LHC Optics corrections

T. Persson

on behalf of the OMC-team

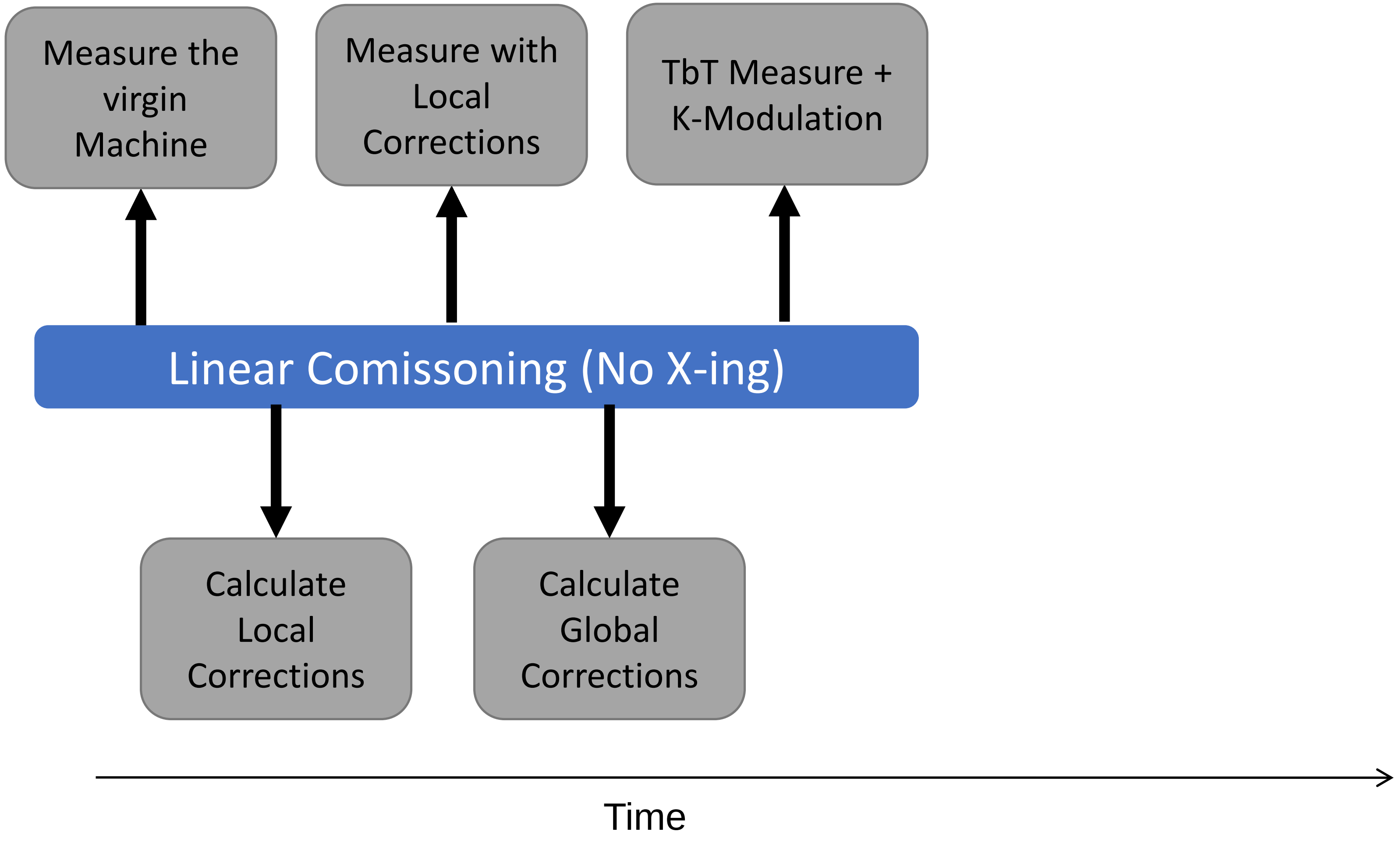
Why do we correct the optics in the LHC?

TO PROTECT THE MACHINE

TO PROVIDE THE DESIGN LUMINOSITY TO THE EXPERIMENTS

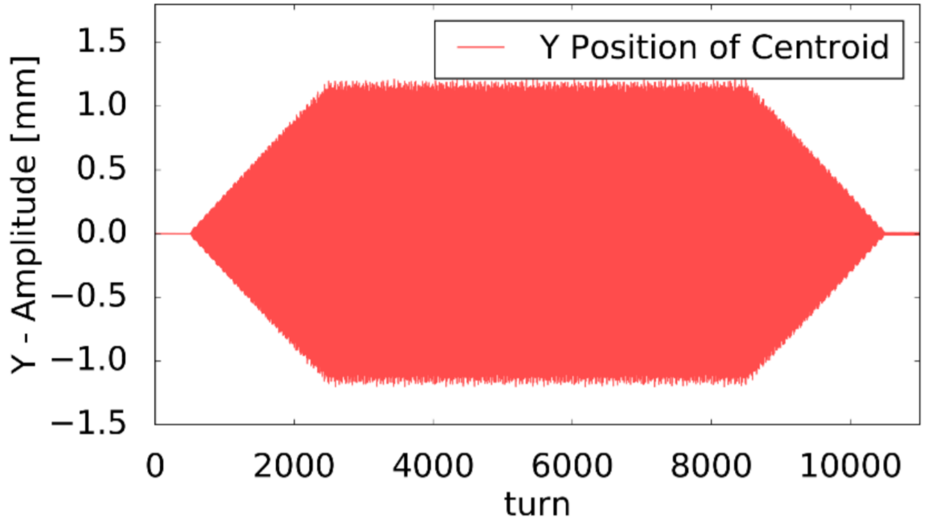
MITIGATE BEAM INSTABILITIES

Correction strategi the first years of comissioing (2010-2015)

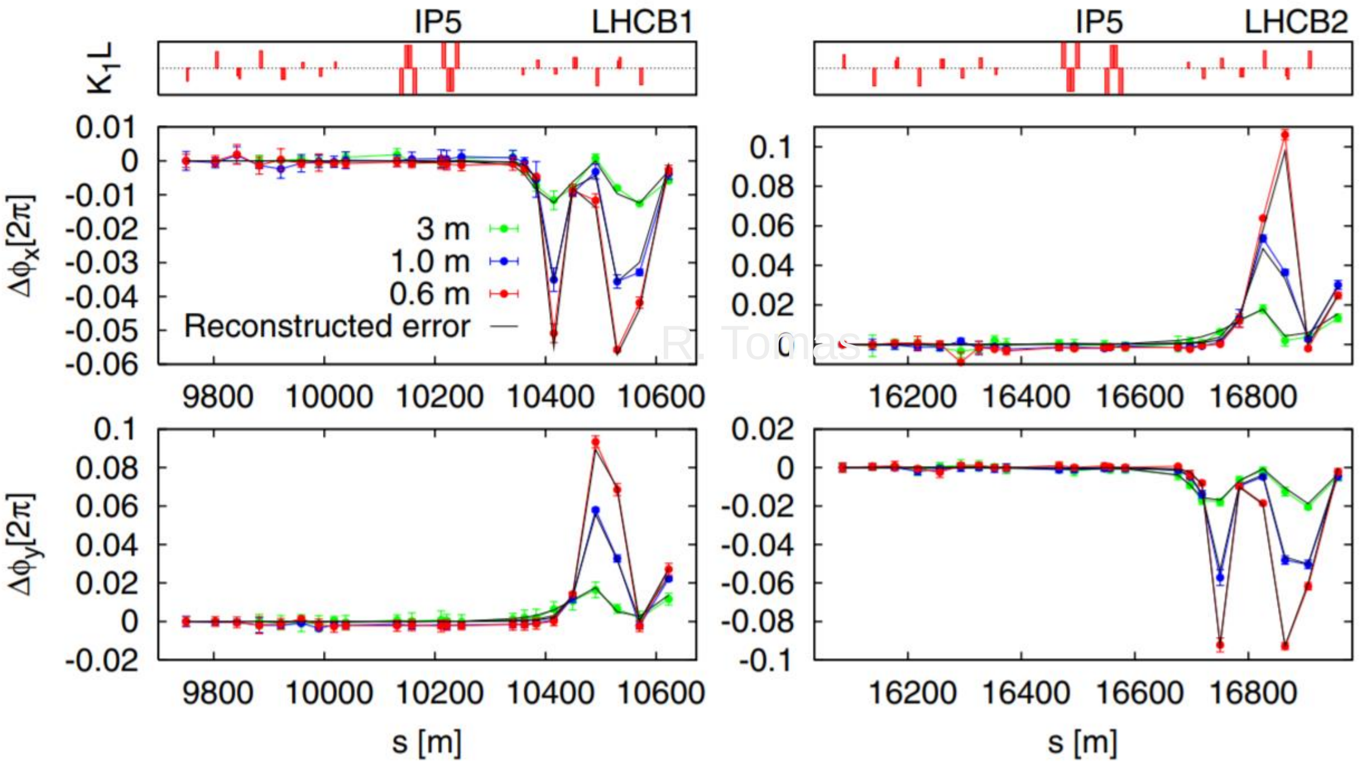


Turn-by-turn measurement

- The typical optics measurements are carried out with the AC-dipole
  - Adiabatic increase and decrease of the amplitude
  - 6600 turns (from 2015) at constant amplitude is recorded by around 500 available BPMs



