What we know on the LHC limits

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Acknowledgements:
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Outline

1. Historical movement of equipment
2. Effect of vibrations on the beam:
   a. movement IT <-> orbit movement
   b. week/months orbit drifts
   c. During one fill (hours/mins) and low frequency vibrations < 3kHz
   d. High frequency vibrations > 3 kHz
   e. Summary
3. Mitigation Methods – fast orbit feedback
4. Summary and next steps

Tunnel excavations and studies at CERN

three interesting events (D. Missiaen, Vibration studies for HL-LHC Civil Engineering, 26.01.2015 + 18.02.2015 and many thanks to the colleagues who searched their memories – Karel Cornelis, Lyn Evans, Werner Herr, Kurt Hubner, Horst Schönauer, Rende Steerenberg, F. Tecker, J. Wenninger):

- construction of LEP/LHC tunnel during SppbarS operation:
  - only effect: more frequent alignment campaigns needed (several mm displacement during one year)
- construction of LEP klystron galleries (about 12 m away) in early 90s and LHC transfer lines and ATLAS/CMS cavern during LEP operation:
  - no effect

  note: LEP max. beta function was about 400 m compared to 6 km during LHC runIII (β^*=40 cm), the IT quadrupoles moved during one fill by about 10 µm due to temperature effects (CERN-SL/96-40) and all oscillations were damped by synchrotron radiation.
- specific studies in the SppbarS on low frequency excitation in view of HERA – still searching for documentation without much luck

Tunnel excavations close to DESY

several construction works close to HERA and PETRA:

- excavation of the XFEL tunnel (about 500 m? distance) with a “Schildvortriebmaschine” (road heading machine with shield tunneling) during operation of PETRA-III -> no effect
  but: during construction of the injector Hall, the operation of PETRA-III was disturbed whenever the “Schlitzwandbagger” (bagger shovel for making slits for reinforced concrete walls) encountered some hard obstacles
- construction of the football stadium right above the HERA tunnel (50 m)
  -> considerable disturbances of HERA, e.g. increase of tail population, correction of orbit to compensate the raise of the ground of the HERA tunnel (kink), …
- excavation of the “Elbtunnel” (about 2 km distance) -> no effect
- effect of passing trucks on the HERA operation

Note:

PETRA is in general less sensitive than the LHC due to its higher revolution frequency, the strong synchrotron radiation damping, its smaller tune spread and smaller beta functions

Courtesy to B. Holzer, W. Bialowons

Effect of vibrations on the beam (1)

Run III parameters:

N_{bunch}=1.25x10^{11}, ε_N=2.0 µm, bunch length= 7.55 cm, N_{tot}=2740, β*(IP1/5)=0.4 m (option med RunII), E=6.5 TeV, σ_{IP}=10.7 µm

For tunneling work in Point 1/5 we assume that:

1) only the elements in the straight section at Point 1/5 are effected
2) main effect is displacement of magnets
   - neglect effect from dipoles D1/D2
   - distortion of the beam by quadrupole displacement
   - no sextupoles in this area

=> consider only effects due to quadrupole misalignment in Point 1/5

=> main effect is closed orbit distortion due to quadrupole misalignment:

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

=> stronger effect from quadrupoles with high k*l and high beta-function

=> main effect expected from inner triplet during collision (closest to tunneling works!!!)

Effect of vibrations on the beam (2)

closed orbit distortion can result in:

1. slow movement of the ground (week/months) during and after the construction (detector and magnets)
   -> correction of long term orbit drifts
   -> more frequent alignment campaigns to avoid reaching the corrector strength limit
2. orbit deviations in the timescale from several minutes to several hours ≃ 1 fill:
   -> losses at collimators and luminosity loss due to slow orbit movements/drifts
   -> could be mitigated by current orbit feedback if BPM precision + stability and corrector strength are sufficient
3. effects of vibrations on the beam (< mins):
   - emittance growth:
     in general two regimes are distinguished:
     - "high frequency" [1], f > 3 kHz : overlap with betatron sidebands at $(\nu_{x/y}-n)\cdot f_{rev,LHC}$
     - "low frequency" [2], 0<f< 3 kHz : $\nu_{x/y} \cdot f_{0,LHC}$ = 3485 Hz, less harmful
   - stronger population of tails due to interplay of orbit jitter and beam-beam (non-linearities)
   - reduction of lifetime

