IT BPM tolerances for HL-LHC orbit correction

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Outline

- Introduction:
    - Orbit correction in the nominal LHC and HL-LHC
    - BPMs in IR1/5
    - General definitions for specifications and errors considered
- Studies and simulations
- Conclusion and outlook

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 optics.
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:

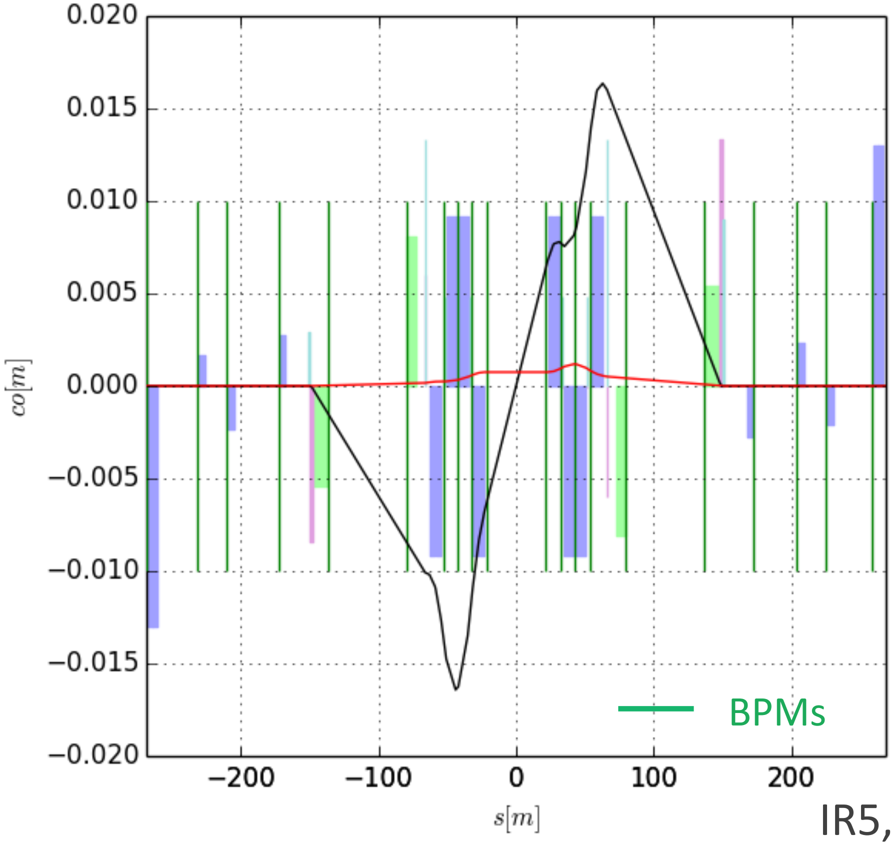
1. **β*-leveling over several hours -> continuous orbit changes**.
   Two cases should be distinguished:
   a) leveling using the **pre-squeeze optics** (for β*>0.44 m) -> **change** of magnet strength in IR1/5
   b) leveling using the **squeeze optics** (for β*<0.44 m) -> **no change** of magnet strength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

