IT BPM tolerances for HL-LHC orbit correction

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Studies

Orbit correction target:

- using triplet BPM to find collisions (e.g. beam-beam separation <3σ)
- using triplet BPM to keep collisions (beam-beam separation < 0.2σ)

Studies:

- Correct orbit by using perfect model and perturbed BPM readings:
  - for accuracy needed to find collisions,
  - for precision needed to keep collision.
- Introduce perturbation in the model:
  - for finding the conditions that would separate beams in collision.
- Correct orbit by using perturbed model and perturbed BPM readings:
  - for max. allowed perturbations between fills to find collisions by using same settings,
  - for max allowed perturbation that does not increase beam-beam separation without corrections.

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Some general definitions for BPM specifications

See “J-J. Gras, J.-P. Koutchouk, Concepts and Glossary for the Specification of the Beam Instrumenation” and J.-P. Koutchouk “Measurment of the beam position in the LHC main rings”.

BPM error model:

- the error of a measurement, e.g. for a BPM measurement:

$$x_{\mathrm{measured}} - x_{\mathrm{true}} = \underbrace{\Delta}_{\text{offset}} + \underbrace{k x_{\mathrm{true}}}_{\text{scale error}} + \underbrace{\psi y_{\mathrm{true}}}_{\text{role error}} + \underbrace{\sum_{k=2}^{\infty} \sum_{j \leq k} \alpha_{kj} x_{\mathrm{true}}^{k-j} y_{\mathrm{true}}^{j}}_{\text{non-linearity}} + \underbrace{\epsilon}_{\text{noise}}$$

- uncertainty: usually the standard deviation σ of the error distribution (in case of numerous sources the Gaussian distribution is a good approximation, for which 2σ correspond to 95.5% confidence level)

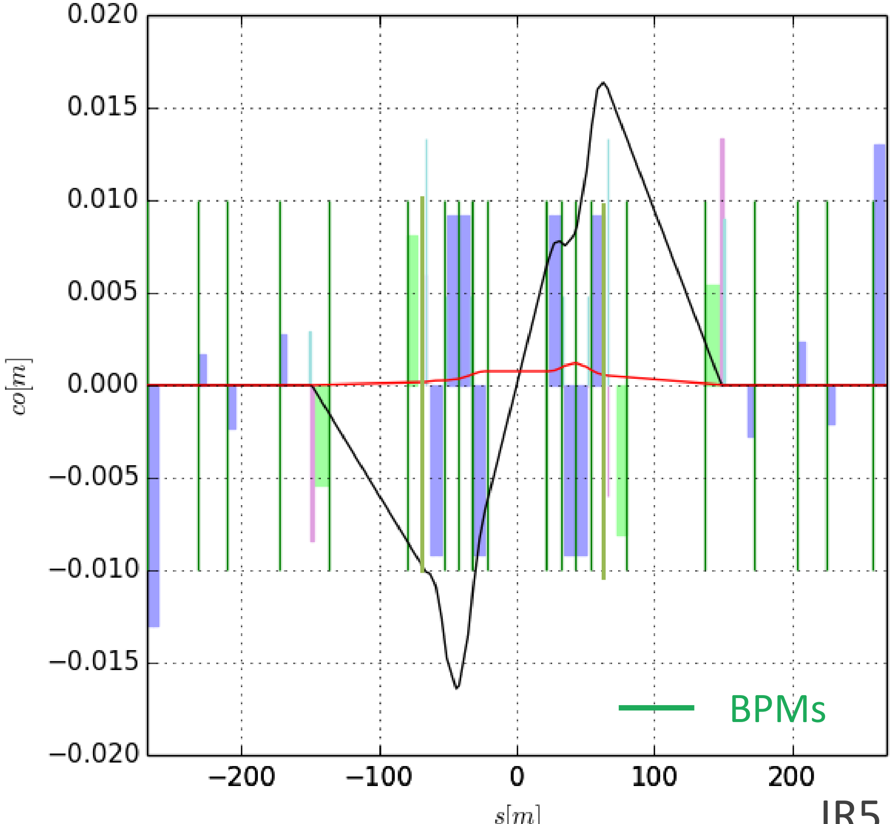
- **resolution:** smallest increment that can be induced or discerned by the measurement device within given conditions (e.g. noise)
- **accuracy:** closeness of the agreement between the result of a measurement and the value of the measured quantity
- **precision:** closeness of the agreement between consecutive measurements for the same measured quantity. It can be also referred with slightly different meaning as **repeatability** or **reproducibility**.

