimators (max rms orbit at any TCP)

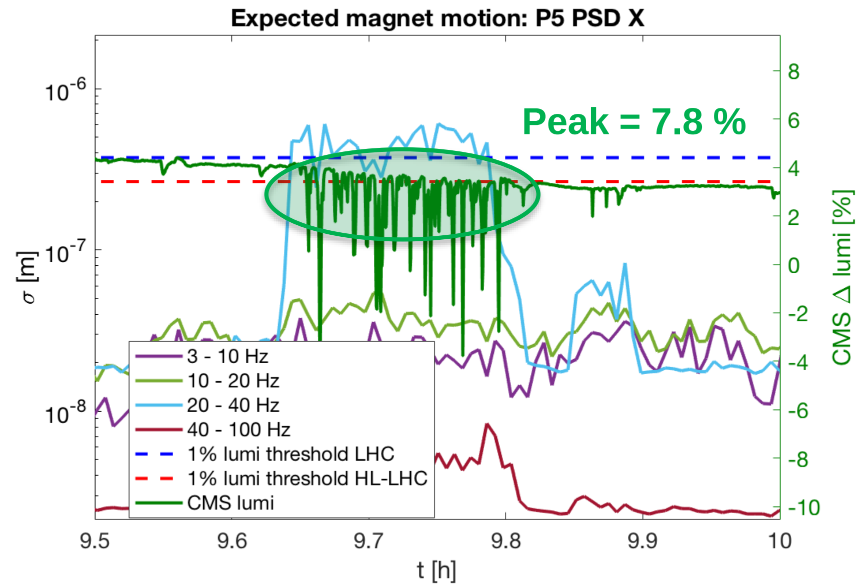
	B1				B2			
	[σ_{beam}/µm]		[µm/µm]		[σ_{beam}/µm]		[µm/µm]	
	Δx	Δy	Δx	Δy	Δx	Δy	Δx	Δy
LHC all quads	0.316	0.273	99	63	0.337	0.268	71	57
LHC IR1/5 only	0.294	0.245	92	52	0.316	0.231	67	49
LHC IR5 only	0.222	0.231	70	49	0.234	0.161	50	35

- Impact at arc BPMs

	B1 [µm/µm]		B2 [µm/µm]	
	Δx (Quad)	Δy (Quad)	Δx (Quad)	Δy (Quad)
LHC all quads	84 (6L7)	86 (11R5)	87 (6R7)	92 (11L5)
LHC IR1/5 only	76 (6L7)	80 (11R5)	82 (6R7)	86 (11L5)
LHC IR5 only	53 (11R7) 49 (6L7)	62 (6L7) 58 (11R5)	66 (6L2) 62 (6R7)	69 (6R5) 61 (11L5)

Some numbers from fill 6757 (June)





- Seen about **0.45 μm rms "magnetic center" motion** in **P5**.
- **Assuming** to be **vertical motion only, this correspond to**
  - 3σ magnetic motion (0.45*3=1.35 um) would give
    - **6.6%** max luminosity loss @ **CMS**
    - **0.7%** max luminosity loss @ **ATLAS**
  - 0.1 sigma (29 μm) rms orbit @ TCP
  - 19 μm rms orbit @ ADT
  - 58 μm rms orbit @ Q1 BPMs
  - **27 μm rms orbit @ ARC BPMs -> compatible with observations:**