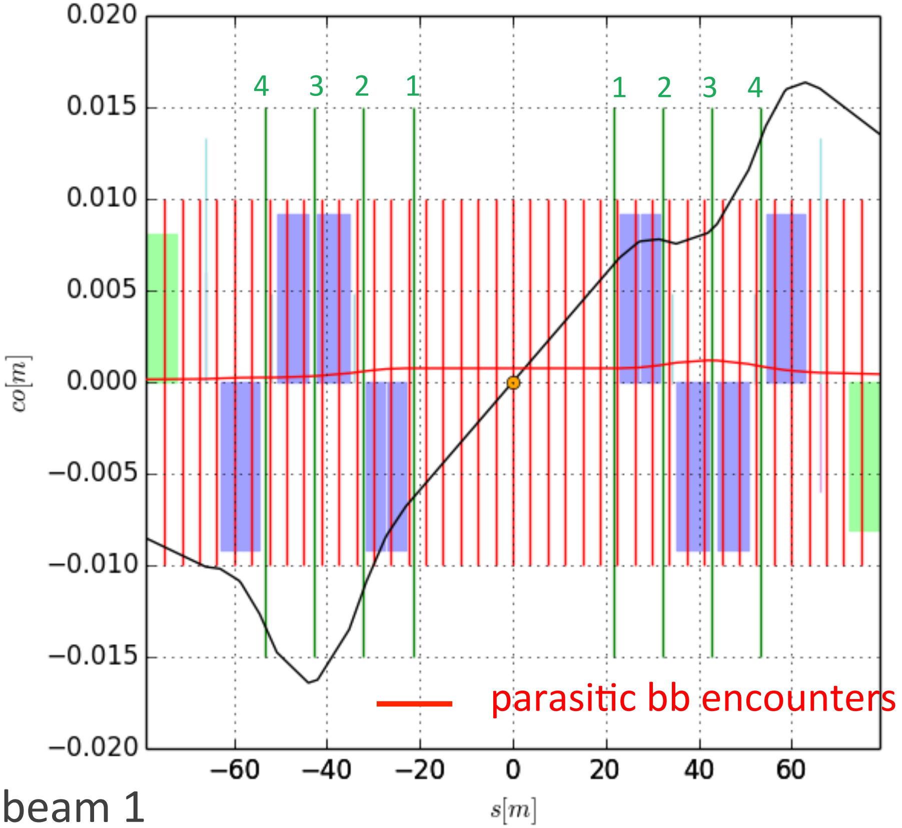
   case b) might be easier to control as IR1/5 stay unchanged (this case would be similar to the nominal LHC, assuming that the orbit at the entrance and exit of IR1/5 can be controlled sufficiently well)
2. orbit deviations (thinking in mm) due to **ground motion** are expected to be similar as for the 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**.
3. **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

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
- higher β-function -> stronger impedance effect

BPM candidates :

- BPM4 (parasitic bb encounter)
- BPM3 and BPM4 (maximum β-function along IT)

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”:

- **Precision:** quality of measurement given in terms of:
  - the **error** of a measurement, e.g. for a BPM measurement:

$$x_{\text{measured}} - x_{\text{true}} = \underset{\substack{\uparrow \\ \text{offset}}}{\Delta} + \underset{\substack{\uparrow \\ \text{scale error}}}{k x_{\text{true}}} + \underset{\substack{\uparrow \\ \text{role error}}}{\psi y_{\text{true}}} + \underset{\text{non-linearity}}{\sum_{k=2}^{\infty} \sum_{j \le k} \alpha_{kj} x_{\text{true}}^{k-j} y_{\text{true}}^{j}} + \underset{\text{noise}}{\epsilon}$$

  - **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

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).

Studies

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

Studies:

1) Correct orbit by using perfect model and perturbed BPM readings:
   - for precision needed to find collisions (at the beginning of the fill),
   - for precision needed to keep collision (during one fill).
2) Introduce perturbation in the model:
   - for finding the perturbation tolerances in order to keep the beams in collision.
3) Correct orbit by using perturbed model and perturbed BPM readings:
   - for max. allowed perturbations between fills to find collisions by using same settings ("golden orbit"),
   - for max allowed perturbation that does not increase the beam-beam separation without further correction during one fill.

Studies

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?

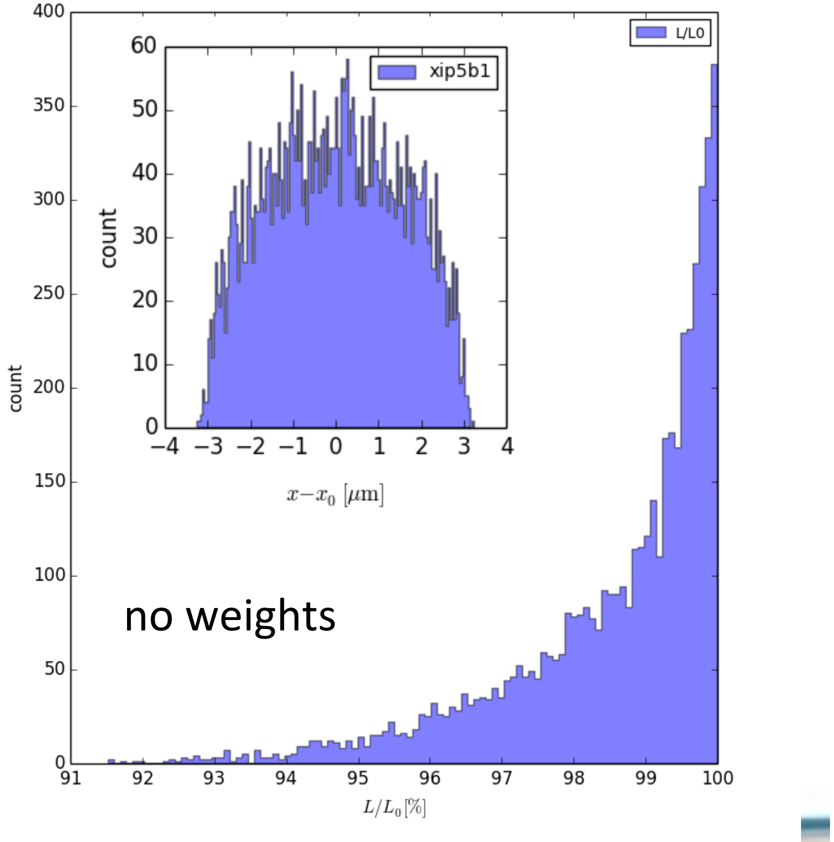
1. consider only orbit deviation in the arc and error on BPM matching constraints
   - ➢ required precision to find collisions from fill to fill
   - ➢ required precision to stay in collision
2. case 1. plus in addition transfer function errors of the IT and correctors
   - ➢ influence of a perturbed 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 1. 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