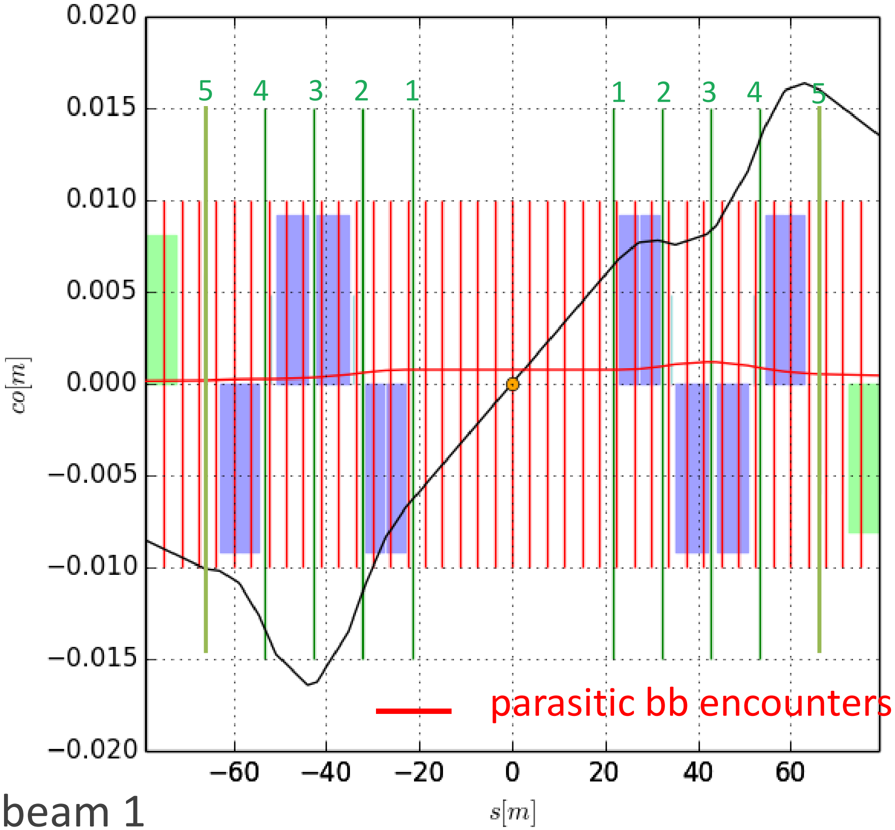
Imperfection considered so far

- BPM imperfections:
  - adding random noise errors in µm assuming an ideal transverse position;
  - longitudinal displacement of the BPMs;
  - Impact of disabling some BPMs.

- Model imperfections:
  - transfer function errors in the correctors (relevant when evaluating the reproducibility of a presetting obtained by arbitrary excitation history);
  - transfer function errors in the triplets (relevant to evaluate the sensitivity to nominal orbit vs real orbit);
  - orbit error from the arc (ground motion, orbit feedback residual imperfections).

BPMs in IR1/5





IR5, beam 1

Suboptimal location of BPMs:

- at parasitic bb encounters it is difficult to measure the individual signal of each beam

BPM candidates :

- BPM4 and BPM 5(parasitic bb encounter)

Specifications and Simulations

Simulation setup:

- treat IR1/5 as line -> only IR5 as IR1/5 are fully "symmetric"
- orbit deviations in the arc are treated as (uniformly distributed) error in initial/final conditions (maximum value of +/-100 μm at BPM at Q6/Q7 is assumed which is then tracked to the beginning/end of the DS)
- BPM precision is treated as (uniformly distributed) error in matching constraints (reference value: +/-1 μm)
- errors considered: transfer function of triplet and correctors, long. misalign. of BPMs

What can we conclude from the simulations?

1. consider only orbit deviation in the arc and error on BPM matching constraints
   - ➢ required precision to find collisions from fill to fill
   - ➢ required precision to stay in collision
2. case 1. plus in addition transfer function errors of the IT and correctors
   - ➢ influence of a perturbed machine (note that the matching constraints at the BPMs are varied around the position of the ideal machine, while the perturbed machine is used for the SVD)
3. case 2. plus longitudinal misalignment of BPMs
   - ➢ as the divergence of the orbit is large in the IT region a longitudinal misalignment of the BPMs could have a big influence

All simulations done for round optics (β^***=0.15 m**)