Orbit Example during Excitation Fill 6757

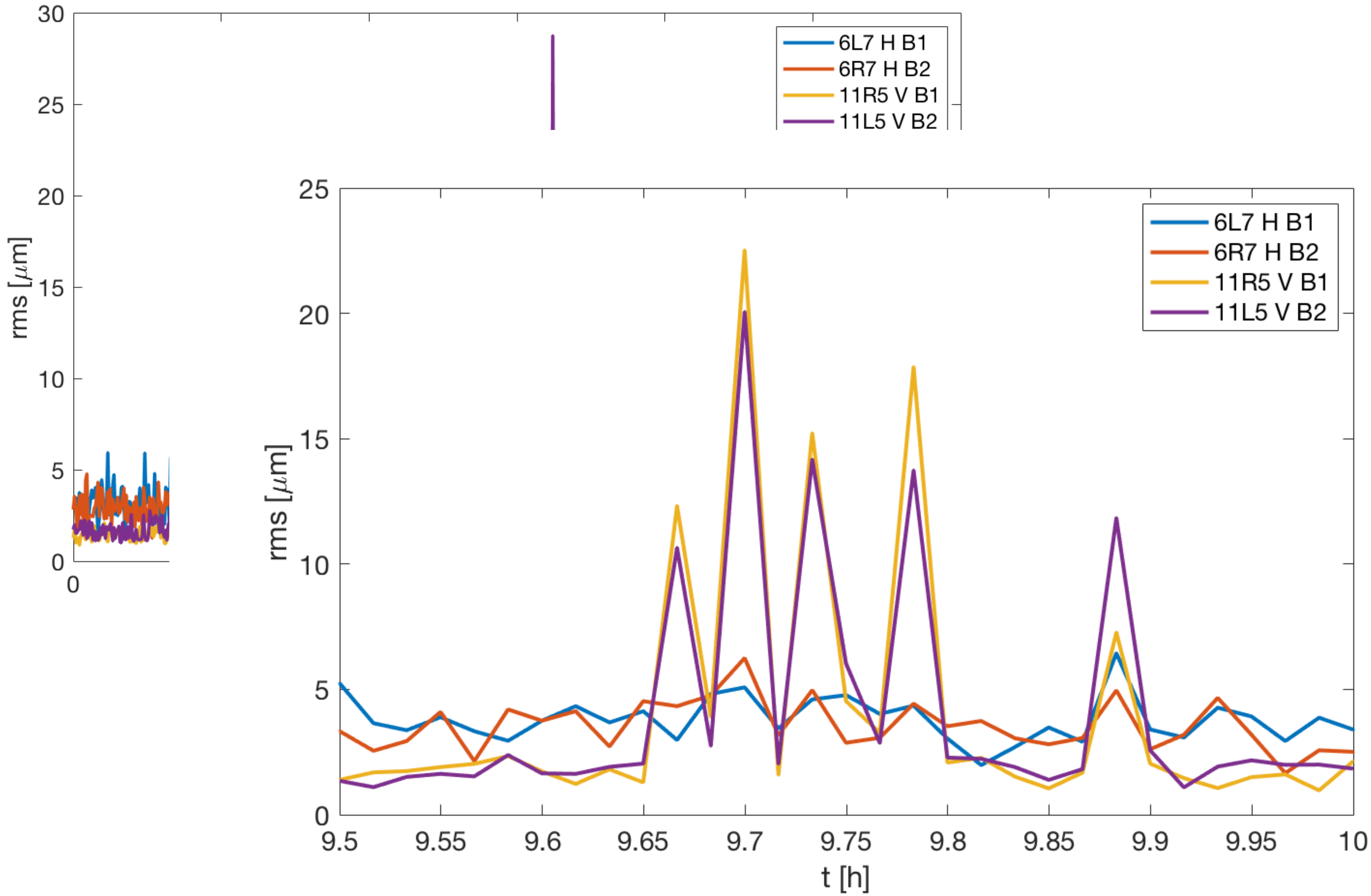
Vertical oscillation with arc amplitudes of 60um.

04/06/2018 13-03-21 (UTC)

From: *Observation on HL-LHC CE vibration on the beam*, M. Schaumann (link)