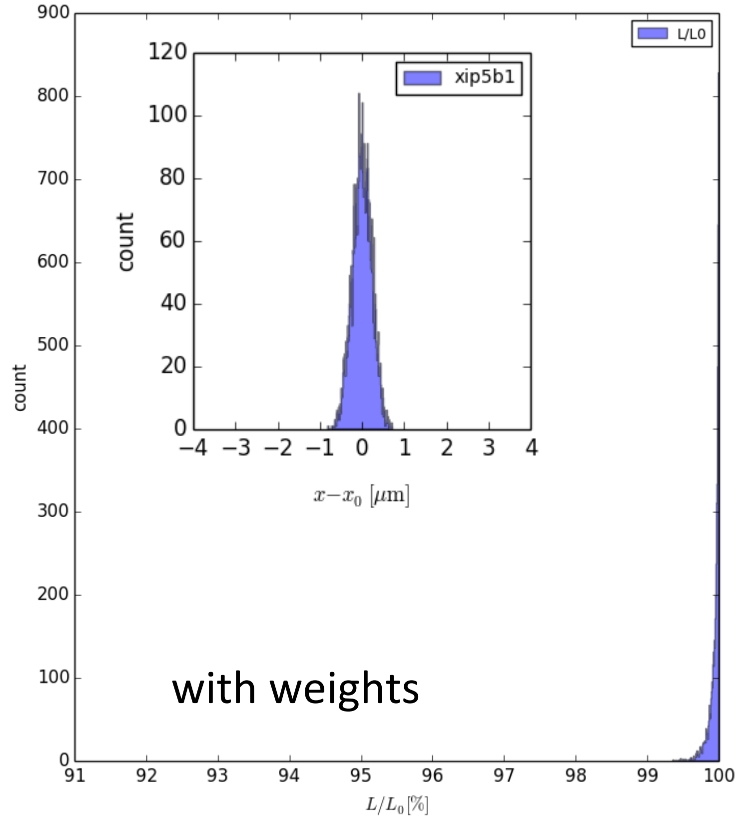
all simulations done for round optics (β*=0.15 m)

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
- act separately on beam 1 and beam 2
- “small” correctors (avoid using strong MCBX and D2/Q4 orb. corr.)
- increased **weight** of the orbit correctors between D1L and D1R (possible as orbit at crab cavities is always controlled well enough <0.01mm)


no weights


with weights

BPM precision

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

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

$\min(L/L_0)$ [%]	$\mathrm{rms}(L/L_0)$ [%]	$L/L_0(2\mathrm{rms}(z_{b1}-z_{b2})$ [%]
99.36	99.94	99.76

BPM precision needed from fill to fill (5% luminosity loss = 0.32 σ, 2 $\mathrm{rms}(z_{b1}-z_{b2})$):

$\text{precision}_{\text{fill to fill}}$ = +/-3.4 μm

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

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

Selecting the efficient BPMs

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

orbit at IP5 (x/y)	max(|z-z0|) [µm]	rms(z-z0) [µm]	2rms(z-z0)/σ_z
all BPMs	1.14/1.12	0.33/0.33	0.092/0.094
no BPM1	1.41/1.44	0.40/0.41	0.113/0.115
no BPM2	1.55/1.38	0.38/0.39	0.108/0.111
no BPM3	1.48/1.48	0.37/0.38	0.106/0.106
no BPM4	1.43/1.25	0.35/ 0.35	0.100/0.100
no BPM5	1.14/1.19	0.33/0.34	0.093/0.095