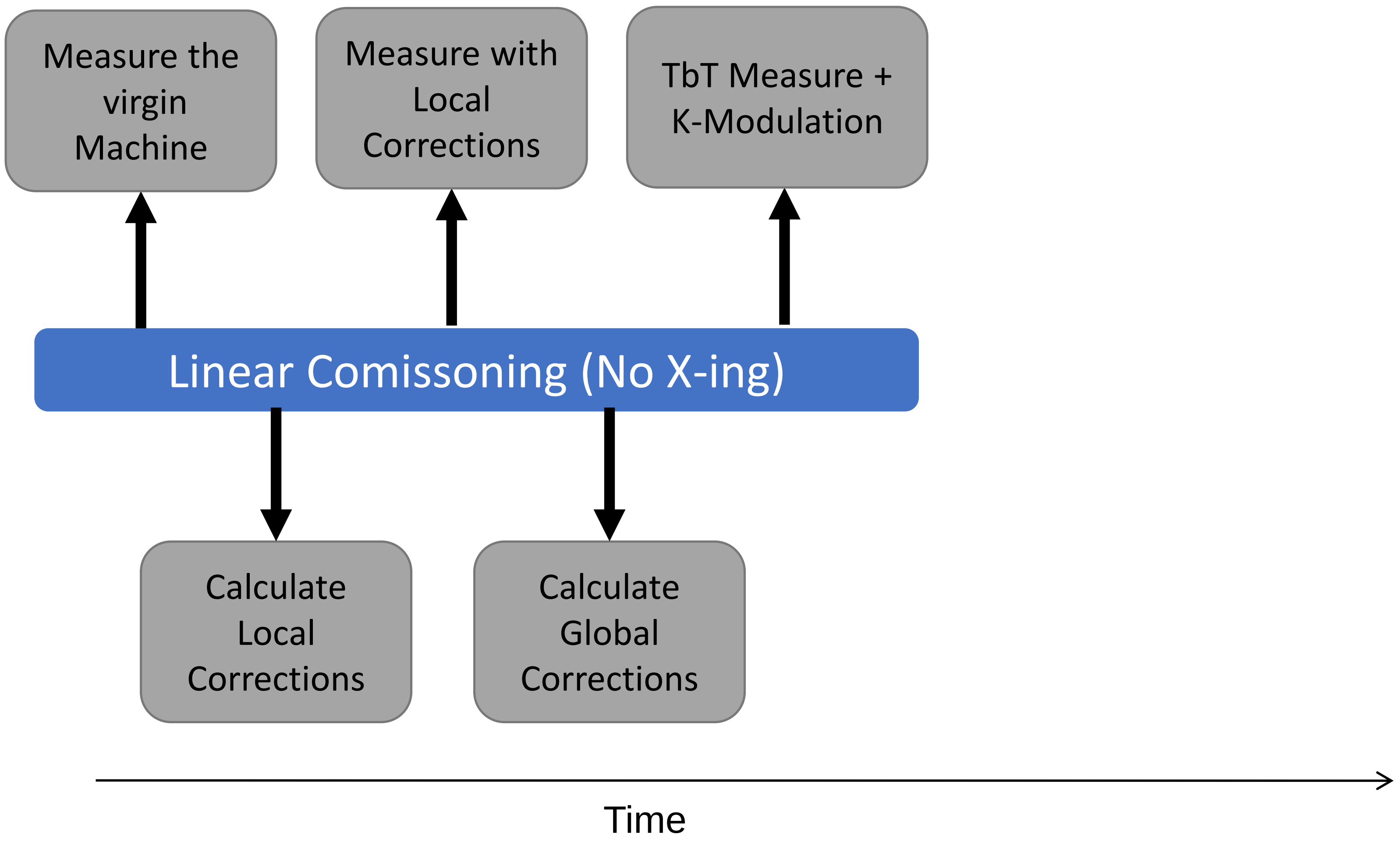
Local correction 2012



By adjusting the errors in the model it is possible to find an error that reproduce the measurement for different β* and the two beams

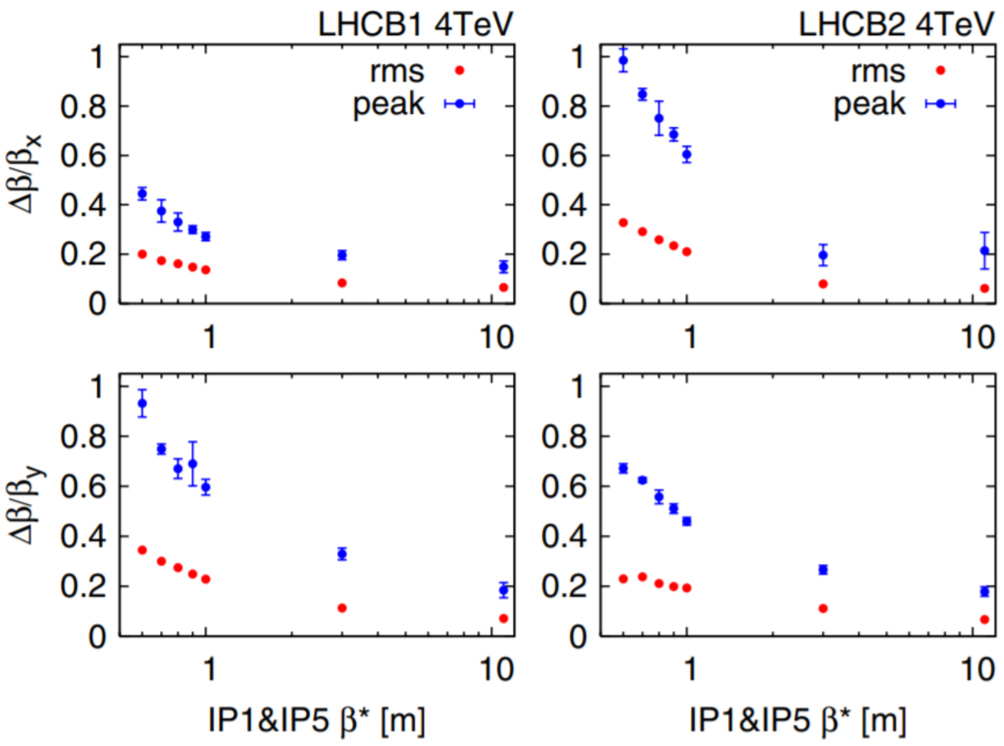
R. Tomas et al. "Record low beta beating in the LHC“

Correction strategi the first years of comissioing

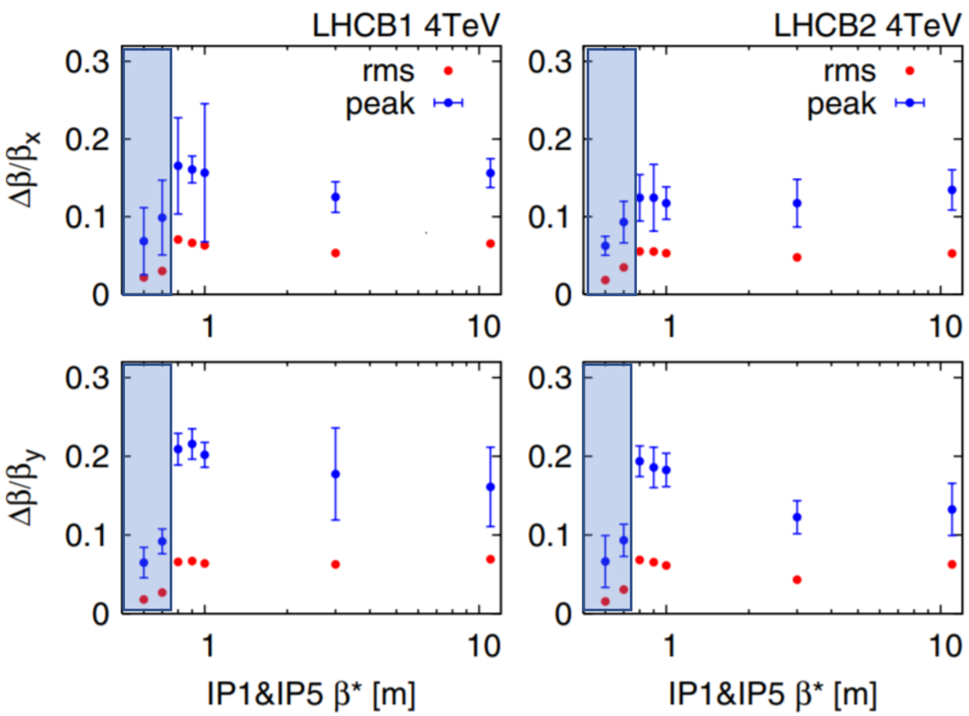


2012

<u>Before correction</u>



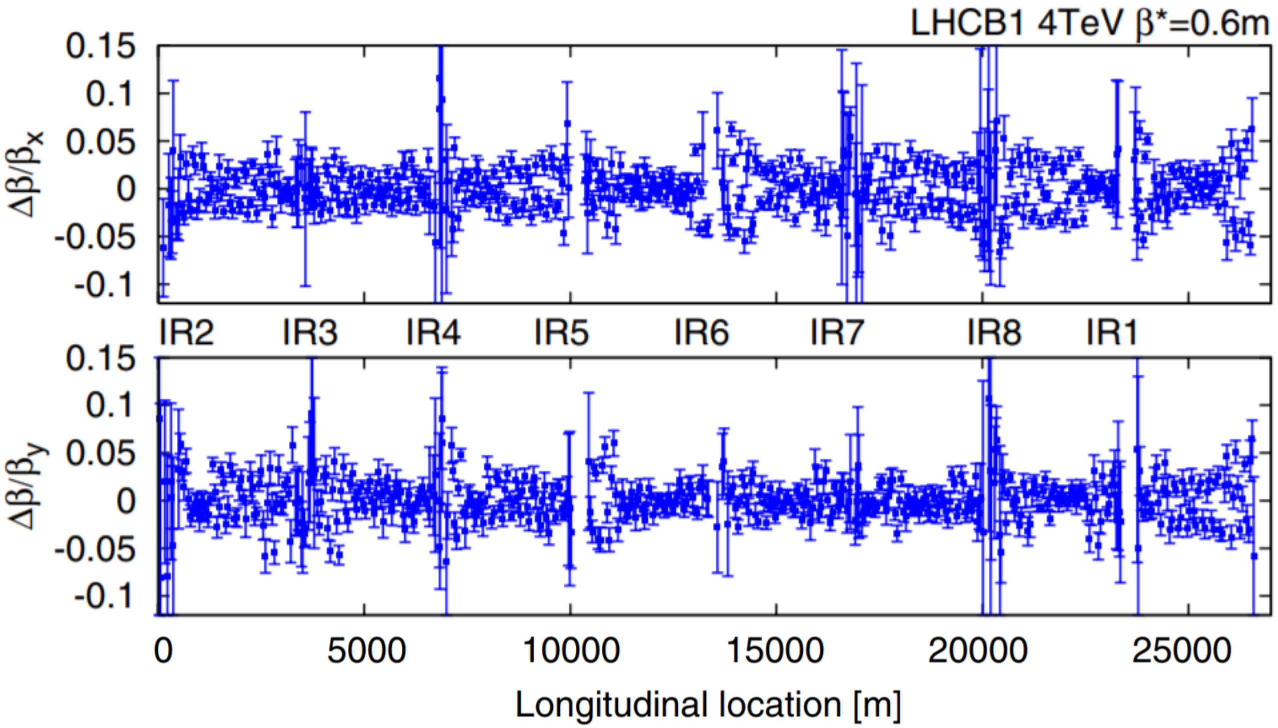
<u>After correction</u>



Global corrections in

[R. Tomas et al. "Record low beta beating in the LHC“]

β-beat in 2012



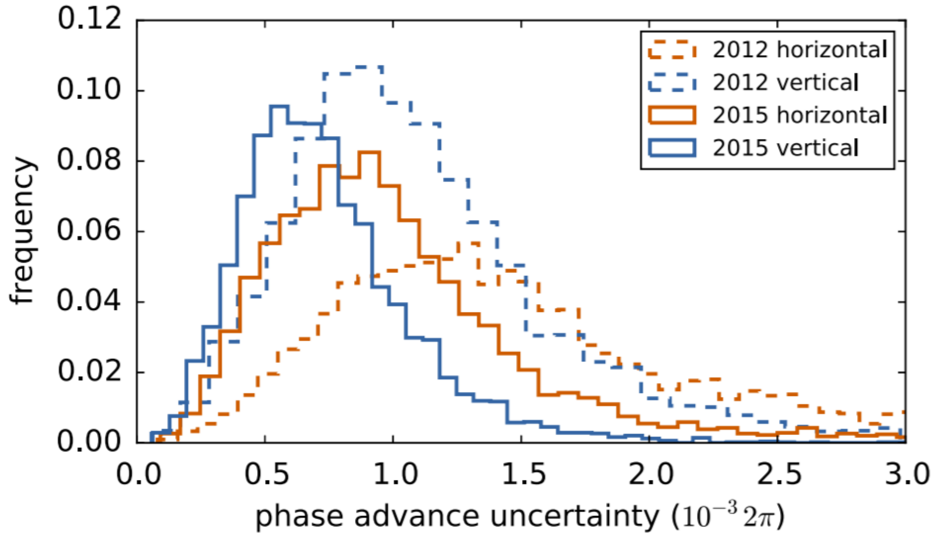
Already a very good control and well within the requirements for a safe machine!

However.. What was limiting us to reach even better corrections? And what are we trying to do now?

What was limiting (1)?