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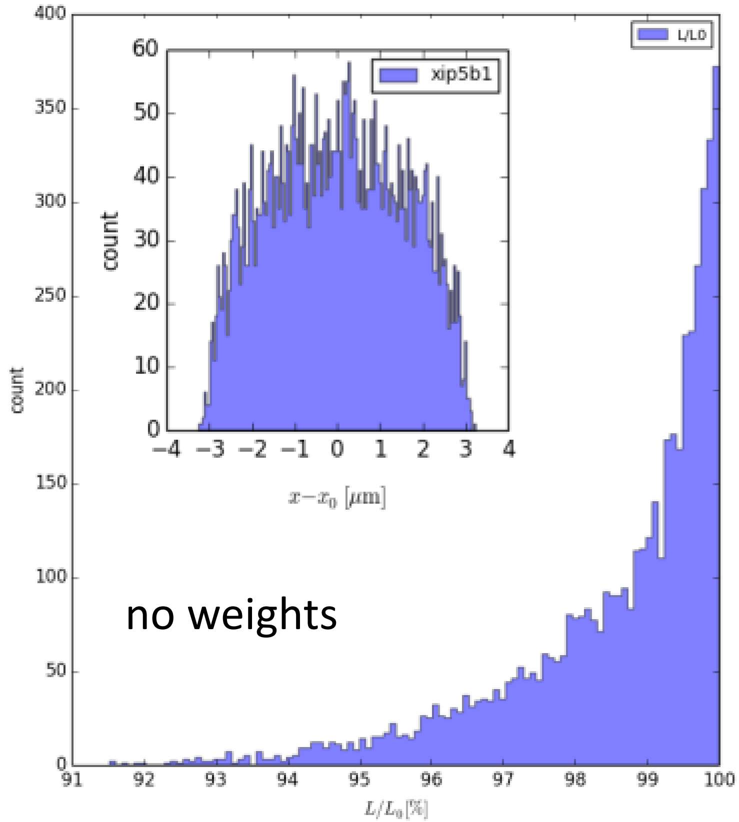
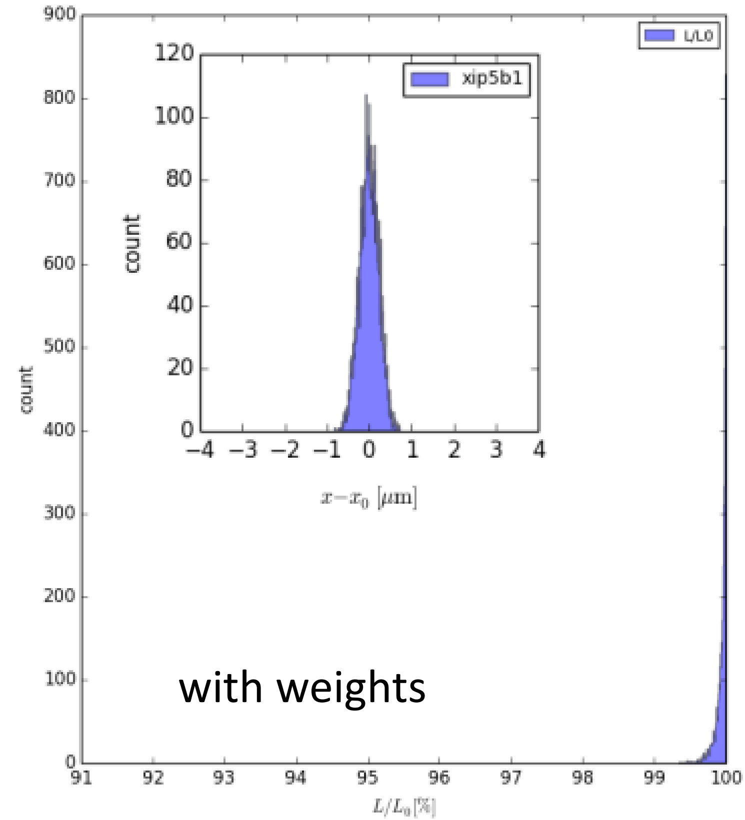
Correction strategy

use orbit correctors at Q5 and Q6/Q7:

- exactly the 8 variables needed to match x/p_x/y/py at the IP for Beam 1 and Beam 2
- Avoid using strong MCBX and D2/Q4 orb. corr.) to act separately on Beam 1 and Beam 2 and avoid large time constants.
- increased **weight** of the BPMs between D1L and D1R (possible as orbit at crab cavities is always controlled well enough <0.01mm).





BPM precision

assuming +/-100 μm max. orbit deviation from arc, +/-1 μm BPM precision as reference value (note: linear scaling with BPM precision), no model errors, **all BPMs**.

orbit at IP5 z=max(x,y)	max(|z-z0|) [μm]	rms(z-z0) [μm]
$x(b1)-x_0(b1)$	0.809	0.230
$x(b2)-x_0(b2)$	0.814	0.234
$y(b1)-y_0(b1)$	0.872	0.233
$y(b2)-y_0(b2)$	0.740	0.232
x(b1)-x(b2)	1.139	0.326
y(b1)-y(b2)	1.119	0.332

Luminosity loss assuming:
β^*=0.15 m, E_b=7.00 TeV, ε_n=2.50 μm,
σ_s=7.50 cm, x-angle=295.0 μrad
=> σ(IP5)=7.09 μm