↓ efficiency decreases

Selecting the efficient BPMs

orbit at IP5 (x/y)	max(|z-z0|) [µm]	rms(z-z0) [µm]	2rms(z-z0)/σ_z	
all BPMs	1.14/1.12	0.33/0.33	0.092/0.094	
no BPM3/4	1.49/1.47	0.41/0.41	0.117/0.116	only BPMs closest to IP (BPM1/2)
no BPM3/5	1.48/1.35	0.38/0.38	0.106/0.107	
no BPM4/5	1.40/1.25	0.36/0.36	0.102/0.102	
no BPM3/4/5	1.47/1.44	0.42/0.41	0.117/0.117	
no BPM1/3/4	1.72/1.88	0.59/0.60	0.167/0.169	case of failure of BPM1 or BPM2
no BPM2/3/4	1.80/1.76	0.58/0.58	0.162/0.163	
no BPM1/3/4/5	1.72/1.81	0.61/0.62	0.172/0.172	
no BPM2/3/4/5	1.84/1.76	0.58/0.58	0.163/0.163	
no BPM1/2	2.09/1.98	0.52/0.54	0.147/0.152	case of failure of BPMs closest to the IP (BPM1/2)
no BPM1/2/3/4	35.88/36.01	11.73/11.61	3.309/3.276	

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 considerably less efficient

Influence of errors – long. misalignment

due to large divergence in triplet region the x-scheme could be sensitive to already small **longitudinal misalignments of the BPMs**

orbit at IP5 (x/y)	ds(BPM) [mm]	max(|z-z0|) [µm]	rms(z-z0) [µm]	2rms(z-z0)/σ_z
all BPMs	0	1.14/1.12	0.33/0.33	0.092/0.094
all BPMs	1.0	1.34/1.30	0.35/0.33	0.097/0.092
all BPMs	10.0	4.43/1.30	1.29/0.33	0.363/0.092

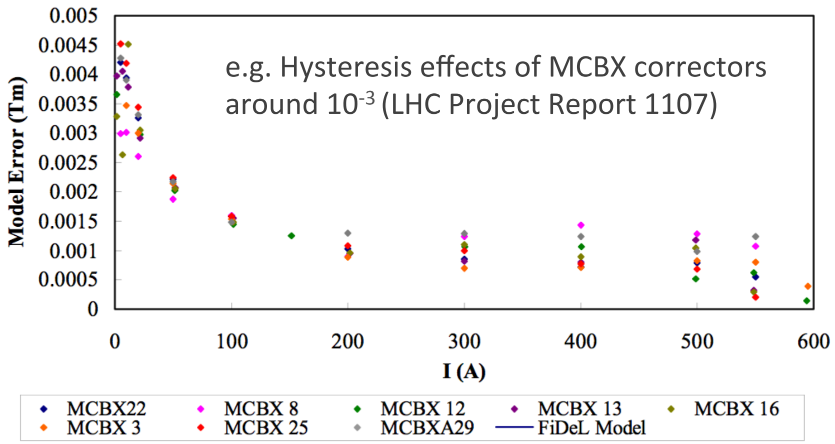
Main conclusion:
BPM should be longitudinally aligned or known in 1-2 mm range.

Influence of errors – transfer function errors

influence of transfer function errors of the IT and correctors

Note: only transfer function errors for correctors not used for the matching (explicitly orb. correctors at Q4, D2 and IT), (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 (x/y)	k_{err} [10^{-4}]	acb* [10^{-4}]	max(|z-z0|) [µm]	rms(z-z0) [µm]	2rms(z-z0)/σ_z
all BPMs	0	0	1.14/1.12	0.33/0.33	0.092/0.094
all BPMs	1.0	0	1.67/1.19	0.42/0.32	0.117/0.092
all BPMs	0	1.0	1.18/1.21	0.33/0.33	0.094/0.093
all BPMs	0	10.0	2.10/2.10	0.66/0.65	0.186/0.183
all BPMs	1.0	1.0	1.70/1.21	0.42/0.33	0.119/0.093



e.g. Hysteresis effects of MCBX correctors around 10^{-3} (LHC Project Report 1107)

Main conclusion:
Triplet transfer function errors starts to play a role from 10^{-4} unit, corrector transfer function errors should be well controlled within 10^{-4}.