   -> higher losses due to orbit jitter at collimators and increased tail population (harder limit)
   + luminosity loss due to emittance blow-up (softer limit)

Note: in 2012 the orbit feedback was not active when in stable beams and its maximum bandwidth was ~0.1 Hz

[1] K.Y. Ng, "*Emittance Growth due to a Small Low-frequency Perturbations*", FERMILAB-FN-575
[2] V. Lebedev, V. Parkhomchuk, V. Shiltsev, G. Stupakov, "*Emittance Growth due to Noise and its Suppression with the Feedback System in Large Hadron Colliders*", SSCL-Preprint-188

Correlation IT movement <-> orbit movement (1)

1. same displacement for all IT magnets in IR (parallel):
   -> no separation of the beams
   -> small residual orbit outside of IR
   -> small residual orbit at collimators

2. alternated displacement of IT magnets in IR (alternate):
   -> maximum separation at IP
   -> residual orbit outside of IR
   -> residual orbit at collimators

3. “side-alternated” displacement of IT magnets in IR (side alternate):
   -> no separation of the beams
   -> maximum residual orbit outside of IR
   -> maximum residual orbit at collimators

Alternate and side alternate are worst case scenarios and assume that the movement of the IT is fully correlated and each IT magnet is displaced with the same (absolute) amplitude **-> pessimistic assumption**

Correlation IT movement <-> orbit movement (2)

orange = maximum separation IP
red = maximum orbit collimators

	misalignment reference value IT: +/-1 µm in z=x,y	max(|z(b1)-z(b2)|) [µm]		max(|z|) [µm]
		IP1	IP5	TCP.[BCD]
only IR1	parallel 	0.00	(0.28)	3.16
	alternate 	14.48	(0.47)	18.78
	side alternate 	0.00	(15.44)	172.54
only IR5	parallel	(0.28)	0.00	3.09
	alternate	(0.77)	14.48	18.80
	side alternate	(15.45)	0.00	170.51
IR1+IR5	parallel IR1 + IR5	0.28	0.28	6.25
	alternate IR1 + side alternate IR5	29.93	0.47	151.74
	side alternate IR1 + alternate IR5	0.77	29.94	191.45
	side alternate IR1 + side alternate IR5	15.46	15.44	342.95

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Week/months orbit drifts

worst case scenario = alternate = scenario with largest separation at IP as in case of orbit distortion outside the IR, the complete arc/ring can be used for the correction -> less stringent:

IR5, corrector strength [T], 7 TeV, maximum over b1/b2 and *.L5/*.R5					
	MCBXH1	MCBXH2	MCBXH3	MCBYH4	MCBCH6
max. strength	1.51			2.25	2.10
crossing	0.19			0.64	0.27
separation	0.10			0.34	0.17
misalignment correction	1.58	1.71	1.39	0.20	0.26

=> in the most unfortunate case, already misalignment larger than 0.8 mm could be right at the limit of the corrector strength (-> more frequent alignment campaigns?). The corrector strength could be further reduced by a more intelligent matching strategy – to be studied if needed.

That the IT magnets experience an alternated misalignment is rather unlikely, e.g. a parallel movement would be more likely in which case a smaller corrector strength would be needed. **-> pessimistic assumption**

During one fill (hours/mins) and low frequency vibrations < 3kHz (1)

Observables:

- luminosity loss (softer limit)
- collimator losses -> do we dump the beam? (harder limit)

Luminosity loss:

assume worst case of alternated displacement of IT magnets =>

1 µm displacement => 14 µm at the IP (1.31 σ or 47% luminosity loss)

0.18 µm displacement => 2.52 µm at the IP (0.24 σ or 2% luminosity loss)

=> to keep luminosity loss below 2% per hour, the IT drift per hour and more stringent the IT vibration has to stay below 0.18 µm

That the IT magnets experience an alternated drift over minutes/hours is rather unlikely, e.g. a parallel movement would be more likely in which case a smaller corrector strength would be needed. **-> pessimistic assumption**