BPM precision needed during one fill (e.g. 1% luminosity loss = 0.14 σ, 2 rms(z_{b1}-z_{b2})):

precision $_{\text{one fill}}$ = +/-1.5 μm

BPM accuracy for finding collisions (e.g. 99% luminosity loss = 3.0 σ, 2 rms(z_{b1}-z_{b2})):

precision $_{\text{one fill}}$ = +/-30 μm

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Selecting the efficient BPMs

Study:
Removing one BPMs at the time.

orbit at IP5 z=max(x,y)	max(|z-z0|) [μm]	rms(z-z0) [μm]	$2rms(z-z0)/\sigma_z$
all BPMs	1.14	0.33	0.094
no BPM1	1.44	0.41	0.115
no BPM2	1.55	0.39	0.111
no BPM3	1.48	0.38	0.106
no BPM4	1.43	0.35	0.100
no BPM5	1.19	0.34	0.095

efficiency decreases

In general:
BPMs closest to the IP are best for orbit control at the IP.

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Selecting the efficient BPMs

orbit at IP5 z=max(x,y)	max(|z-z0|) [μm]	rms(z-z0) [μm]	2 rms(z-z0)/σ_z	
all BPMs	1.14	0.33	0.094	
no BPM3/4	1.49	0.41	0.116	only BPMs closest to IP (BPM1/2)
no BPM4/5	1.40	0.36	0.102	
no BPM3/4/5	1.47	0.42	0.117	
no BPM1/3/4	1.72	0.59	0.169	case of failure of BPM1 or BPM2
no BPM2/3/4	1.80	0.58	0.163	
no BPM1/3/4/5	1.72	0.61	0.172	
no BPM2/3/4/5	1.84	0.58	0.163	
no BPM1/2	2.09	0.52	0.152	case of failure of BPMs closest to the IP (BPM1/2)
no BPM1/2/3/4	35.88	11.73	3.309	

Main conclusion:
at least one of the BPMs closest to the IP (BPM1/2) is required to ensure a luminosity loss smaller than 1-2% assuming a BPM precision of 1 μm, while BPM3/4/5 are considerable less efficient

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Influence of errors – long. misalignment

Due to large divergence in triplet region the x-scheme could be sensitive to already small longitudinal misalignments

orbit at IP5 Z=max(x,y)	ds(BPM) [mm]	max(|z-z0|) [μm]	rms(z-z0) [μm]	2rms(z-z0)/σ_z
all BPMs	0	1.14	0.33	0.092
all BPMs	1.0	1.34	0.35	0.097
all BPMs	10.0	4.43	1.29	0.363

Main conclusion:
BPM should be longitudinally aligned or known in 1-2 mm range.

Influence of errors – transfer function errors

influence of transfer function errors of the IT and correctors

- influence of a perturbed machine (the matching constraints at the BPMs are varied around the position of the ideal machine, while the perturbed machine is used for the SVD)

orbit at IP5 z=max(x,y)	k_{err} [10^{-4}]	acb* [10^{-4}]	max(|z-z0|) [μm]	rms(z-z0) [μm]	2 rms(z-z0)/σ_z
all BPMs	0	0	1.14	0.33	0.092
all BPMs	1.0	0	1.67	0.42	0.117
all BPMs	0	1.0	1.21	0.33	0.094
all BPMs	1.0	1.0	1.70	0.42	0.119

Main conclusion:
Triplet transfer function errors starts to play a role from 1 unit.

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Specifications and Simulations

What do we need to specify?

1. **from fill to fill:**
   min precision: required to find collisions at the beginning of a fill
   ideal precision: should allow to find 95% of the luminosity by using only the BPMs (no lumiscan)
2. **during one fill (after recalibration at the beginning of the fill):**
   precision: required to keep the beams in collision without loss of luminosity

Simulation method:
ideal case:

- optics model including all errors, in particular misalignment errors
- try to correct orbit similar to the correction as done currently in the LHC**: global SVD** for each beam individually using the orbit response matrix of the “idealized” optics model (no errors)

but: misalignment errors are not known well enough

Conclusion

- For the HL-LHC β*-leveling in IR1/5 is foreseen resulting in continuous optics changes.
- Frequent lumiscans not affordable due to time and emittance losses in the process.
- Ideally triple BPM could provide measurements to:
    a) find collisions at the beginning of the fill (e.g. obtain 1% luminosity signal);
    b) keep the beams in collision without loss of luminosity (e.g. keep 99% luminosity).
- If using all BPMs and no errors a precision of +/- 1.5 µm is precision is needed to keep beam in collision, and a factor 20 more is sufficient to find collisions.
- Only a selection of BPMs is sufficient, where the two BPMs closest to the IP are most efficient (other BPMS should both be kept for statistics and redundancy).
- Influence of errors:
    - the BPMs should be longitudinally aligned or know up to about mm;
    - transfer function errors of the triplet and corrector up to 10^{-4} are acceptable.
- Future work:
    - introduce more realistic BPM imperfection models (input from BI needed);
    - perform correction with perturbed model using the ideal response matrix as done in reality;
    - validate simulation setup by producing LHC orbit correction features;
    - plan MD in run II to validate the ability to control orbit in the D2 Q4 region as required by crab cavity and at IP as allowed by present and foreseen instrumentation.