- Measurement noise
  - In 2012 we excited for 2200 turns and in 2015 6600 turns

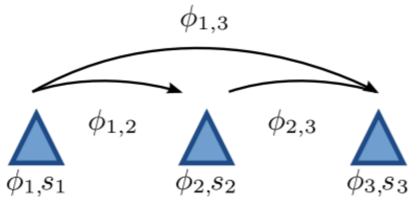
    -> Reduced the statistical noise
  - In 2022 we will be able to use 3 bunches which will further increase the statistics!

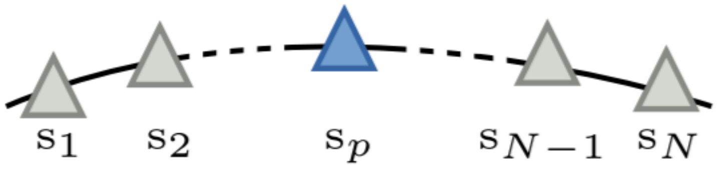


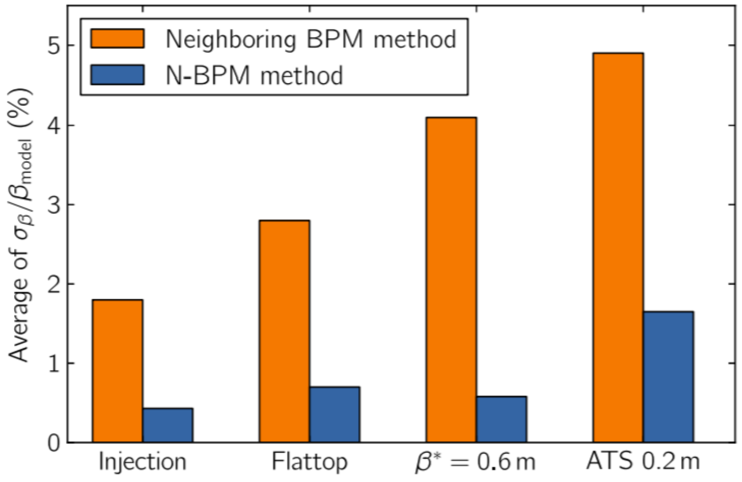
T. Persson et al. ,"LHC optics commissioning: A journey towards 1% optics control"

What was limiting (2) ?

- The β-functions were reconstructed from the phase advance using the 3-bpm Method
- The N-BPM method was developed
  - Based on more BPMs and different combinations
  - Reduce significantly the uncertainty on the β-functions
- Extended later with analytical error estimates
  - Significantly faster and better for pushed optics



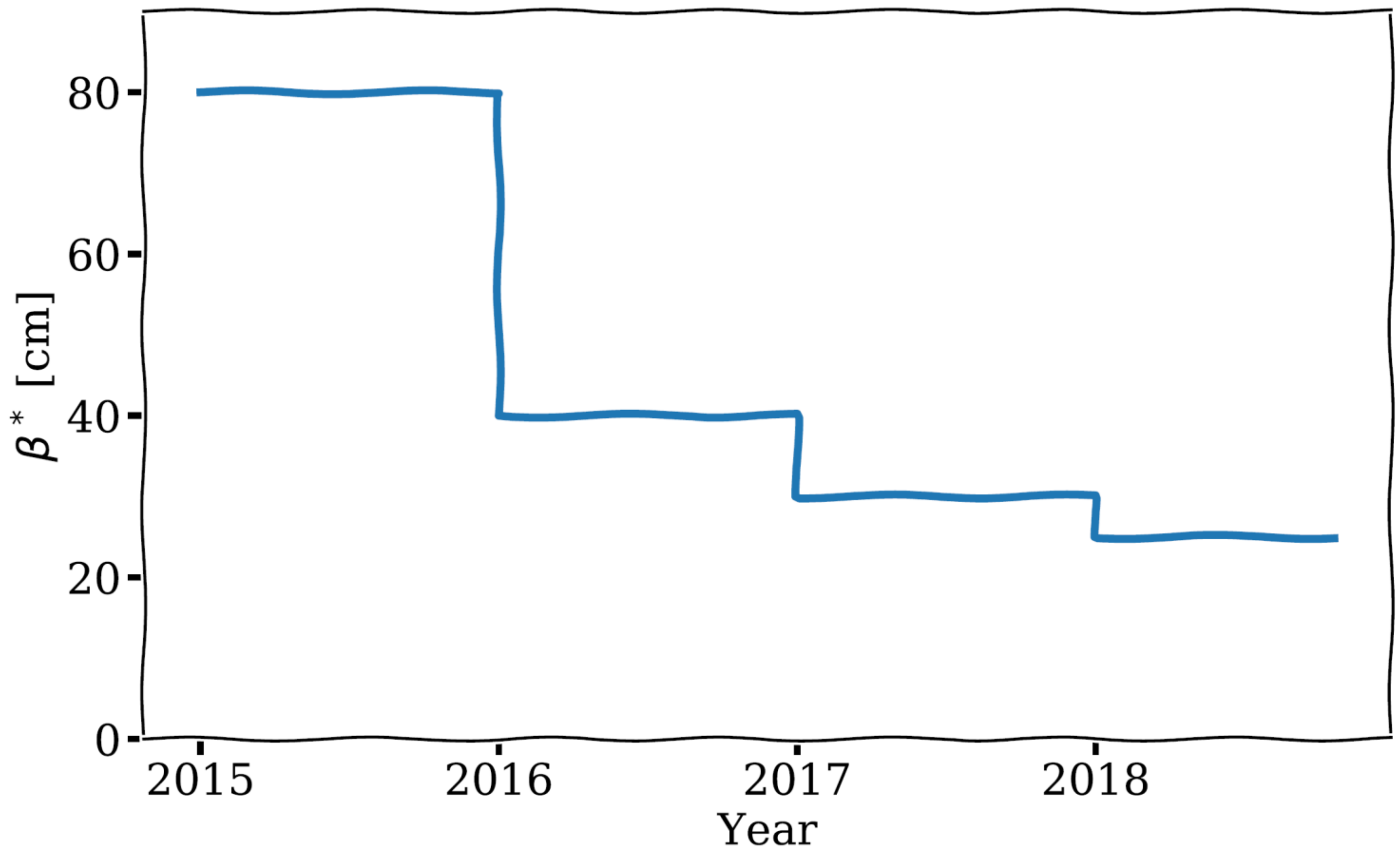




[A. Langner and R. Tomas, "Optics measurement algorithms and error analysis for the proton energy frontier"]

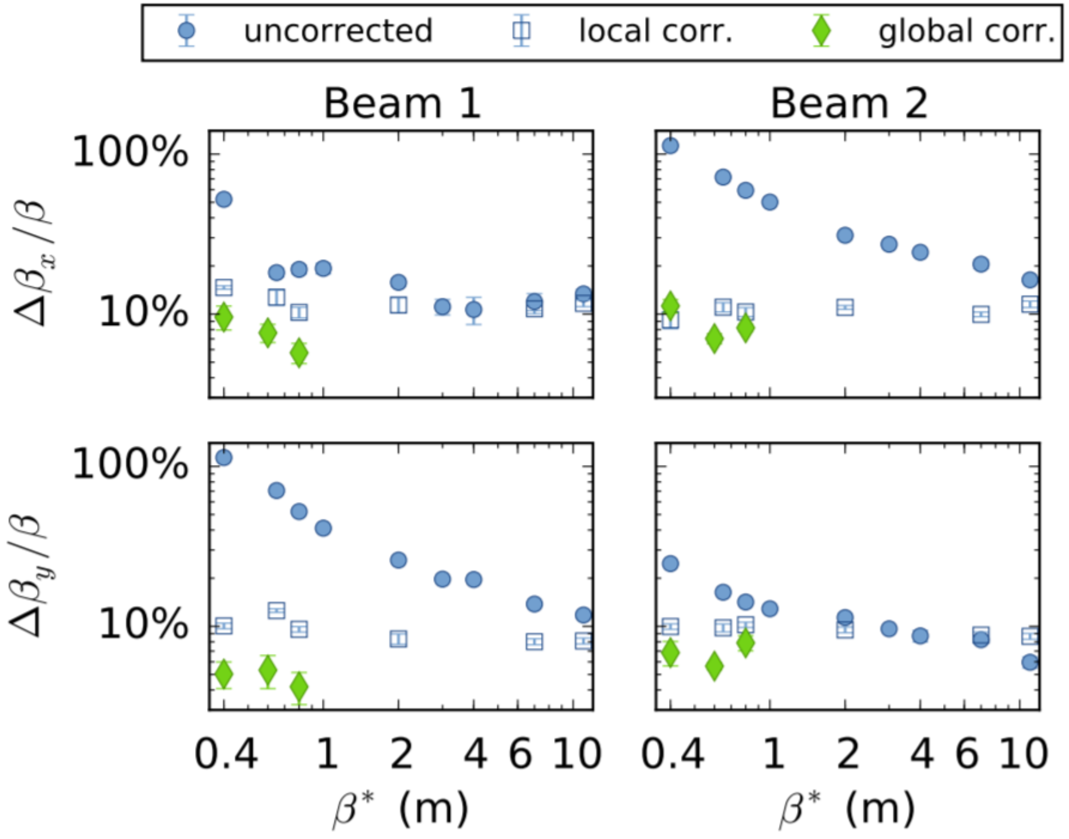
[A. Wegscheider et al, "Analytical N beam position monitor method"]

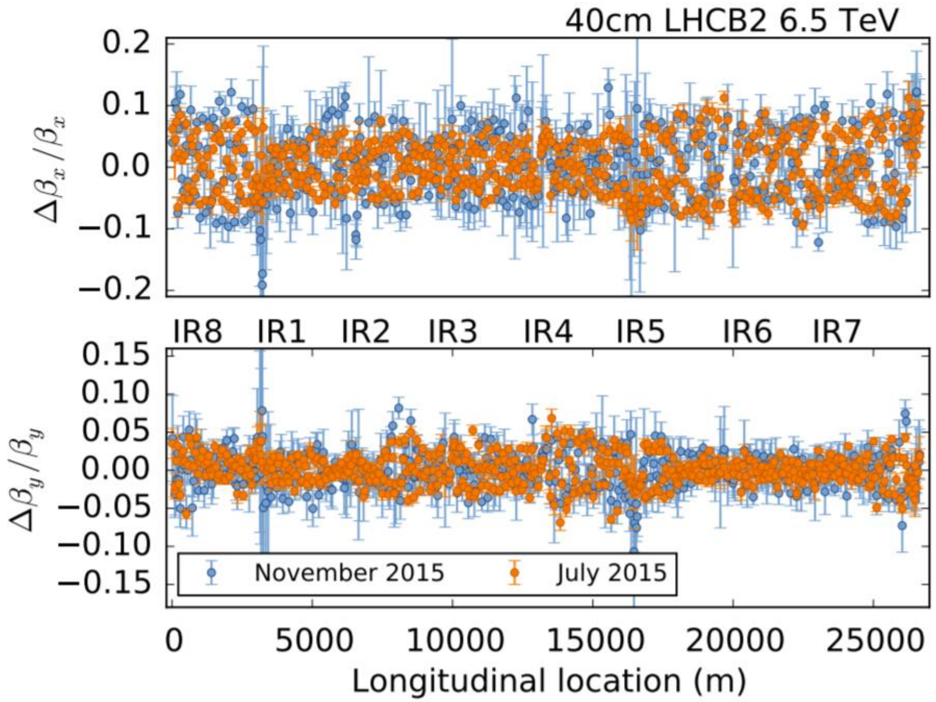
Operational β* in Run 2



The β* is used to label the optics and has been reduced every year from 2015-2018
Small β* at the IP requires high β-functions in the triplet and hence more sensitive to imperfections

β-beat in 2015





IP	Beam	β^*_x [cm]	β^*_y [cm]	w_x [cm]	w_y [cm]
1	1	88 ± 1	86 ± 1	25 ± 2	23 ± 1
1	2	82 ± 1	83 ± 1	18 ± 2	21 ± 1
5	1	86 ± 1	86 ± 5	22 ± 2	24 ± 9
5	2	87 ± 1	83 ± 2	24 ± 2	16 ± 5

How to improve the β* measurements?