That for a low frequency excitation the movement of the IT is fully correlated is unlikely. **-> pessimistic assumption**

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During one fill (hours/mins) and low frequency vibrations < 3kHz (1)

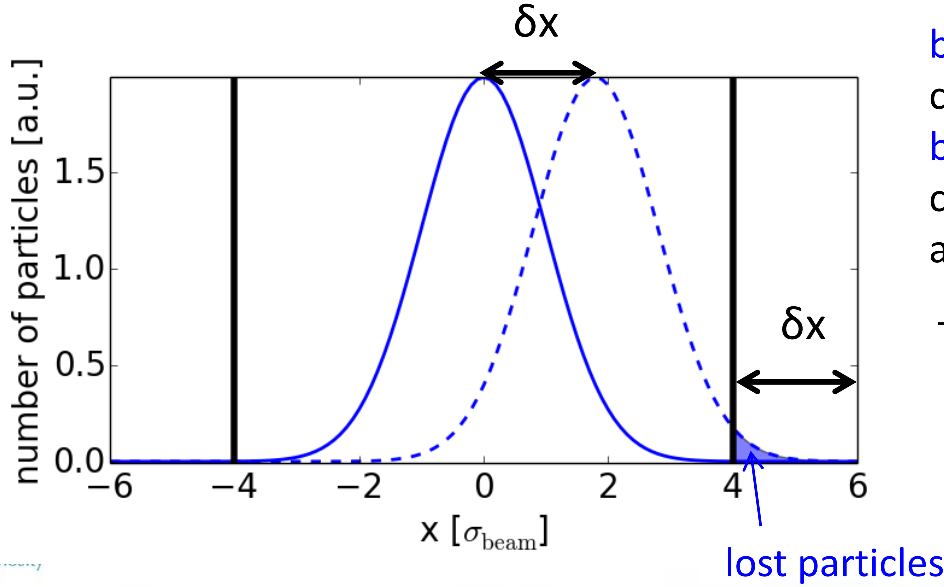
Collimation:

principle: orbit movement -> beam gets scraped at the collimator

Note: in Run I already about 40 µm orbit deviation at the TCPs caused high losses. For Run III this will be even more critical due to the higher energy (see G. Arduini, M. Lamont, LHC Commissioning 2012, Summary of week 19)

different scenarios to be evaluated:

1. construction work off -> construction work starts



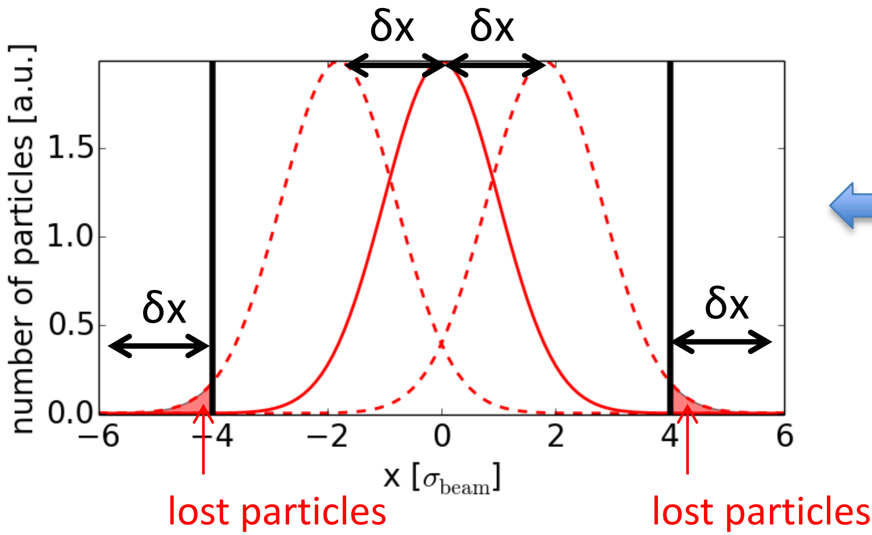
blue solid = beam distribution at collision **(no excitation)**
blue dashed = beam distribution at collision **(no excitation)** displaced by an orbit movement δx