Conclusion

- For the HL-LHC β*-leveling in IR1/5 is foreseen resulting in continuous optics changes.
- Frequent lumiscans are not affordable due to time and emittance losses in the process.
- Ideally triplet 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 needed to keep beam in collision, and a factor 10 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 known up to about a few mm;
    - ○ transfer function errors of the triplet and correctors up to 10^{-4} are acceptable.

Next steps

- introduce **more realistic BPM imperfection** models (input from BI needed);
- perform correction with perturbed model using the ideal response matrix as done in reality:
    - simulation setup as presented in this talk (treat IR1/5 as line), but using **the ideal response matrix f**or the SVD
    - obtain a **better model/understanding of the perturbations** in particular the misalignment (not easy and would involve rather extensive analysis of the available data and eventually building up of a new, more sophisticated model of the ground motion);
    - validate simulation setup by **reproducing LHC orbit** (also not straight forward due to not well enough known misalignment errors);
- 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.

Backup slides

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":

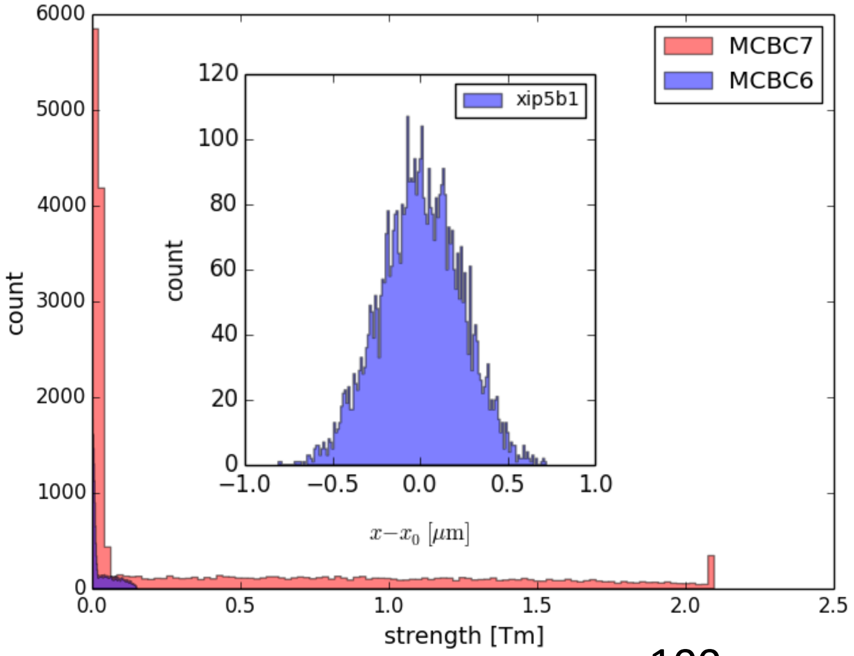
- **sensitivity:** change of the beam observable divided by the corresponding change of the primary observable
- **dynamic range**: range of values of the beam observable which can be measured with a given **precision** goal
- **Time dependence:**

  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)

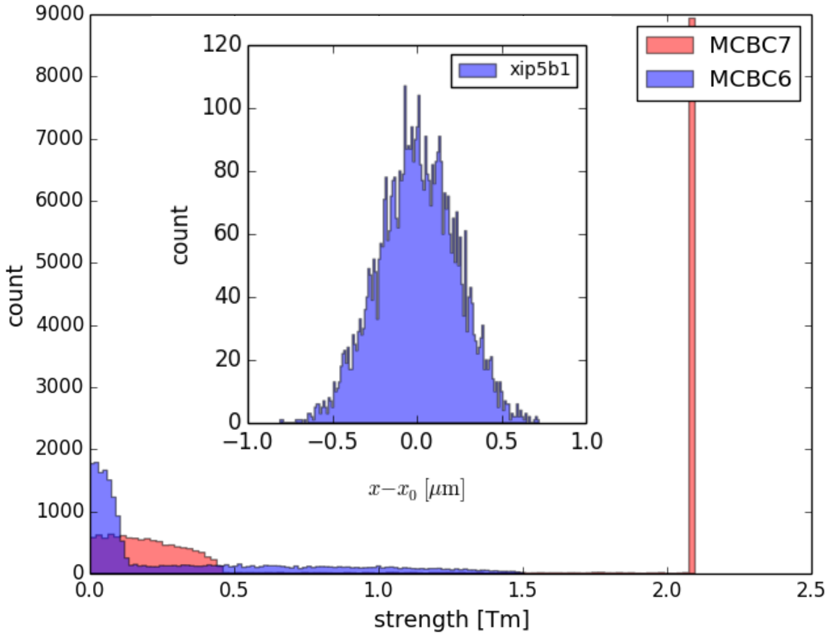
  reproducibility: closeness of the agreement between the results of successive measurements of the same measurand carried out under conditions which have been restored after a change (except time obviously) The systematic part of the reproducibility error is generally called the **drift**.