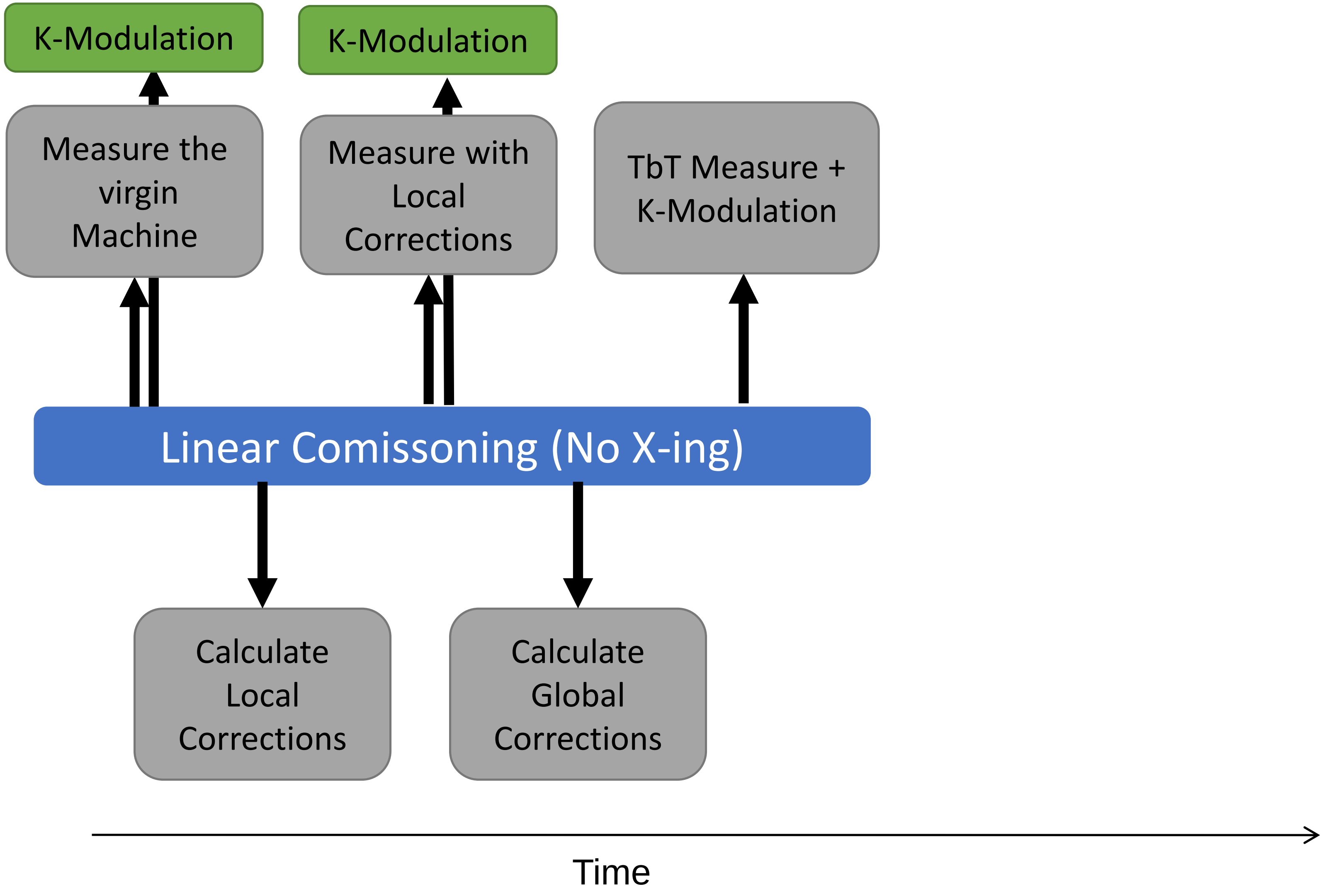
Problem:

Different local corrections can correct the phase error but still cause significant difference in the waist of the β-function

Solutions:

- K-modulation of the magnets closest to the IP and use this information to constrain the local corrections.
- Get precise β-functions from the amplitude of the oscillations

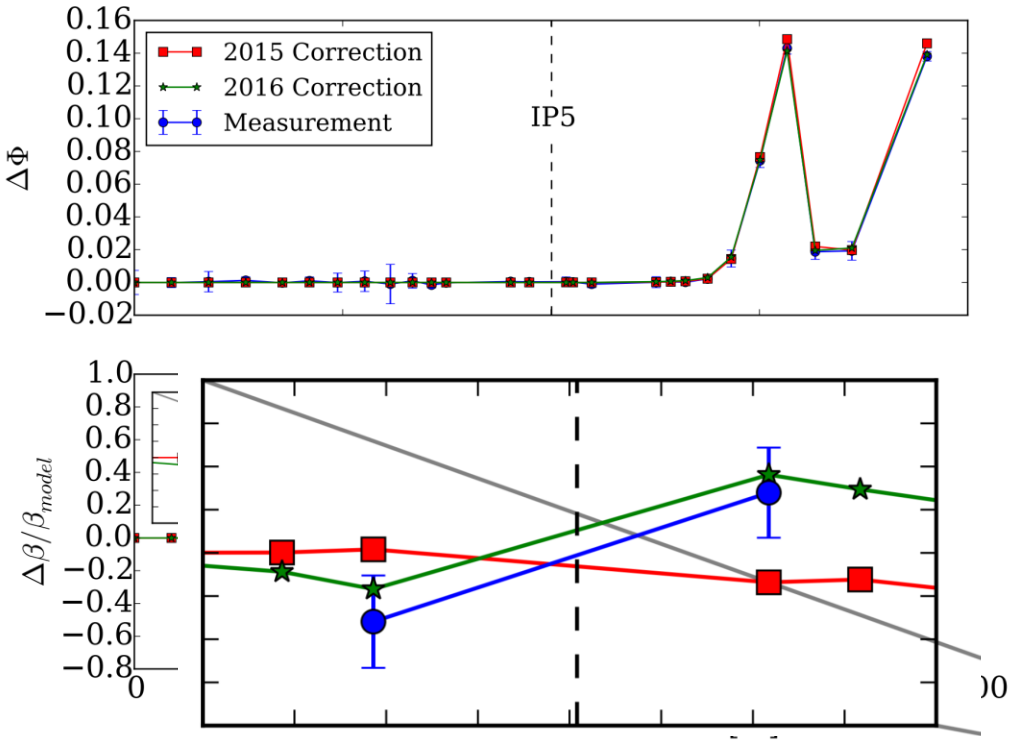
Commisiong strategy 2016

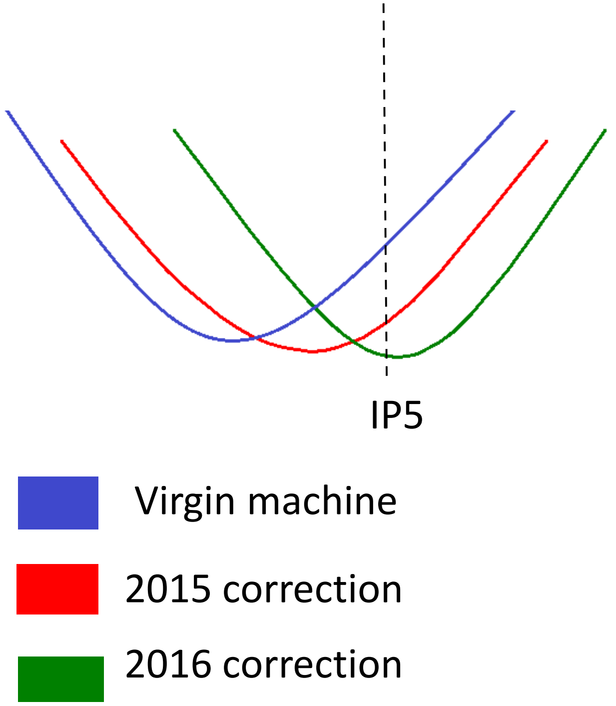


Local corrections

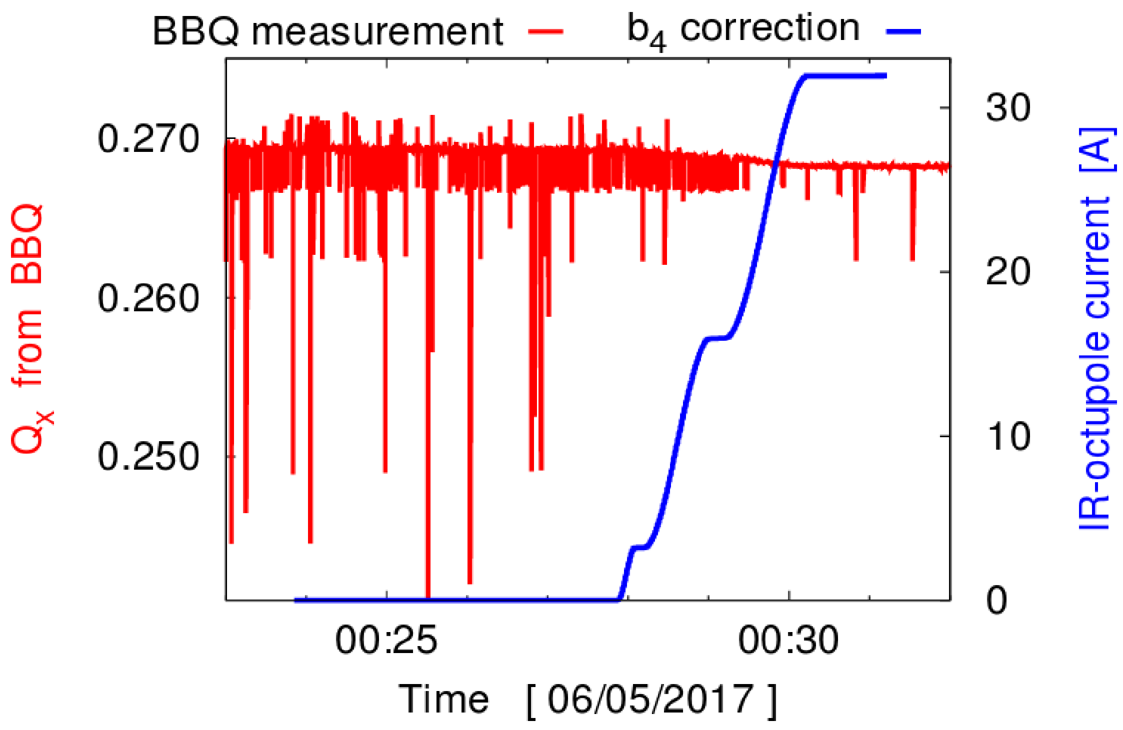
- The local phase corrections are degenerate. Possible to find several combinations that correct the phase