Orbit Example during Excitation Fill 6757

- From ARC orbit data, std over 25 Hz data



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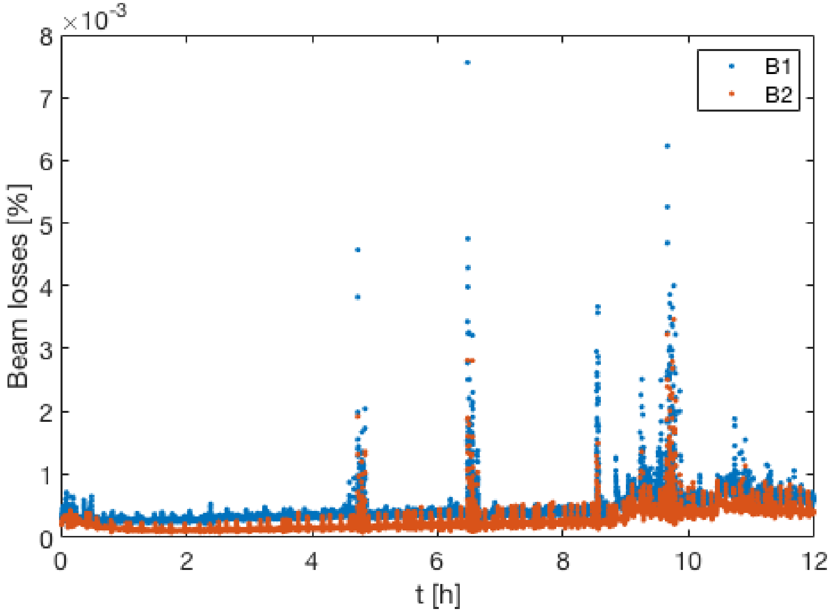
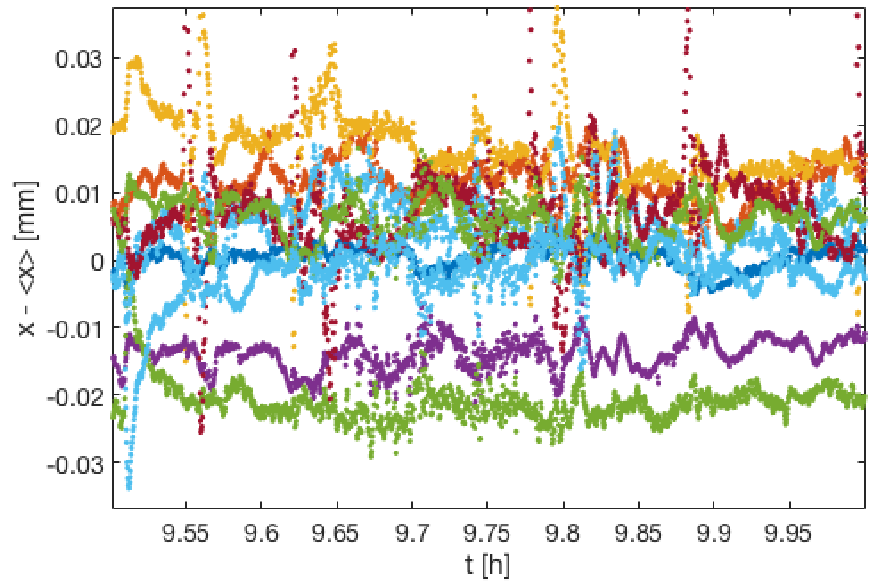
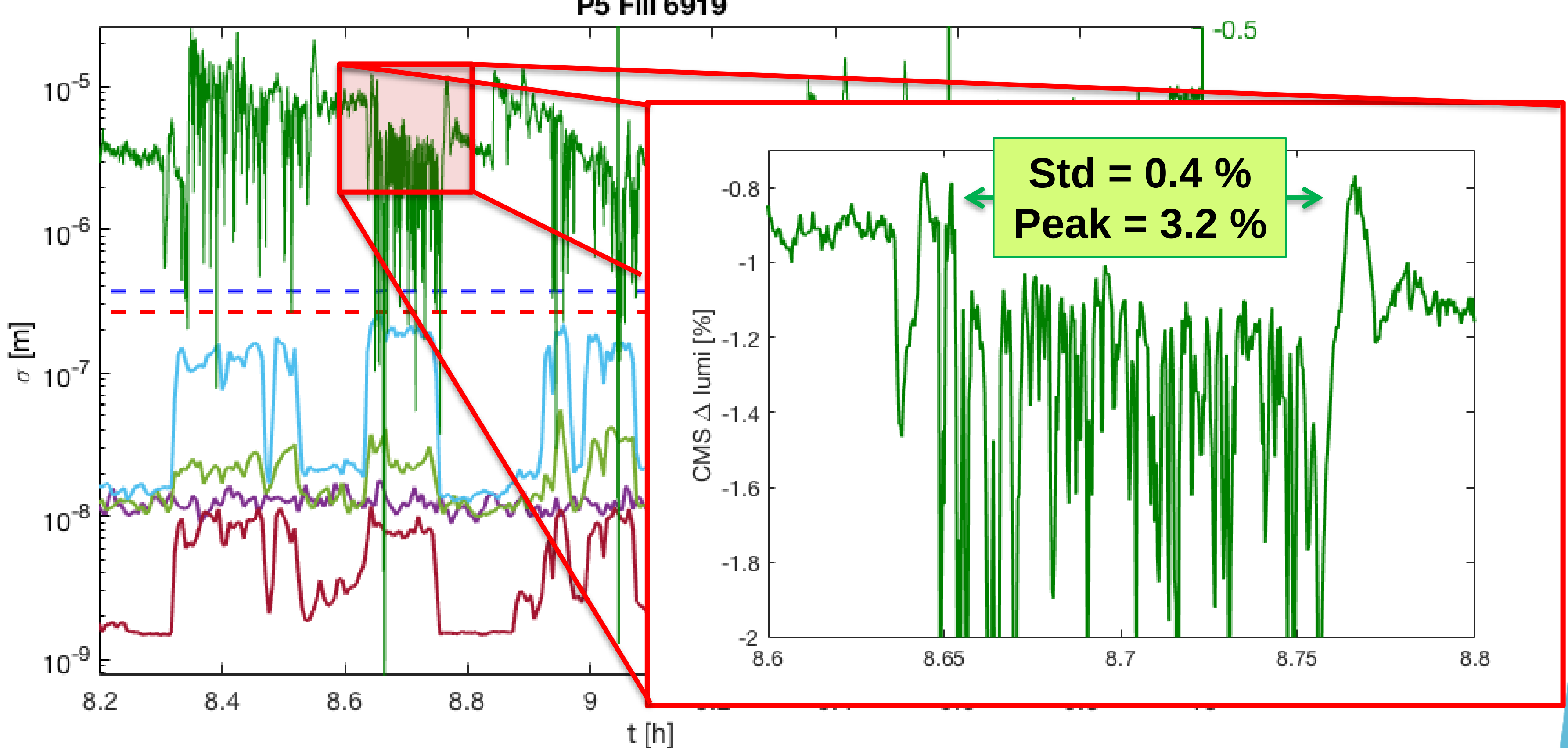
Some numbers from fill 6757 (June)