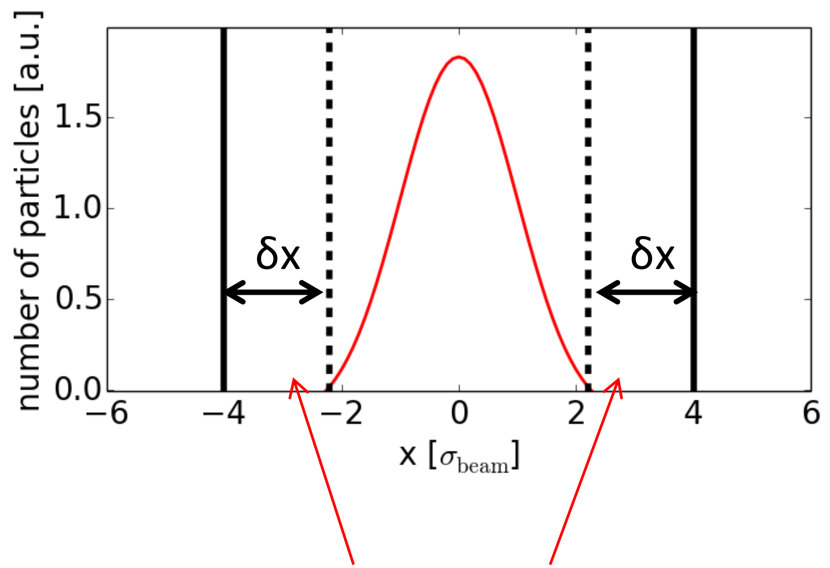
-> particles lost over several, but few turns, e.g.:
200 Hz -> 11245/200 turns = 57 turns

During one fill (hours/mins) and low frequency vibrations < 3kHz (1)

Collimation - different scenarios to be evaluated:

2. construction work on – same amplitude of orbit distortion:





red solid = beam distribution at collision with excitation

red dashed = beam distribution at collision with excitation and displaced by orbit movement δx

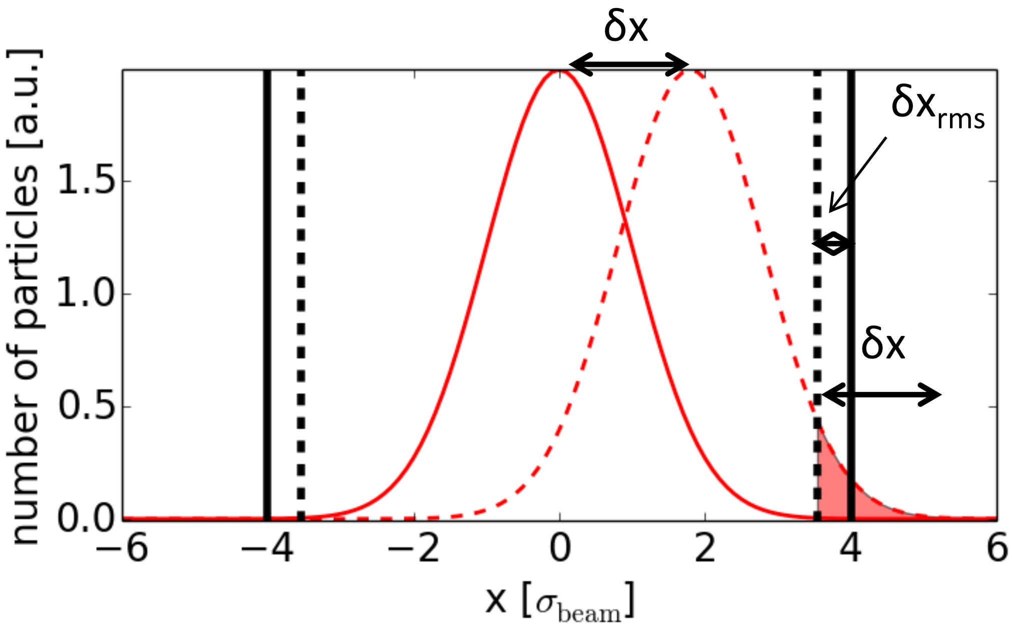
-> scenario equivalent to collimators at n-δx sigma + losses for beam distribution with low frequency excitation (possibly higher diffusion rate -> higher losses)