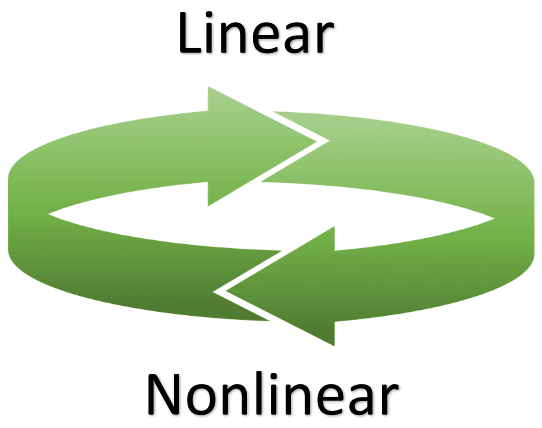
– No guarantee that the waist or β_{IP} is well corrected





Octupole IR correction (b_4)



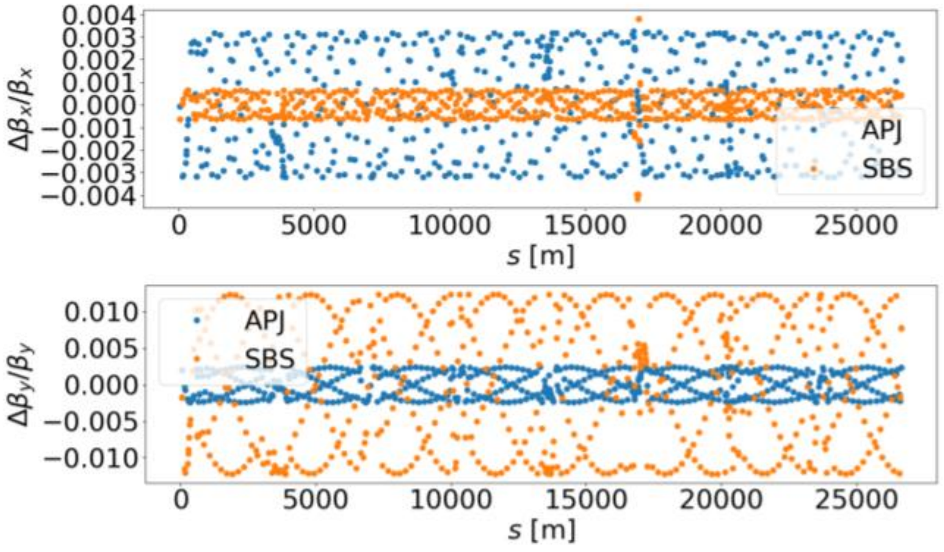


- Octupole correction based on amplitude detuning measurement in 2016
  - Improved the tune measurement from the BBQ
    - ➔ Improved K-modulation quality

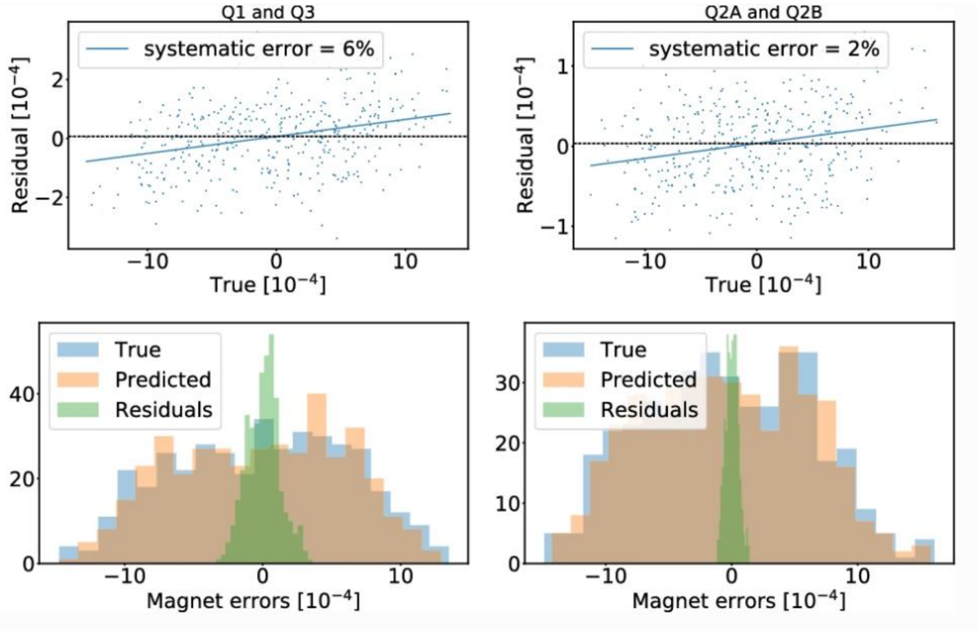
3 different methods to correct the local errors in 2022 and beyond

- Segment-by-Segment
- Machine learning
- Action-phase-jump

Action-phase-jump

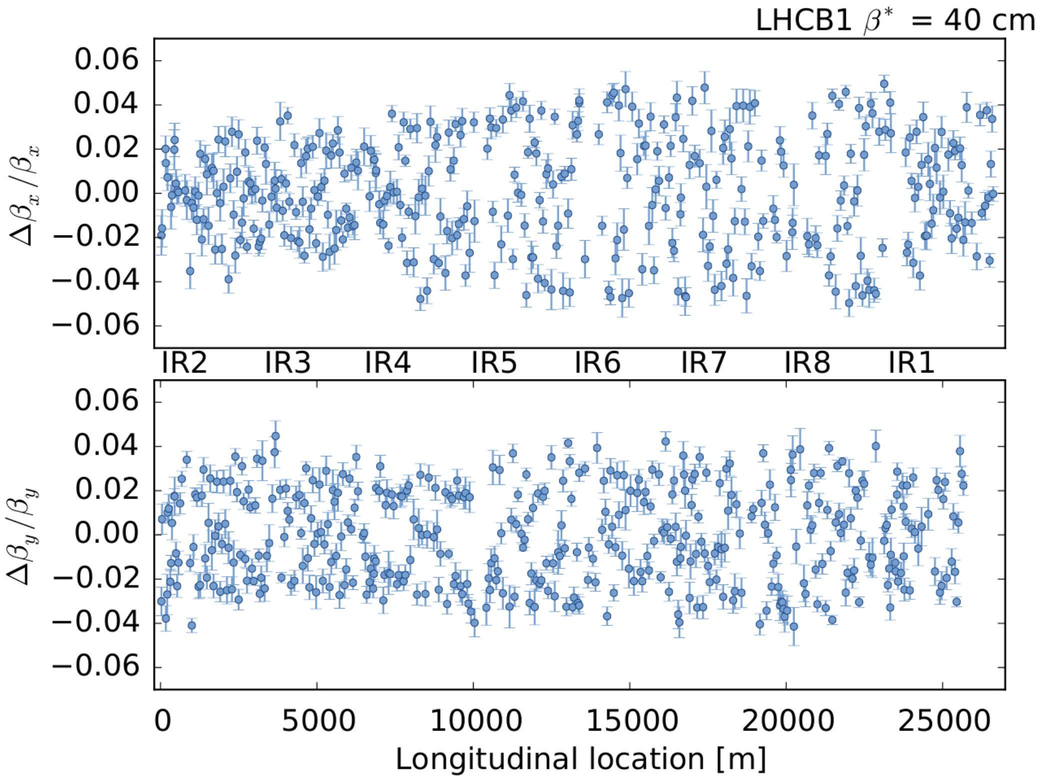


Machine learning

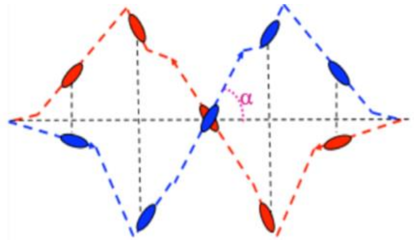


Effect of crossing angles

- Crossing angles are needed at the IRs so beams only collide at the IPs.
- Optics measured in June (commissioning without crossing angles in April)
    - **Difference between the two measurements shown in plot below**
- Consistent with simulation of the **IR sextupoles errors** + crossing angles

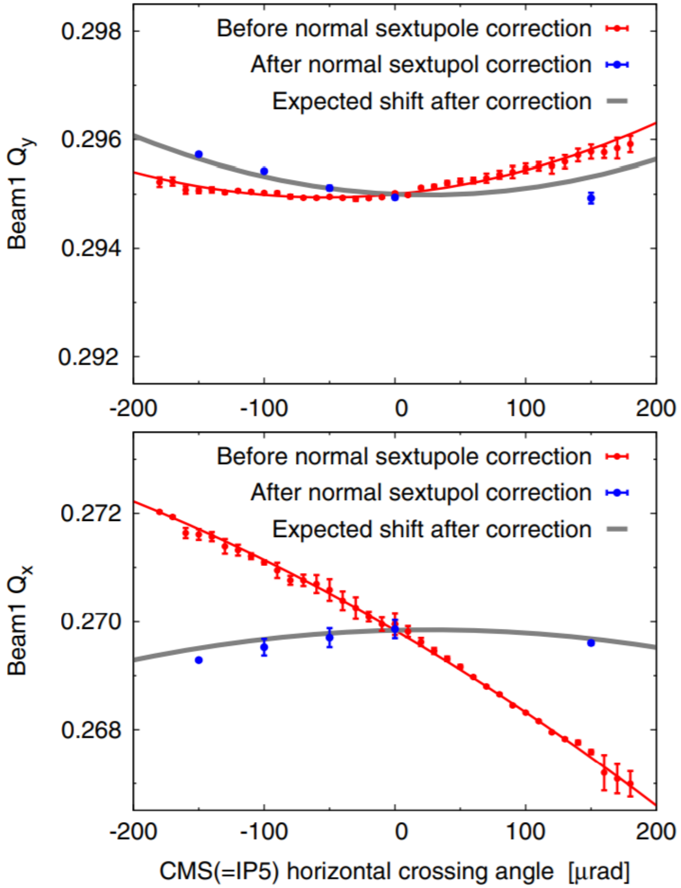


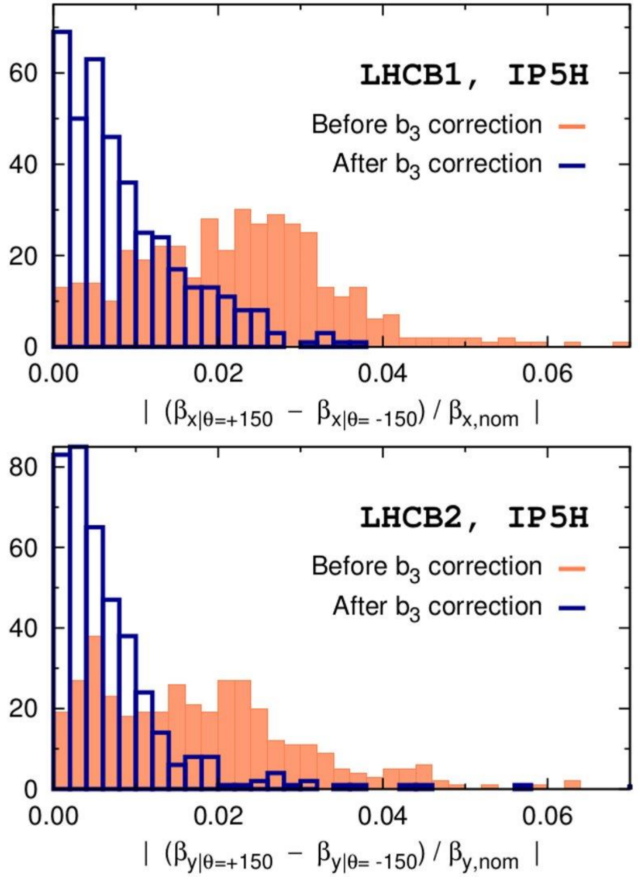
An increase of the peak β-beat in the order of ~**3%** due to crossing angles + **IR sextupole errors**