- A few 10^-5 losses measured.
  - Under investigation if it is possible to associated a number to orbit jitter at collimators.
- Some disturbances of the logged orbit at Q1 DOROS BPM
  - No clear signal expected since BPMs are integrating over 1 s and motion is at frequencies of the order of 20 Hz.
- Now investigating if ARC BPMs are already storing in Timber some useful information
  - E.g. rms measured over 25 Hz data.

Fill 6919 (July)



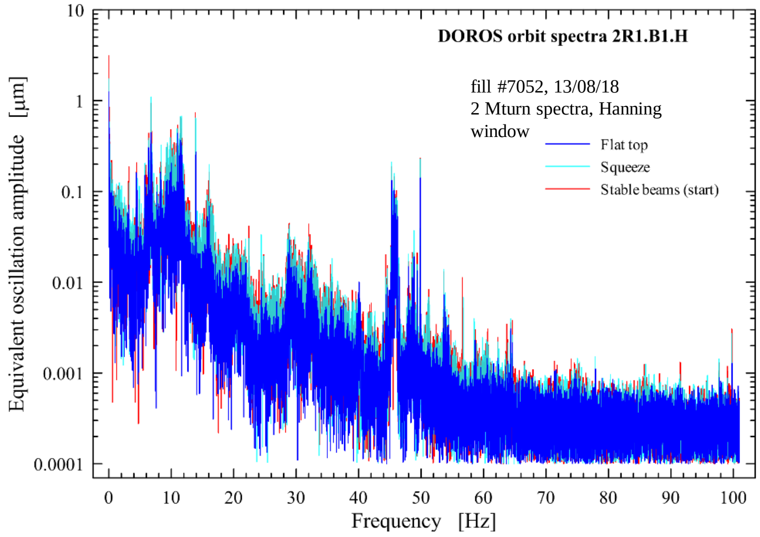
- Seen about 0.2 µm rms magnetic center motion. Expected:
  - 1.4% peak luminosity loss @ CMS (0.15% @ ATLAS)
  - 0.04 sigma (13 µm) rms orbit @ TCP
  - 9 µm rms orbit @ ADT
  - 12 µm rms orbit @ ARC BPMs
  - 26 µm rms orbit @ Q1 BPMs