- tails depleted due to continuous movement
- increased loss rate due to higher diffusion rate ("tighter settings" + increase of diffusion rate due to excitation)

During one fill (hours/mins) and low frequency vibrations < 3kHz (1)

Collimation - different scenarios to be evaluated:

3. construction work on – varied amplitude of orbit distortion:



δx = sudden orbit movement

$= \delta x_{tot} - \delta x_{rms}$

⇒ to calculate the losses at the collimators we need:

1. orbit movement at TCPs due to misalignment of IT
   -> measurements of vibration spectrum
2. tail/beam distribution, colliding, squeezed, 6.5 TeV
3. tail/beam distribution, colliding, squeezed, 6.5 TeV + low frequency excitation

} MD request (items 2–3)

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During one fill (hours/mins) and low frequency vibrations < 3kHz (1)

Collimation – rough estimate using the 40 µm limit from RunI:
worst case scenario: side alternated displacement of IT

	misalignment reference value IT: +/-1 µm in z=x,y	max(|z(b1)-z(b2)|) [µm]		max(|z|) [µm]
		IP1	IP5	TCP.[BCD]
only IR1	side alternate	0.00	(15.44)	172.54
only IR5	side alternate	(15.45)	0.00	170.51
IR1+IR5	side alternate IR1 + side alternate IR5	15.46	15.44	342.95

only IR1/5: ±170 µm <-> ±1 µm => ±40 µm <-> ±0.24 µm
IR1/5: ±343 µm <-> ±1 µm => ±40 µm <-> ±0.12 µm

next step: calculate particles lost at TCP with measured beam distribution and expected (more realistic) misalignment of IT (work in progress)

It misalignment scenarios assume fully correlated movement
-> pessimistic assumption

Limit of "±40 µm" should still be confirmed by more detailed studies
-> are ±40 µm an optimistic assumption?

High Luminosity LHC

High frequency vibrations > 3 kHz (1)

Observables:

emittance growth -> change of beam distribution

⇒ luminosity loss (hard limit), beam losses (probably softer limit as amplitudes are very small), lifetime …

Emittance growth for high frequency excitation:

1. emittance growth from misalignment of one quadrupole [1]:

$$\left(\frac{d\langle\epsilon\rangle}{dt}\right)_0 = \frac{1}{4\pi}\beta_0(kl)^2 \sum_{n=-\infty}^{+\infty} S_{\Delta x}(2\pi f_0(\nu - n))$$

   note: only components equal to the betatron sidebands contribute to emittance growth. The betatron sidebands are given by

$$(\nu_{x/y} - n)f_0, \quad n = 0, \pm1, \pm2 \cdots$$

   with $\nu_{x/y}$ = hor./vert. tune = 62.31/60.32 and f_0 = revolution frequency = 11245

   -> lowest frequency for LHC= $\nu_{x/y}$ f_0 = 3485 Hz

2. emittance growth including the effect of the feedback system [1]:

$$\left(\frac{d\langle\epsilon\rangle}{dt}\right) = \frac{16\pi^2\Delta\bar{\nu}^2}{g^2}\left[\left(\frac{d\langle\epsilon\rangle}{dt}\right)_0 + \frac{f_0 g^2}{2\beta_1}X^2_{\mathrm{noise}}\right]$$

   g = feedback gain (g>>Δν), X_{noise} = precision of feedback pickup, β_1= β at location of pickup, Δν = rms tune shift (= rms beam-beam tune shift)

[1] V. Lebedev, V. Parkhomchuk, V. Shiltsev, **G. Stupakov**, "*Emittance Growth due to Noise and its Suppression with the Feedback System in Large Hadron Colliders*", SSCL-Preprint-188

High frequency vibrations > 3 kHz (2)

Rough estimate:

- Run III bb tune shift: $\Delta\nu$(IP1+IP5) = 0.2 ξ =0.2*0.016 =0.0032
- feedback parameters LHC: X_{noise}=1 µm, β_1= 180 m, g=0.01
  -> more ambitious feedback parameters to limit emittance growth due to pick-up noise
  -> assumed feedback parameters: X_{noise}=0.02 µm, β_1= 180 m, g=0.3