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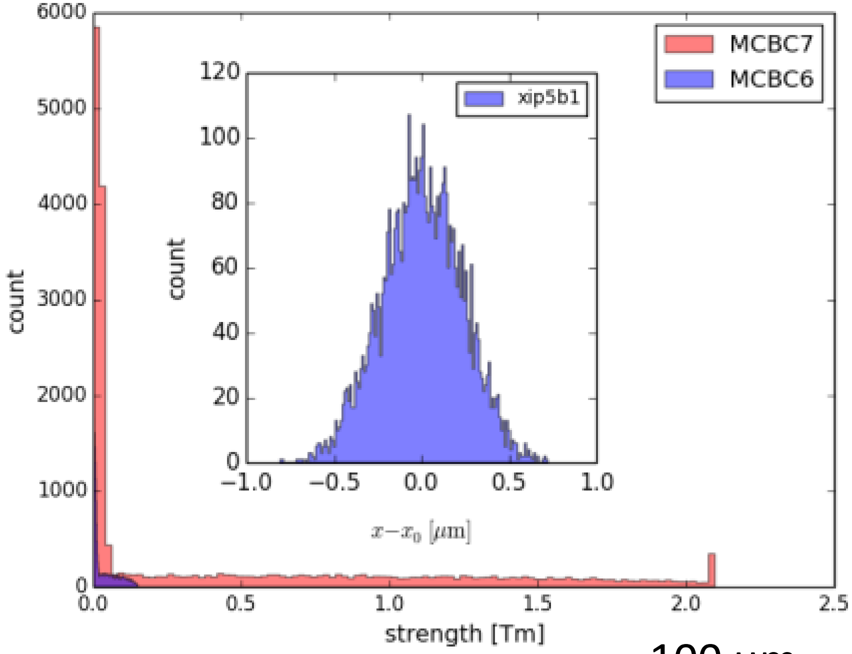
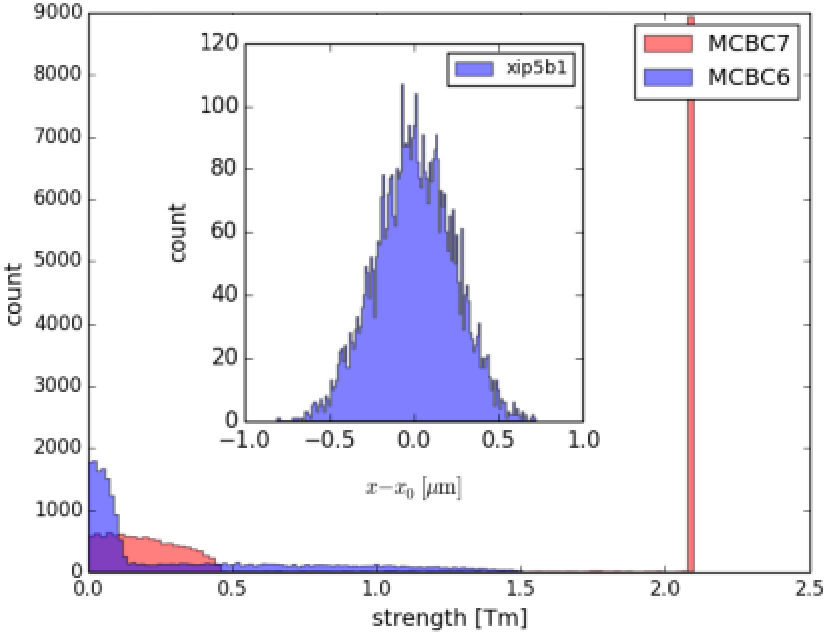
Backup slides

Arc imperfections

An increase of the imperfections in the arc only results in an increase of the MCBC7 corrector strength (which needs to be sufficient), but does not influence the orbit at the IP