Sextupolar corrections in IR1 and IR5

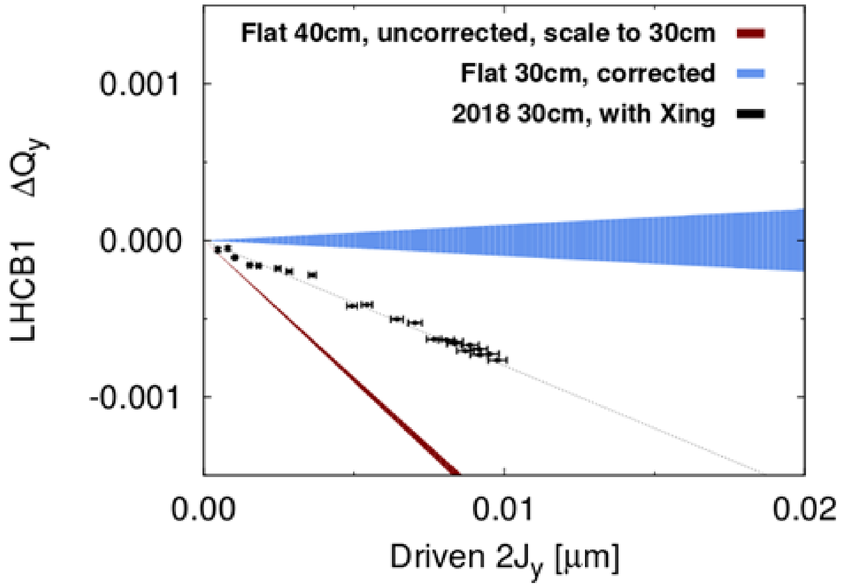
- The crossing angles in the IRs are changed and the feed-down tune and coupling is measured.
- Based on this the nonlinear corrections are calculated
- Important since we use the crossing angles to level the luminosity!

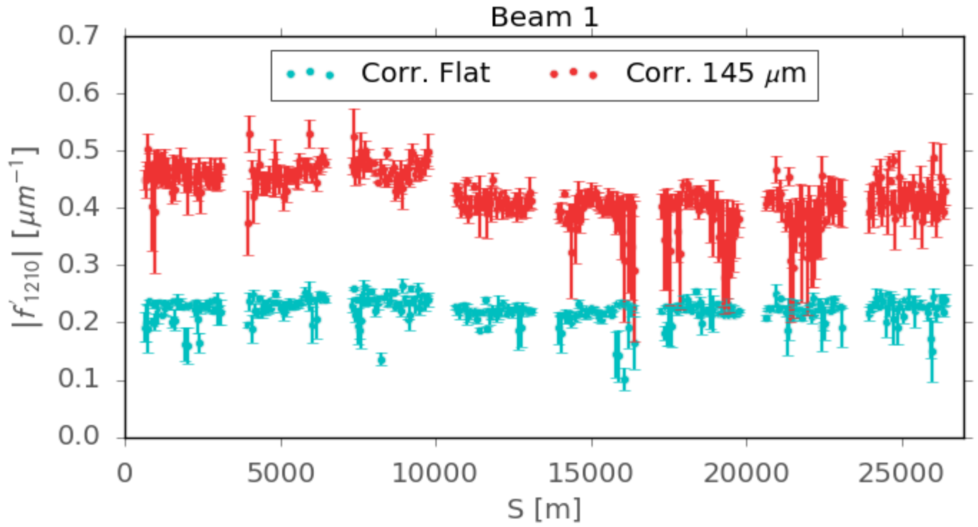




E. H. Maclean et al, "New approach to LHC optics commissioning for the nonlinear era"

Amplitude detuning with X'ing

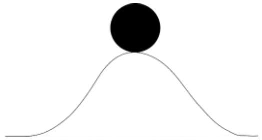




- The amplitude detuning and the RDTs from a_4 change with the x'ing angle

➔Feed down from decapole and/or dodecapoles!

- **Crucial to correct in HL-LHC:**
- We aim to get more experience in Run 3



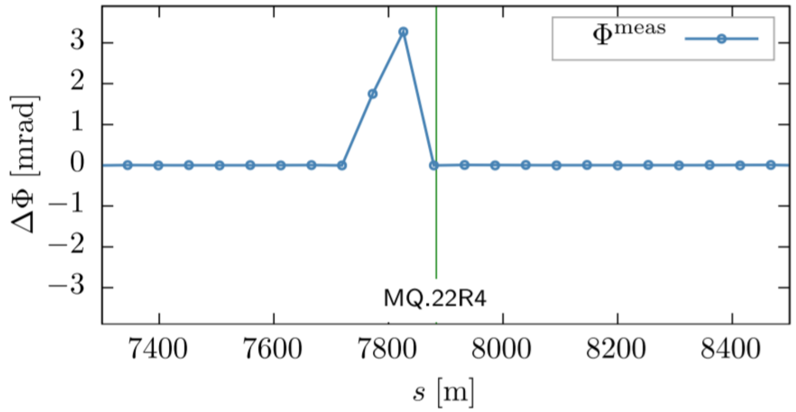
E. H. Maclean et al, "New approach to LHC optics commissioning for the nonlinear era"

F. Carlier

Additional measurement and reconstruction method to be used in 2022

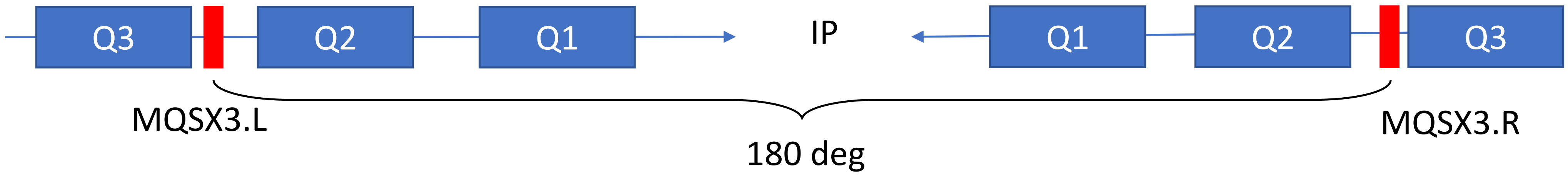
New local observable

- Phase advance between two elements does in general depend on all element in the machine
- Possible to construct a local observable for linear lattice imperfections
  - The effect of quadrupolar field errors up to first order
  - Only depends on the phase advance between 4 BPMs
  - Could help to better localise imperfections in the machine



A. Wegscheider et al, Local observable for linear lattice imperfections in circular accelerators

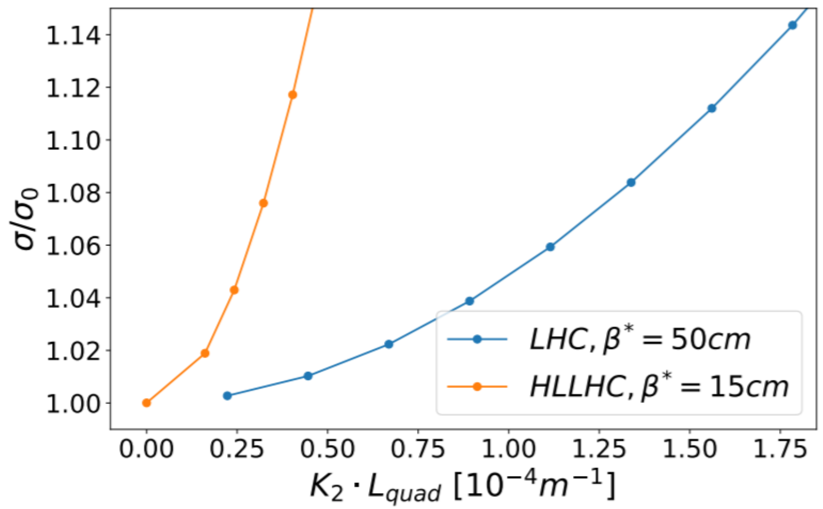
Local coupling



- Local coupling corrections has been part of the correction strategy since the start of the LHC.
  - They rely on the measurement of the f_{1001} and the f_{1010} and are corrected with two common skew quadrupoles, one on each side of every IP.
  - Creates an almost closed bump.
    - Increasing MQSX3.L and at the same time decrease MQSX3.R changes the coupling at the IP but almost undetectable outside
    - A knob doing exactly this re-balancing between right and left is called the collinearity knob
- A mistake in the implementation of the corrections in 2018 highlighted the importance of them
  - Reduced the luminosity with around 50%!

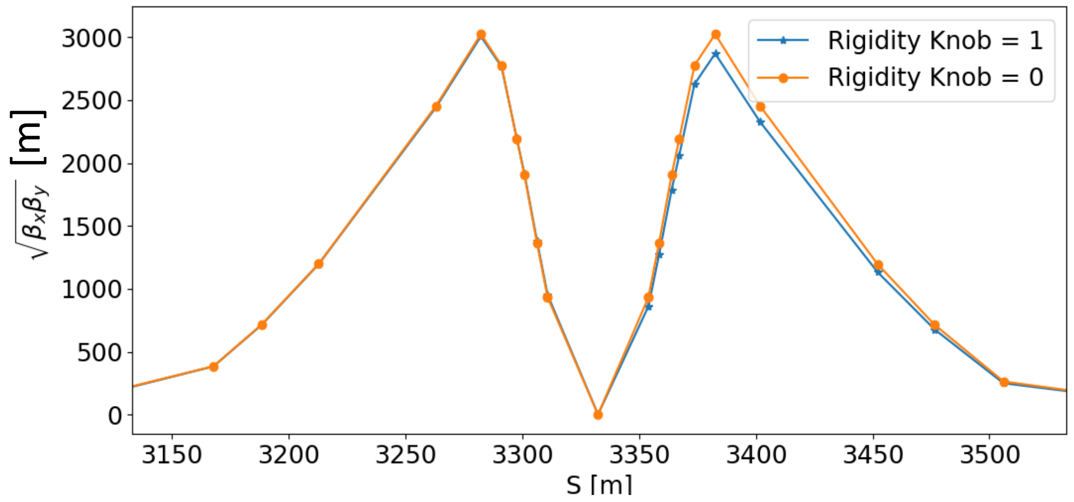
The impact of local coupling on beam-size

- Relative small errors in the local coupling can cause a large increase of beam size!
- So far we have been limited by how well we can measure the coupling RDTs
  - Challenging because of the phase advance in this region