-> assume 1% emittance growth per hour:

power spectral density: $$\sum_{n=-\infty}^{+\infty} S_{\Delta x}(2\pi f_0(\nu - n)) \leq 7.5 \times 10^{-13} \mu\mathrm{m}^2/\mathrm{Hz}$$

white noise: $$\Delta x_{\mathrm{rms}} = \sqrt{\langle \Delta x^2 \rangle} < 0.23 \text{ nm}$$

The model of white noise assumes a contribution also from the high frequency part of the spectrum, in particular the betatron sideband.

next step: check formula in strong-strong beam-beam simulations (simulations of beam-beam ongoing) and experimentally (MD requests on noise)

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Summary of theoretical estimates

Acceptable amplitude vary according to the time scale:

- Long time scale (weeks/months):

  few 10th of mm

  determined by available corrector strength
- Time scale < hours (no orbit feedback):

  a) continuous drift:

  below 1 μm/hour (at the triplet)

  in order to avoid luminosity loss (<2%/hour) and losses

  b) "sudden shock":

  well below 1 μm (at the triplet)

  in order to avoid sudden loss spikes at the collimators
- one up to a few hundred Hz (no orbit feedback):

  well below 1 μm (at the triplet)

  in order to avoid luminosity loss (<2%) and losses
- kHz range:

  <1 nm (at the triplet)

  note: most dangerous if overlap with betatron => emittance growth

weeks/months: mm
hours/minutes: μm
low frequency and sudden shocks: below μm
kHz range: nm

High Luminosity LHC

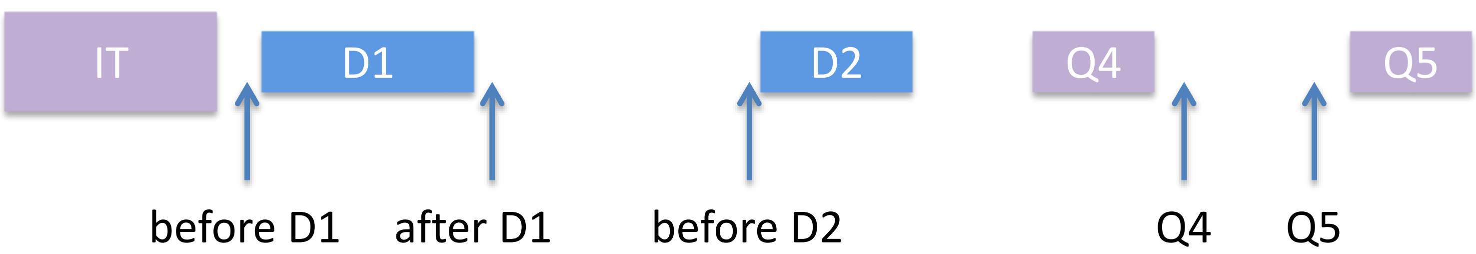
Mitigation methods – fast orbit feedback (1)

Fast orbit feedback:

- motivated by orbit feedback installed at RHIC, which damps the mechanical vibration mode of the cold mass at 10 Hz ([1]-[5])

  [1] R. Michnoff et al., “RHIC 10 Hz Global Orbit Feedback System”, PAC 2011
  [2] P. Thieberger et al., “The Dipole Corrector Magnets for the RHIC fast global orbit feedback system”
  [3] C. Montag, “Fast IR Orbit Feedback at RHIC”, PAC 2005
  [4] C. Montag et al., “Status of Fast IR Orbit Feedback at RHIC”, EPAC 2006
  [5] C. Montag et al.,” Observation of helium flow induced beam orbit oscillations at RHIC“, NIM A, 564 (2006) 26-31

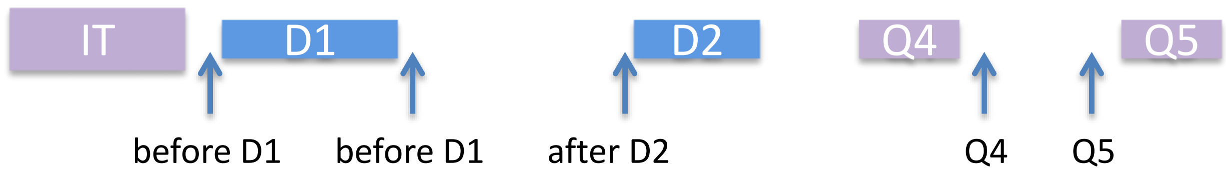
- **Idea:** installation of a fast orbit feedback at the LHC (0-200 Hz) in order to correct the closed orbit distortion -> install additional warm magnets next to IT