100 µm



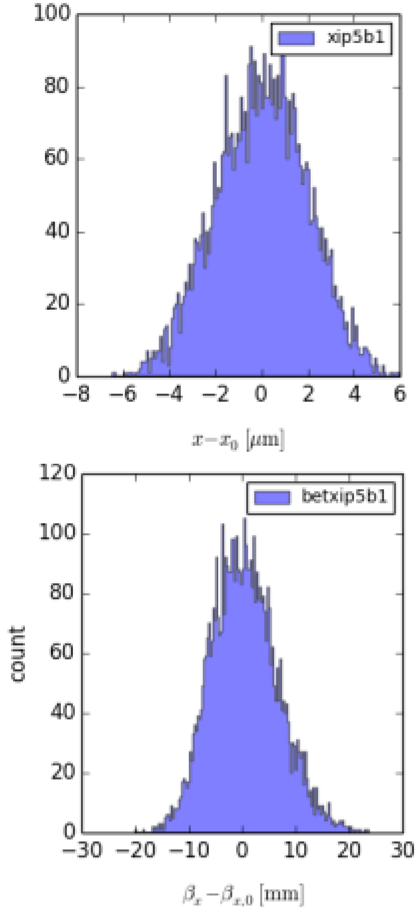
1 mm

orbit at IP5 (x/y)	max(|z-z0|) [µm]	rms(z-z0) [µm]	2rms(z-z0)/σ_z
100 µm	1.14/1.12	0.33/0.33	0.092/0.094
1 mm	1.14/1.12	0.33/0.33	0.092/0.094

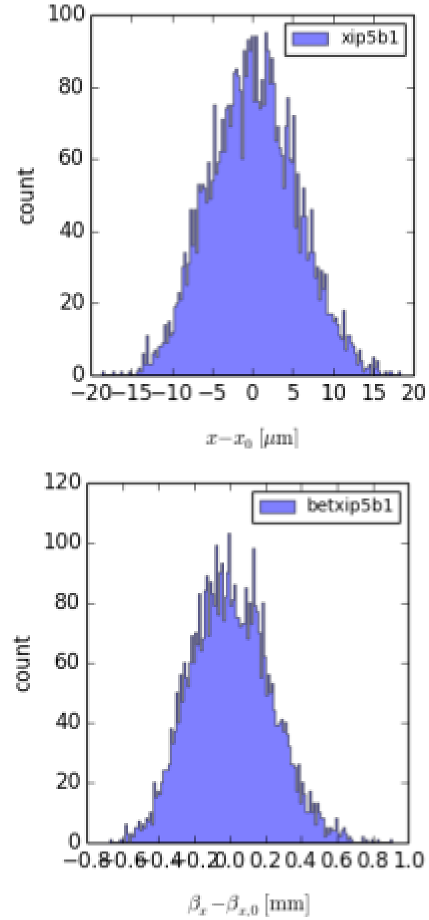
Influence of errors

influence of transfer function errors of the IT and correctors:

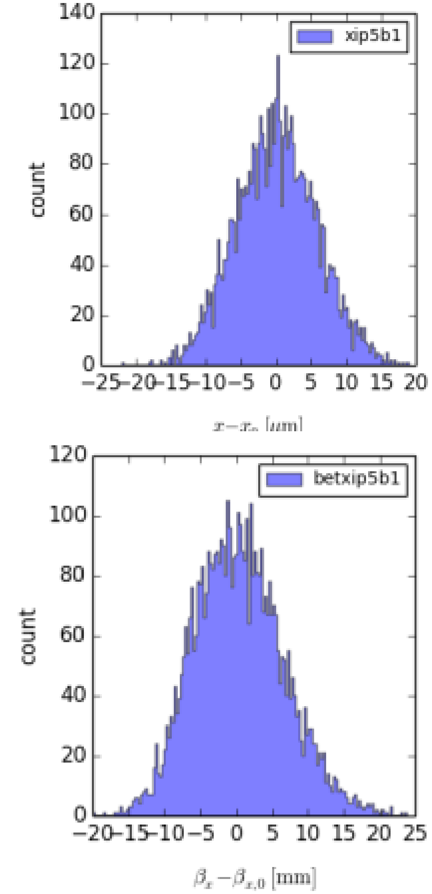
- no correction
- closed orbit of complete ring (no only IR1/5)



$k_{err}=10^{-4}$



acb=10^{-3}



$k_{err}=10^{-4}$, acb=10^{-3}

Orbit correction in the nominal LHC

Following discussion with J. Wenninger

Orbit correction method:

1. orbit correction for each beam individually using **SVD** and limiting the number of eigenvalues (see J. Wenninger, LBOC 11.02.2014). Explicitly **global orbit correction** and no individual correction of IRs. Orbit response matrix of injection optics used for SVD also in collision optic.
2. 200-300 μm orbit drift (+/-10 μm at the IP – see Stability of Luminosity Optimizations, J.Wenninger, LBOC 30.10.2012) from fill to fill and **ground motion like behavior** of the orbit drift
   ⇒ orbit distortion mainly due to misalignment caused by ground motion
3. **BPMs in IT region** (3 per side/beam/plane) currently not used in operation
4. **BPMs closest to the IP are best to correct the orbit at the IP**. Correction possible with 2 out of 3 BPMs.