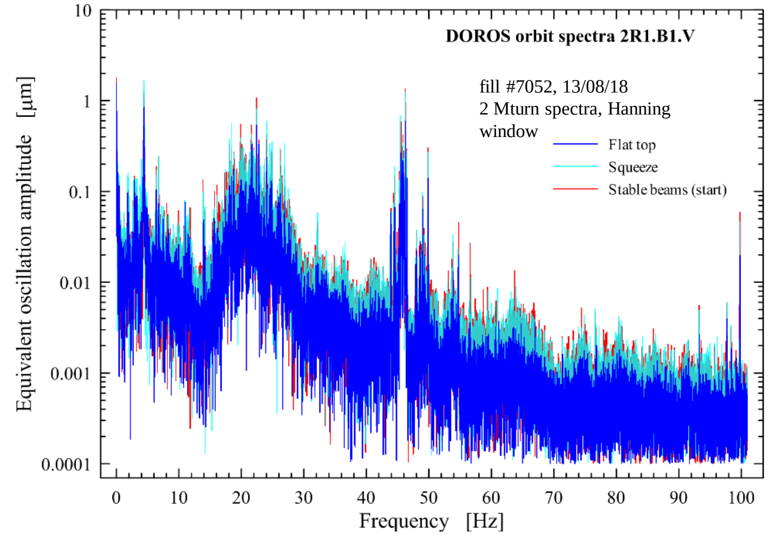
Conclusions

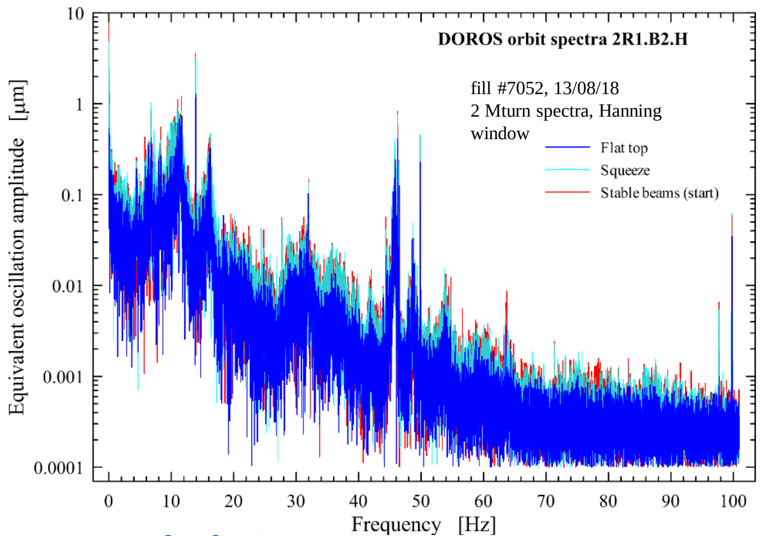
- Actual LHC is very close to HL-LHC in terms of sensitivity to ground motion.
  - Still, main players remain the IP1/5 triplets.
- Ground motion activity due to HL-LHC civil works showed up into beam signals.
  - From July 2018, 11 days with multiple alarms linked to surface activity [M.Guinchard]
  - Events caused **luminosity loss dips** of the order of a few, mainly at CMS.
    - Hardly noticeable for typical LHC operation.
    - In **HL-LHC** they would be slightly more visible.
  - Observed signals are compatible with measured transfer function of triplets.
    - Important to measure HL-LHC triplet transfer function.
    - Simulations by D.Ramos and M. Martos ongoing.
- ADT spectra compatible with ground motion spectra.
  - Another confirmation of the measured Q1 transfer function.
  - Trying now to see if we could get a "number" on the observed motion
- Other fills/signals under analysis.
  - Triplet in P1 seems to less sensitive to measured ground motion
    - More rigid? Geophone "too sensitive"? Different ground?