Mitigation methods – fast orbit feedback

Fast orbit feedback:

- needed corrector strength:



correctors	misalignment	$\|z(b1)-z(b2)\|_{max}(IP)$ [µm]	$\|z(S.DS.R5.B[12]\|_{max}$ [µm]	corrector strength @6.5 TeV [10^{-3} Tm]
no correctors	parallel	0.26	1.19	-
	alternate	14.38	10.05	-
	side alternate	14.38	78.56	-
before D1	parallel	0.17	0.08	0.12
	alternate	19.60	6.26	1.51
	side alternate	0.19	0.10	4.14
after D1 + before D2	**parallel**	**0.11**	**0.12**	**0.86**
	alternate	**0.22**	**0.22**	**6.08**
	side alternate	**0.20**	**0.21**	**6.08**
Q4+Q5	parallel	0.00	0.00	6.27
	alternate	0.00	0.00	37.59
	side alternate	0.00	0.00	37.59

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Note: BPMs precision > 1µm

Summary

- Historical events:
  - construction work during LEP and SppbarS operation did not show any effect
  - at DESY an effect on PETRA-II and HERA was observed
- theoretical estimates for vibration limits:
  - weeks/months: mm
  - hours/minutes: µm
  - low frequency and sudden shocks: below µm
  - kHz range: nm

  in general: calculation of worst case orbit displacement assumes that IT movement is correlated -> real displacement within the best and the worst case scenario
- mitigation methods: fast orbit feedback (<200 Hz)
  - corrector strength look feasible (a few 10^{-3} Tm at 6.5 TeV)
  - install correctors at D1 and D2 looks like the most promising option

Next steps

- evaluate in more detail the limits on collimation using the new information obtained from the measurements of the frequency spectrum expected due to the construction works (see M. Guinchard, “Results of the SM18 measurements”) and cross check estimates with experience during RunI/II
- simulations to evaluate effect of low frequency excitation on emittance and tail population
- study feasibility of fast orbit feedback
- further analysis of RunI data in view of effect of low and high frequency excitation (see “Measurements during operation and MDs”, this meeting)
- measurements at LHC amongst others proposed MD on low frequency excitation (see “Measurements during operation and MDs”, this meeting)

Thank you for your attention!

Theoretical Background - Literature

Ground motion LEP/LHC: in general not much available (measurements in view of a linear collider study and in ATLAS/CMS experimental hall)

[1] **L. Vos**, "*Ground motion in LEP and LHC*", CERN-LHC-NOTE-299
[2] M.P. Zorzano, T. Sen, "*Emittance Growth for the LHC Beams Due to Head-On Beam-Beam Interaction and Ground Motion*", FERMILAB-TM-2106
[3] V.E. Balakin, **W. Coosemans** et al., "*Measurments of Seismic Vibrations in the CERN TT2A Tunnel for Linear Collider Studies*", CLIC-Note 191

Ground motion HERA:
all publications can be found at http://vibration.desy.de/documents/papers/