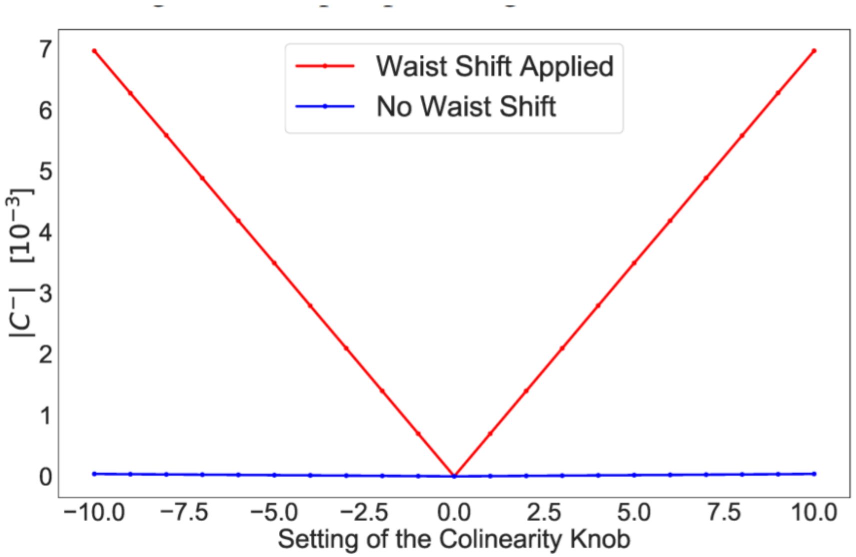


New method to measure the local coupling

- Principle of the rigid waist shift:
  - Unbalance the strength of the left and the right triplet
    - Breaks the left-right symmetry



- The colinearity knob gives no contribution to the global observable |C-|
  - After applying the rigidity knob there is a dependency

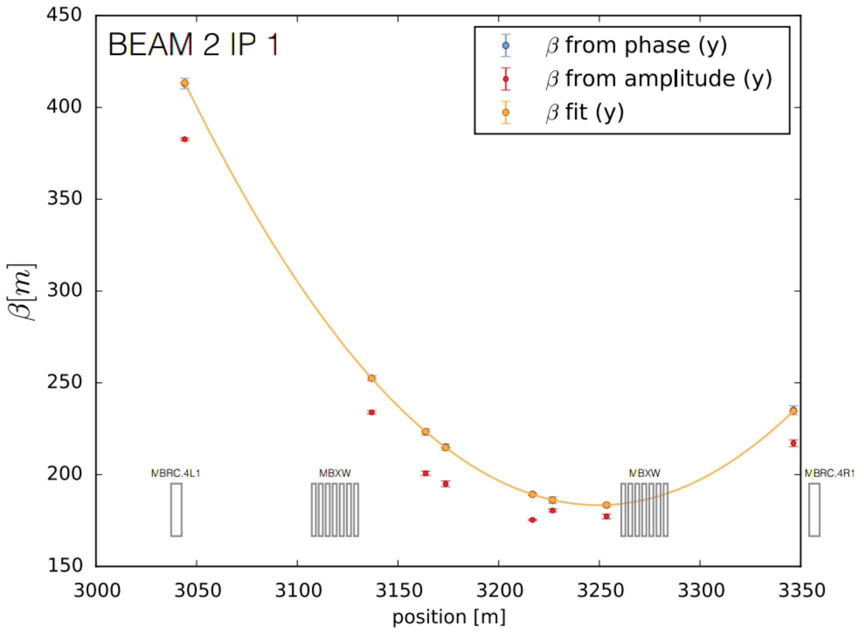


F. Soubelet et al, Prospect for Interaction Region Local Coupling Correction in Run 3

Optics to calibrate BPMs

Ballistic Optics

- Can reconstruct the β at a BPM and propagate it to the IP
  - Needs very precise calibration of the BPMs
- We can use the β reconstruction from phase to compare with what we get from β from amplitude, and then use this to calibrate BPMs relative to the arc BPMs
- Also ballistic for IR4
  - Turning off Q5 there which could help calibration of in instruments in that area



A. García-Tabarés Valdivieso

60 deg phase advance optics

- Would be a different optics with different settings
  - Helps in identifying underlying alignment and magnetic errors
  - In particular, the momentum compaction factor is different

Parameter [Unit]	60°LHC	90°LHC
β_{min}/β_{max} [m]	63/182	32/177
η_{min}/η_{max} [m]	2.5/4.1	1.1/2.2
Momentum Compaction [10^{-4}]	6.9	3.5
Transition Energy [GeV]	40.0	53.6
Natural Chromaticity at 450 GeV	- 60	- 83
Corrected Chromaticity at 450 GeV	2	2
Sextupole Strength at 450 GeV [Tm^{-2}]	56	142
Tune at Injection Optics (H,V)	45.28/44.31	62.28/60.31

J. Keintzel

Mom. Comp. Factor Measurements

- Fit of relative energy (momentum) offset over frequency
- Problem: no device in LHC to measure energy → Use TbT measurements

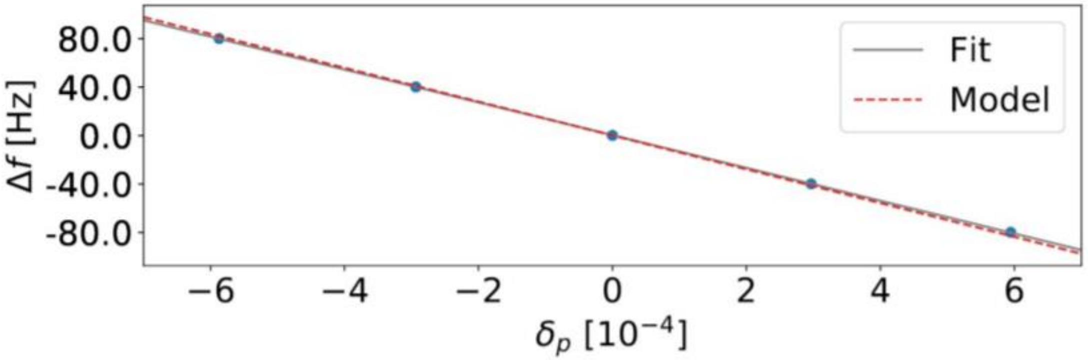
$$\delta_p = \frac{\langle \eta_x^{\mathrm{mdl}} CO_x \rangle}{\langle (\eta_x^{\mathrm{mdl}})^2 \rangle}$$

Measured closed orbit and model dispersion at arc BPMs

- Fit using

$$\delta_p = -\left(\frac{1}{\gamma_{\mathrm{rel}}^{-2} + \alpha_C} \right) \frac{\Delta f}{f}$$

E = 6.5 TeV and therefore the relativistic gamma is negligible



*Relative error between measurement and model about **-3 %***

Beam Position Monitor Errors

- Measured closed orbit used for momentum offset calculation

$$\delta_p = \frac{\langle \eta_x^{\mathrm{mdl}} CO_x \rangle}{\langle (\eta_x^{\mathrm{mdl}})^2 \rangle}$$

Measured closed orbit not necessary real orbit

$$CO_x^{\mathrm{meas}} = C \times CO_x^{\mathrm{real}}$$

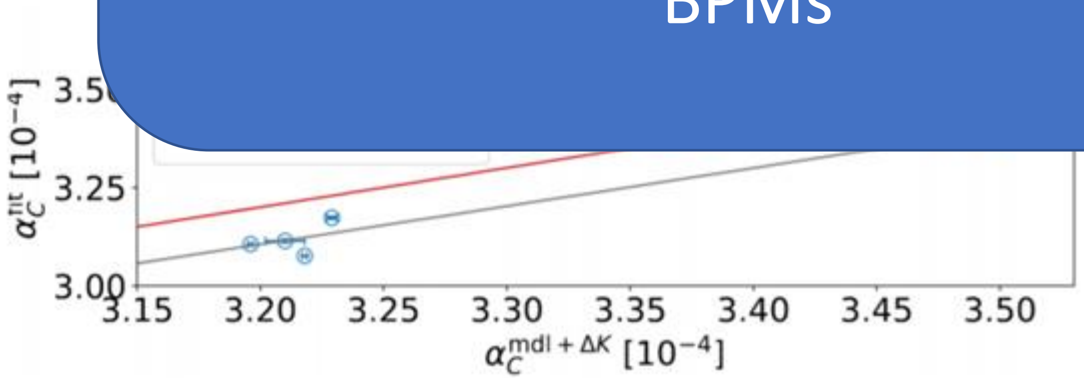
BPM calibration C can modify real orbit to measured one

- What would ca
- If average C_i o
- → δ_p^{meas} would
- → Slope of δ_p o
- → Momentum c

$x,i\rangle$

, 2020

Takeaway: Around 3% error tentatively attributed to the arc BPMs -> IR BPM calibration from ballistic optics are also off because the method uses the arc BPMs



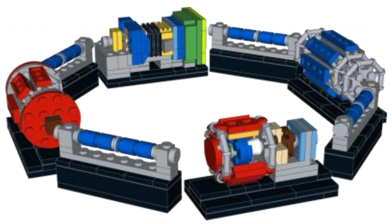
J. Keintzel

Summary

- We have overcome some limitation every year:
  - 2015: Reduced statstical errors and better reconstruction of the β-functions (N-BPM method)
    → Better corrections and reduced error bars
  - 2016: Include the results from K-modulation
    → Better control of the β*
  - 2017: Correct with X-ing + sextupolar and octupolar corrections
    → Improved control of the optics also with X-ing angles in the IPs
  - 2018: Use RDTs to correct skew octupolar error (a_4)
    → Demonstrated nonlinear corrections based on RDTs which will be important in the HL-LHC era

Future challenges

Challenges



Solutions

Challenges	Solutions
Measure β* < 0.2 m	• K-modulation • Luminosity waist shift scans • Machine learning techniques
Correct Local Coupling	• RDTs measurement • Triplet scaling • Luminosity scans
Correct Nonlinearities	• RDTs • Amplitude detuning • Feed-down measurements
Precise BPM calibration	• Ballistic optis • 60 deg phase advance optics

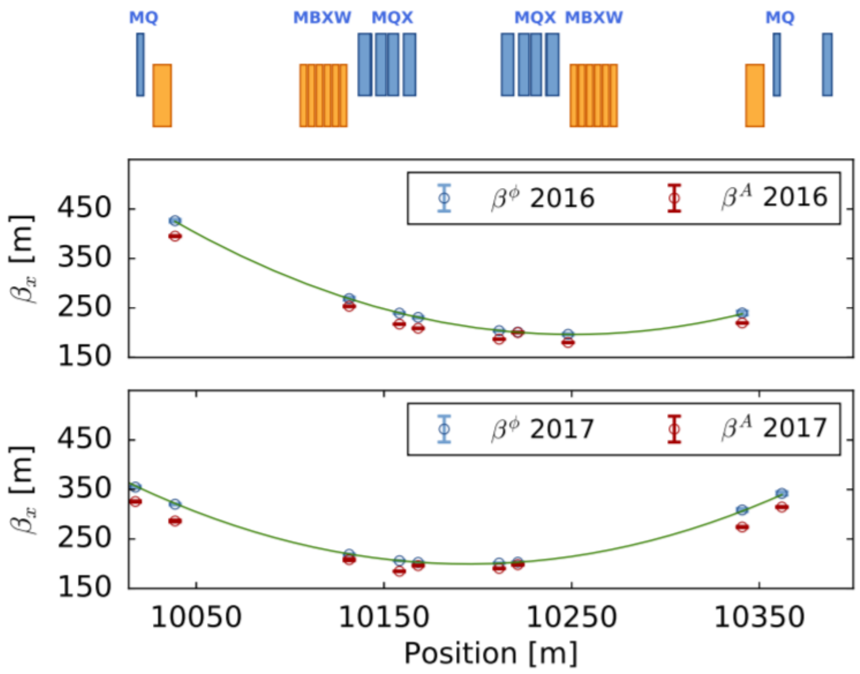
Thank you for listening!

Please, contact me or any of the team members for any questions you might have!