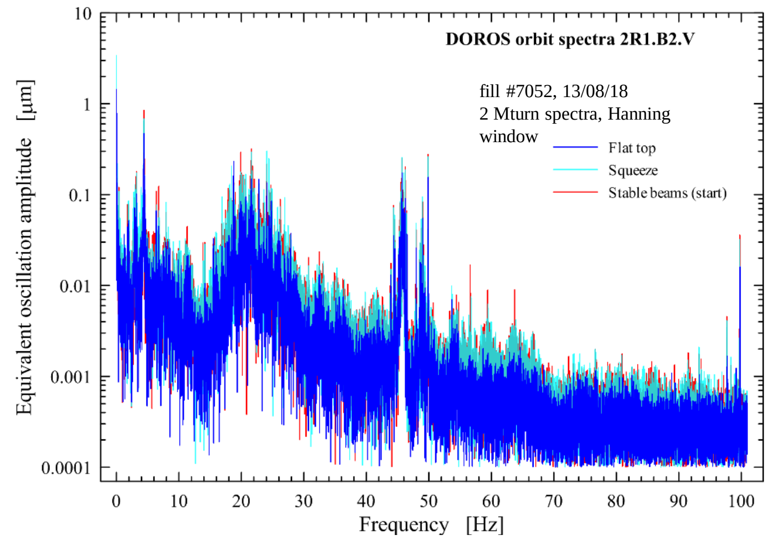
- Thanks for your attention and comments -