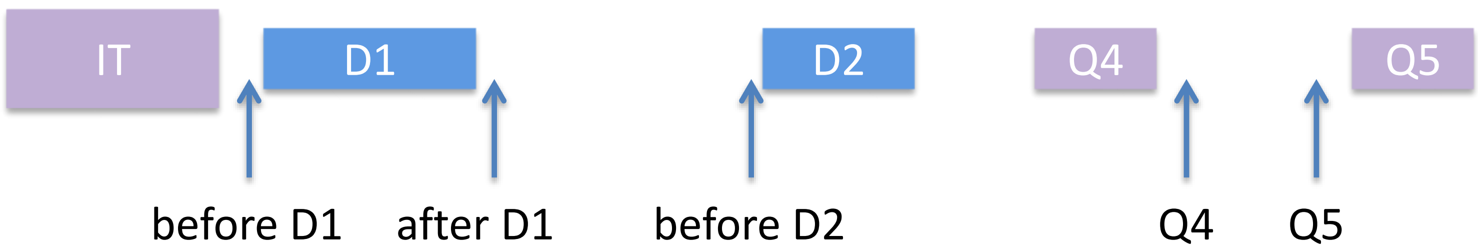
Detailed studies for SSC (theoretical background):
low frequency ($f < f_{rev}\nu$):
[4] K.Y. Ng, "*Emittance Growth due to a Small Low-frequency Perturbations*", FERMILAB-FN-575
high frequency ($f \geq f_{rev}\nu$):
[5] V. Lebedev, V. Parkhomchuk, V. Shiltsev, **G. Stupakov**, "*Emittance Growth due to Noise and its Suppression with the Feedback System in Large Hadron Colliders*", SSCL-Preprint-188
[6] Y.I. Alexahin, "*On the emittance growth due to noise in hadron colliders and methods of its suppresion*", NIM A 391, p. 73-76, 1996

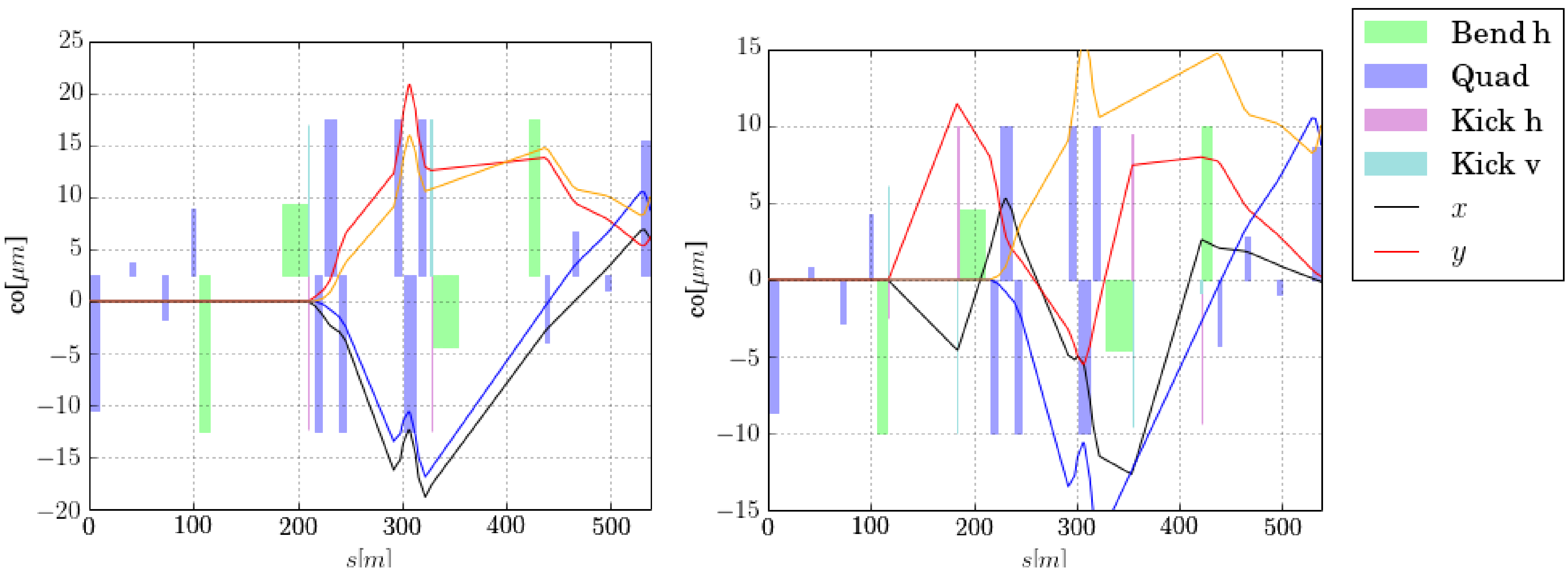
Ground motion CLIC: http://clic-stability.web.cern.ch/clic-stability/Ground_motion.htm

Mitigation methods – fast orbit feedback

Fast orbit feedback:

- needed corrector strength:





alternate, before D1

alternate, after D1 + before D2