Orbit correction strategy:

1. correct to golden orbit of previous fill at the end of the squeeze
2. lumiscan to optimize luminosity -> redefinition of "golden orbit"
3. orbit correction to the golden orbit defined by the initial lumiscan
   note: BPMs at IT are NOT included in the correction
4. in case of relevant drop of luminosity, additional lumiscan

Orbit correction in the HL-LHC

Similarities and main differences to nominal LHC:

1. **β*-leveling over several hours -> continuous orbit changes**.
   Two cases should be distinguished:
   a) leveling using the **pre-squeeze optics** (for β*>0.44 m) -> **change** of magnet strength in IR1/5
   b) leveling using the **squeeze optics** (for β*<0.44 m) -> **no change** of magnet strength in IR1/5 + adjacent arcs

   case b) might be easier to control as IR1/5 stay unchanged (this case would be similar to the nominal LHC, assuming that the orbit at the entrance and exit of IR1/5 can be controlled sufficiently well)
1. orbit deviations (thinking in mm) due to **ground motion** are expected to be similar as for the LHC as the machine stays unchanged except the IT. As k*l of the nominal and the HL-LHC triplet is approximately the same, the **same orbit deviation in terms of mm is expected**.
2. **smaller beam size** – round optics and ε_N=2.5 µm: 7 µm beam spot size (thus smaller orbit deviation already result in a considerable loss of luminosity)

Orbit correction strategy:

1. correct to golden orbit of previous fill at the end of the squeeze
2. lumiscan to “recalibrate BPMs”-> redefinition of “golden orbit”
3. orbit control using the BPMs, explicitly no further lumiscans
   -> high repeatability, reliability and precision of BPM readings during one fill needed

Some general definitions for specifications

See “J-J. Gras, J.-P. Koutchouk, Concepts and Glossary for the Specification of the Beam Instrumenation” and J.-P. Koutchouk “Measurment of the beam position in the LHC main rings”:

- **sensitivity:** change of the beam observable divided by the corresponding change of the primary observable
- **dynamic range**: range of values of the beam observable which can be measured with a given **precision** goal
- **Time dependence:**

  repeatability: closeness of the agreement between the results of successive measurements of the same measurand carried out under the same repeatability conditions (‘short’ period of time)

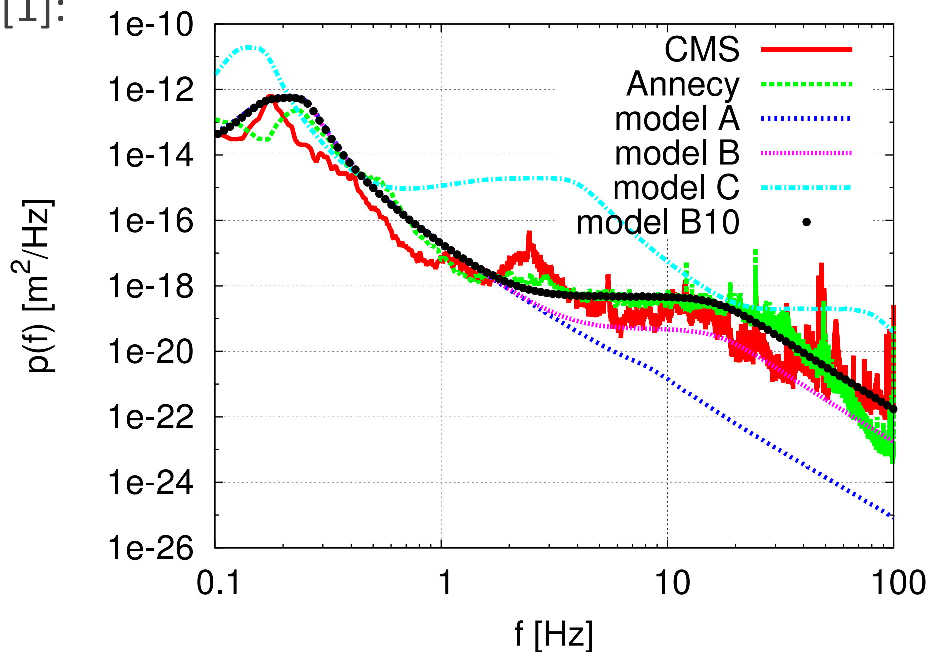
  reproducibility: closeness of the agreement between the results of successive measurements of the same measurand carried out under conditions which have been restored after a change (except time obviously) The systematic part of the reproducibility error is generally called the **drift**.