2 Mturn orbit spectra @ 2R1, from FT to SB fill 7052





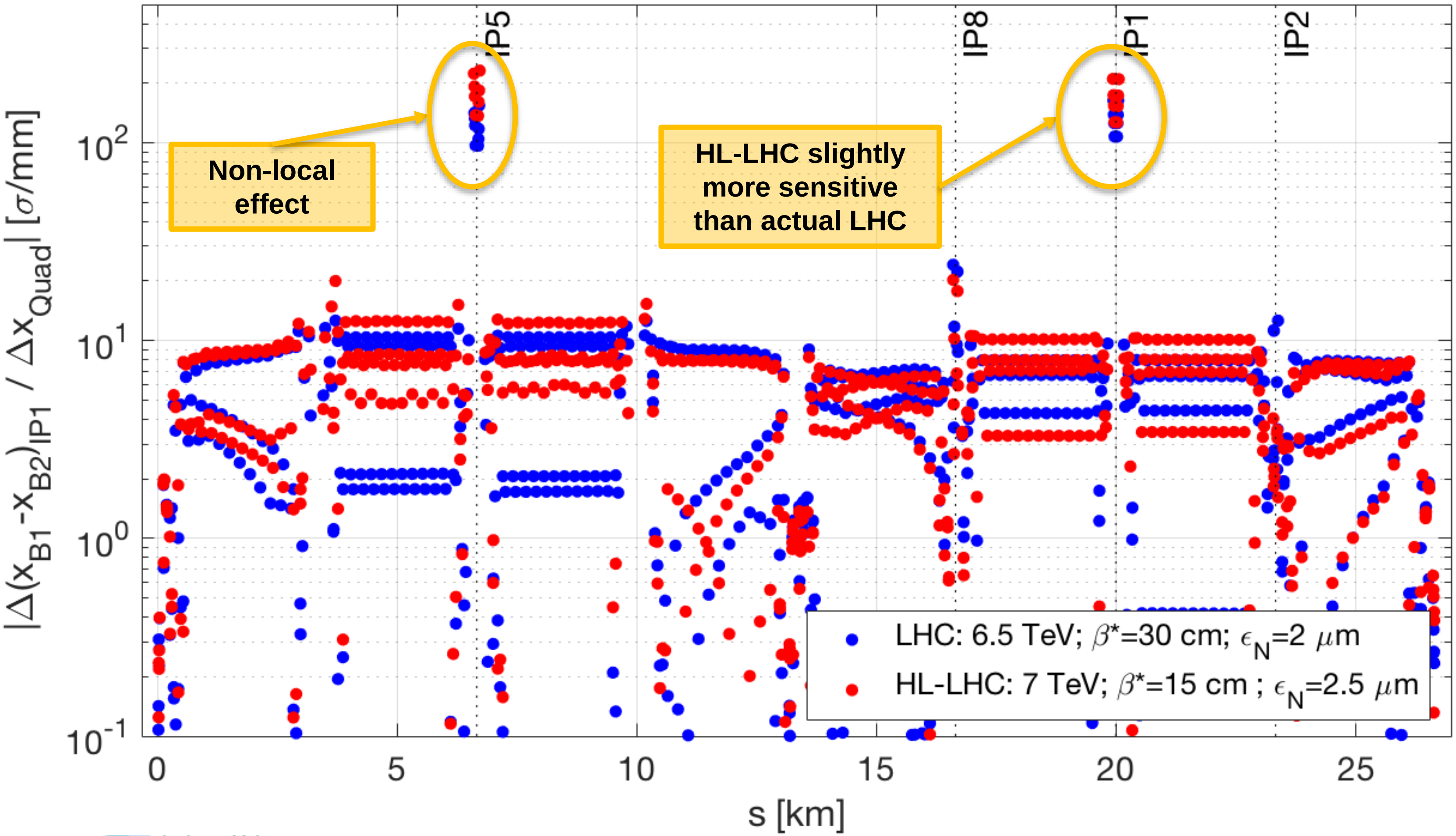




M. Gasior, J.Olexa, CERN-BE-BI

Looking at the whole machine: impact on IP1

- Horizontal B1-B2 separation at IP1

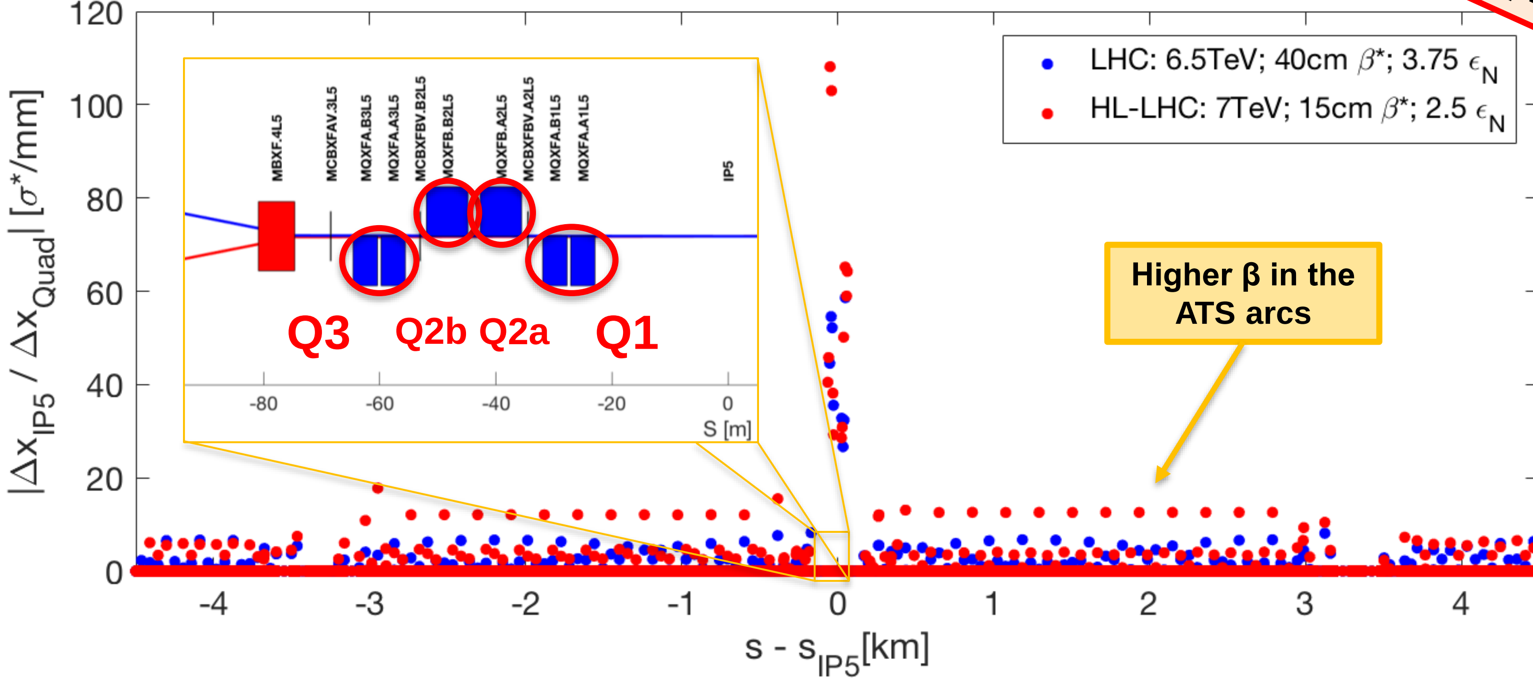


Impact of quad misalignment on closed orbit

- Expected B1 **closed orbit** variation at IP5:

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

Computed for LHC @ ε_N=3.75 μm; β*=45 cm



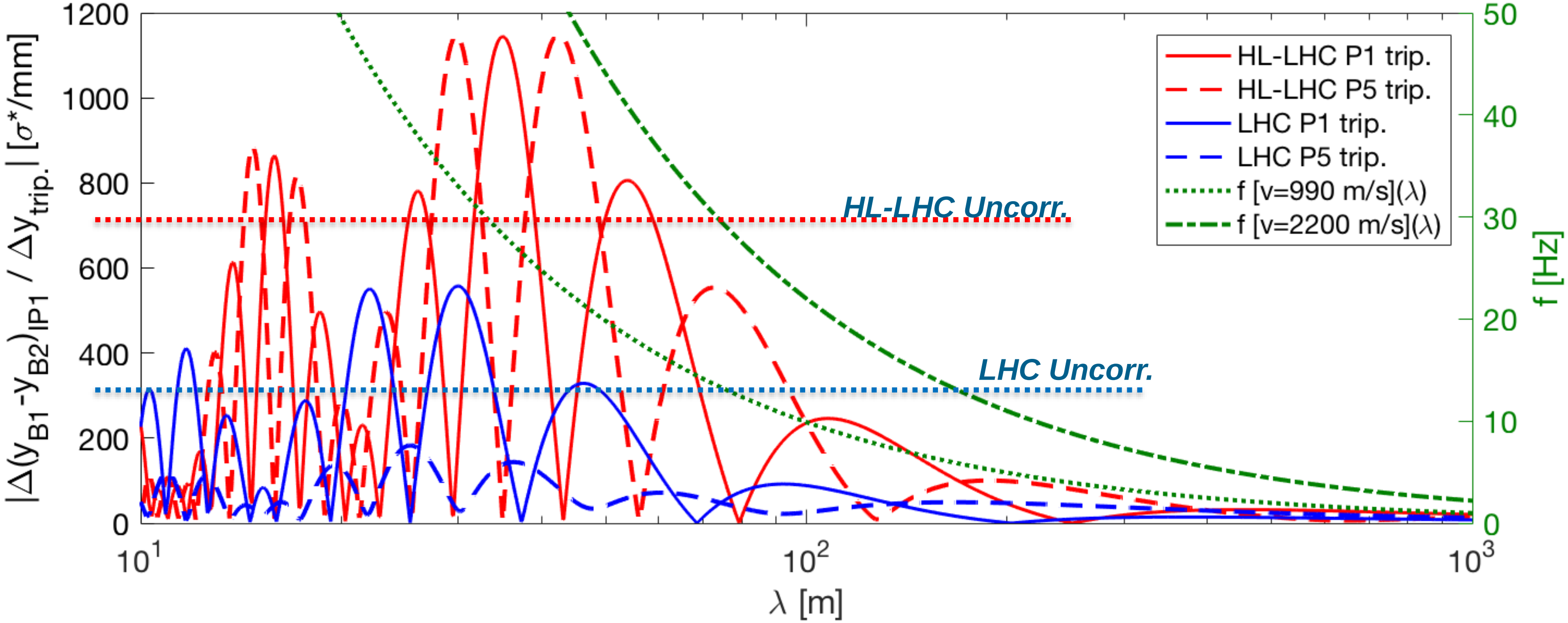
- **Design** HL-LHC up to **x2 more sensitivity** to errors than **design** LHC to be expected

From 119th WP2 meeting (link)

Computed for LHC @ ε_N=3.75 μm; β*=40cm

Note: 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.**

From 119th WP2 meeting (link)