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



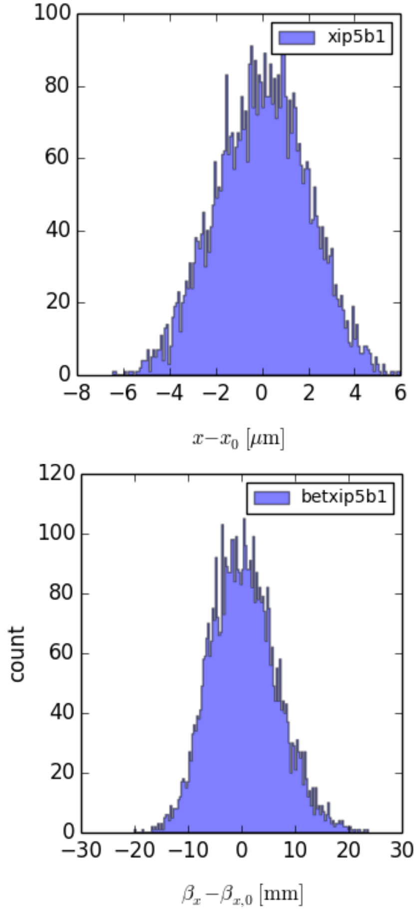
1 mm

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			

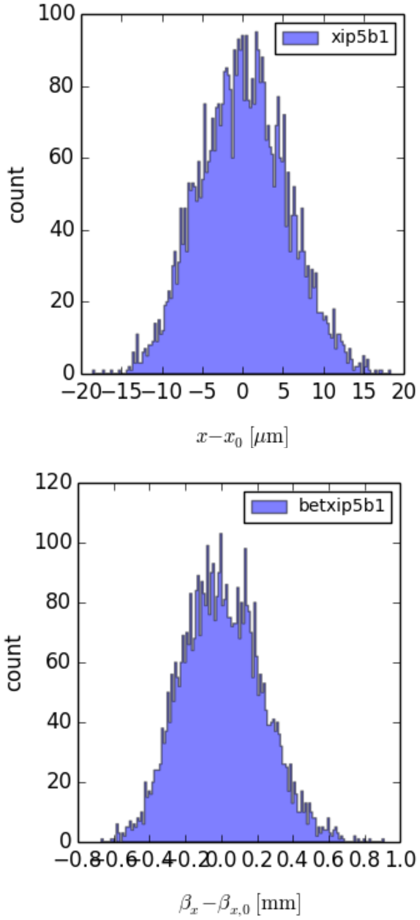
Influence of errors

influence of transfer function errors of the IT and correctors:

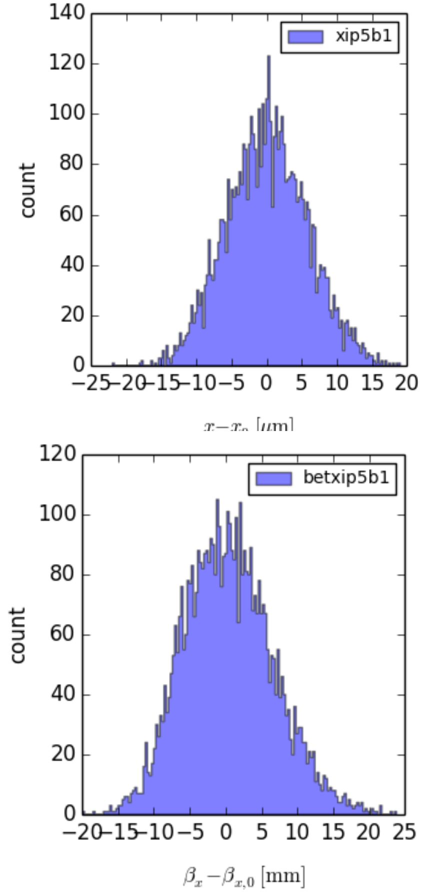
- no correction
- closed orbit of complete ring (no only IR1/5)



k$_{err}$=10^{-4}



acb=10^{-3}



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