Short term effect of ground motion

Ground motion model used for simulations:

Real spectrum for short time scales (<1min) [1]:

- CMS: measurement [1]
- Annecy: measurement [2]
- model A/B/C: ground motion models [3]
- model B10 (black): model B with 10x more noise for the range >2 Hz (D. Schulte)



ATL law for long time scales (>1min) [4]:

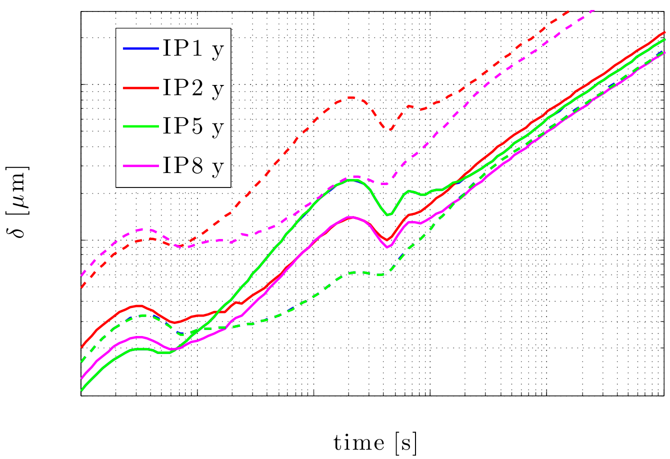
$$\langle dY^2 \rangle = ATL,\ A = 10^{-5\pm1}\ \mu\mathrm{m}^2/(\mathrm{sm})$$

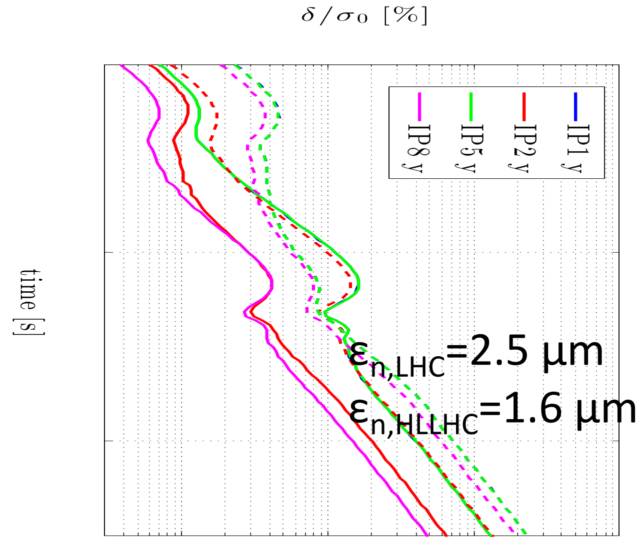
with T=time interval between measurements, L=distance between measurement points

[1] A. Kuzmin, Technical Report EDMS Nr. 1027459, CERN, 2009
[2] B. Bolzon, PhD Thesis, Université de Savoie, 2007
[3] International Linear Collider Technical Review Committee: Second Report, SLAC Report-606 (2003)
[4] V. Shiltsev, PRSTAB 13, 094801 (2010)

Misalignment of IT due to ground motion

Simulation results: — nom. LHC, 4 TeV, β*=60 cm – – HLLHCV1.0, 7 TeV, β*=15 cm





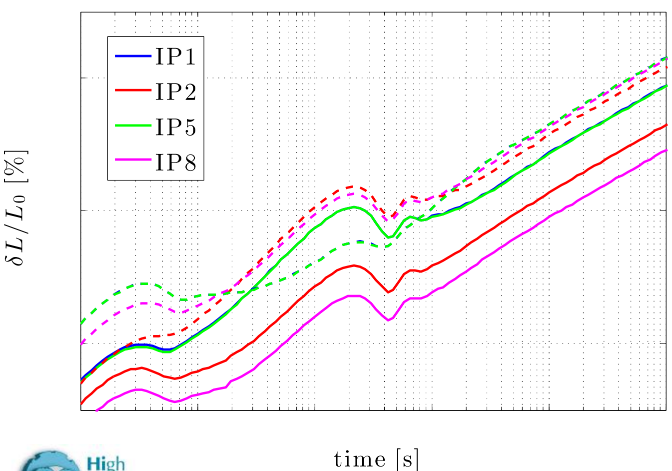
offset at IP

$$\sim (k \cdot l)$$

and

$$(k \cdot l)_{\mathrm{nom.}} \gtrsim (k \cdot l)_{\mathrm{HLLHC}}$$

➡ similar effects for nominal LHC than HL-LHC



J. Pfingstner

luminosity loss

$$\sim \exp\left[-\frac{(\delta x/2)^2}{\sigma_x^{\star 2}\cos^2\phi + \sigma_z^2 \sin^2\phi} - \left(\frac{\delta y}{2\sigma_y^*}\right)\right]$$

and

$$\beta^*_{\mathrm{nom.}} > \beta^*_{\mathrm{HLLHC}}$$

➡ larger effect for HL-LHC than nominal LHC

➡ more than 1% luminosity loss after 10^3 s = 17 min

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HL-LHC BPMs

BPM	s	d par	betx	bety	mux	muy
Q1						
Q1-Q2a						
Q2a-Q2b						
Q2b-Q3						
Q3-CP						
CP-D1						
D1						
D2						
Q4						
Q5						
Q6						