Backup

β from amplitude

- $A = \sqrt{2J\beta}$, where A is the amplitude of the oscillation, J the action
- If we measure the amplitude and the action then we can reconstruct the β-function at each BPM.
  - The BPMs need to be calibrated very precisely
- We can also reconstruct the β functions from the phase advance
  - Large uncertainties close to IR -> A dedicated calibration optics where the triplets were turned off



$$\beta(s) = \beta^* + \frac{(s-\omega)^2}{\beta^*}$$

A. García-Tabarés Valdivieso and R. Tomás, "Optics-measurement-based beam position monitor calibrations in the LHC insertion regions"

Scans with luminosity

- Nominal bunches colliding in IP1 and IP5
  - Scanning dedicated waist shifts knobs
  - Tested in MD, but time-consuming
    - -> Only planes and beams where we have suspicion something could be wrong
  - Scan the collinearity knob in IR1 and IR5 for validation of the local coupling corrections

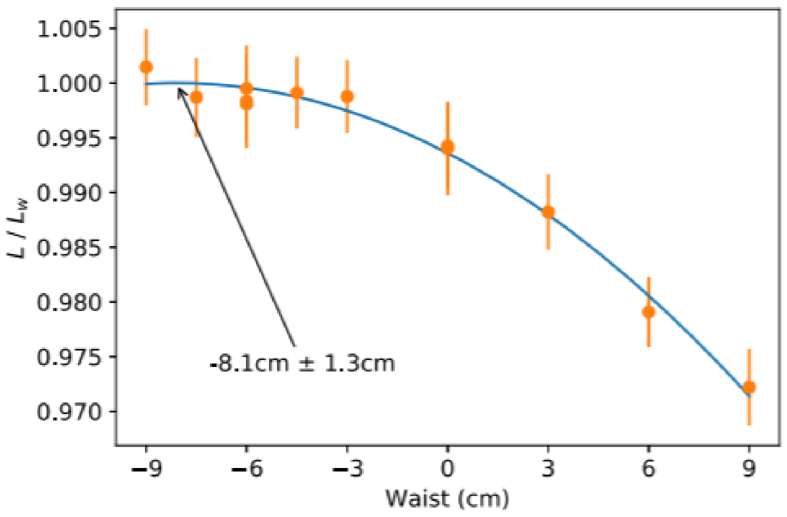


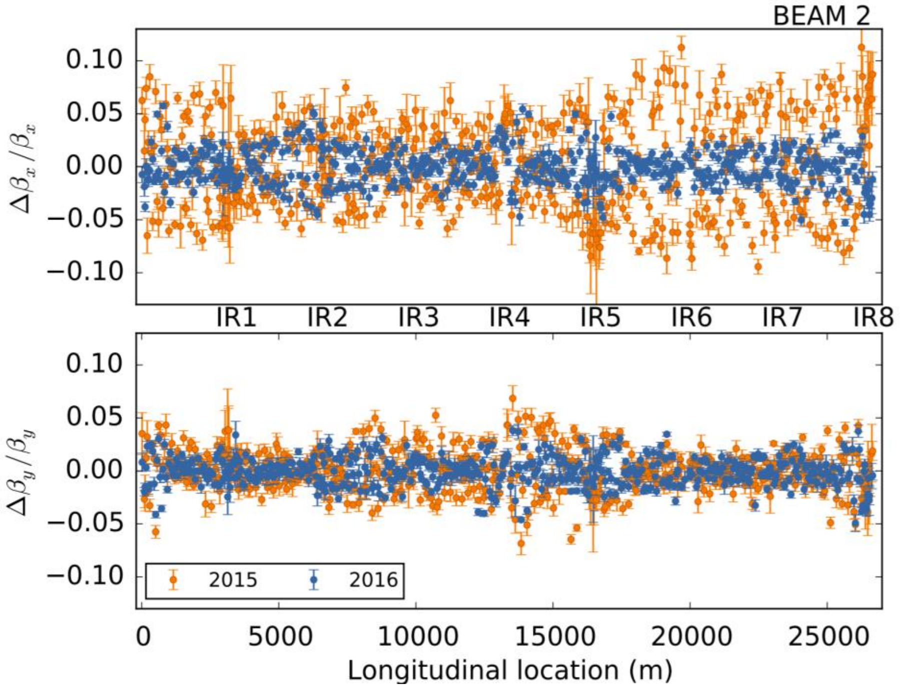
FIG. 14. Luminosity scan of Beam 1 on the vertical plane.

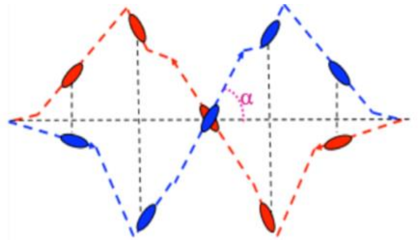
[J. Coello et al, ``New local optics measurements and correction techniques for the LHC and its luminosity upgrade'']

Final Corrections 2016

IP	β_{IP} [m]	β_{IP} err [m]	Waist [m]	waist err [m]
ip1b1.X	0.398	0.007	0.047	0.009
ip1b1.Y	0.401	0.002	-0.009	0.009
ip1b2.X	0.398	0.001	0.009	0.011
ip1b2.Y	0.402	0.001	0.072	0.010
ip5b1.X	0.399	0.003	-0.009	0.008
ip5b1.Y	0.400	0.001	-0.028	0.010
ip5b2.X	0.395	0.003	0.070	0.013
ip5b2.Y	0.396	0.004	-0.025	0.011
Average	**0.403**	**0.003**	**0.016**	**0.010**
RMS β-beat in IP %	**1%**			

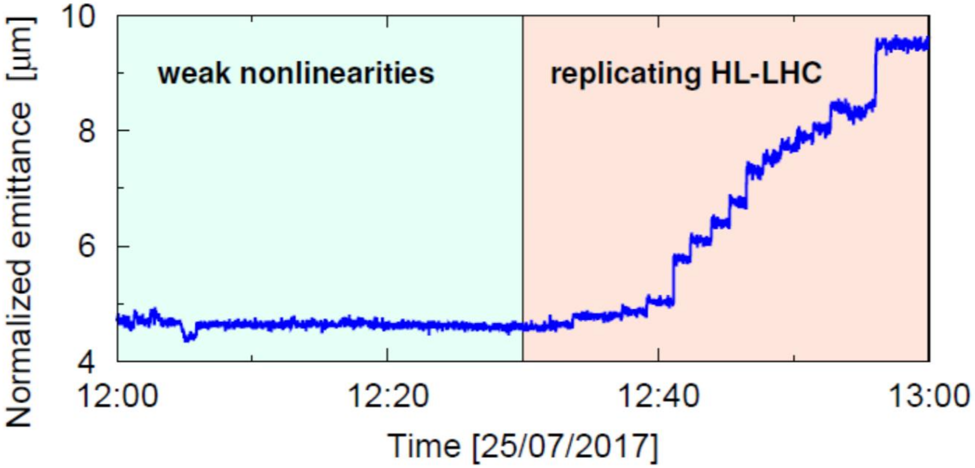
No X'ing!





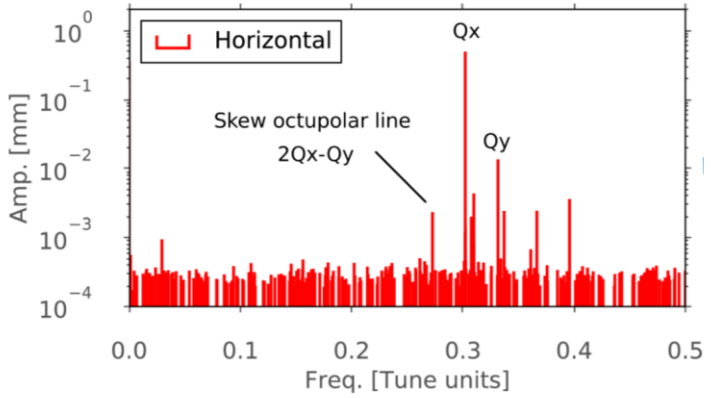
Nonlinearities

- As the β* is squeezed further the importance of the nonlinearities becomes more and more important
  - Huge impact on the foot print which is crucial for beam-instabilities
  - Feed-down to transverse coupling and β-beat
  - Reduce dynamic aperture
  - Negative impact on the linear commissioning!

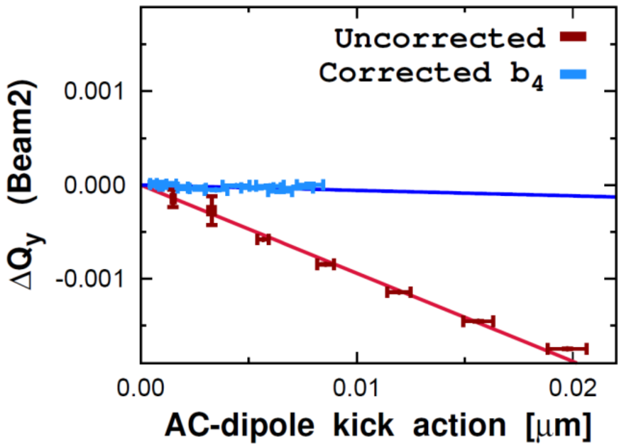


Measuring nonlinearities

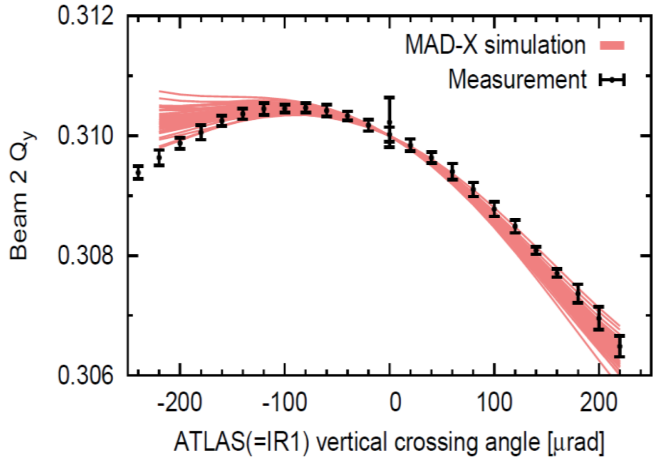
Resonance driving terms



Amplitude detuning



Feed-down to tune and |C-|

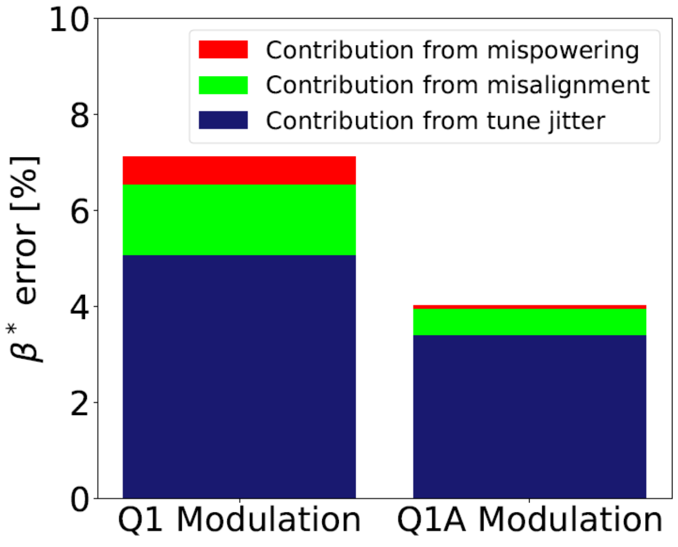


Each method merits a presentation of its own!

E. H. Maclean et al, "New approach to LHC optics commissioning for the nonlinear era"

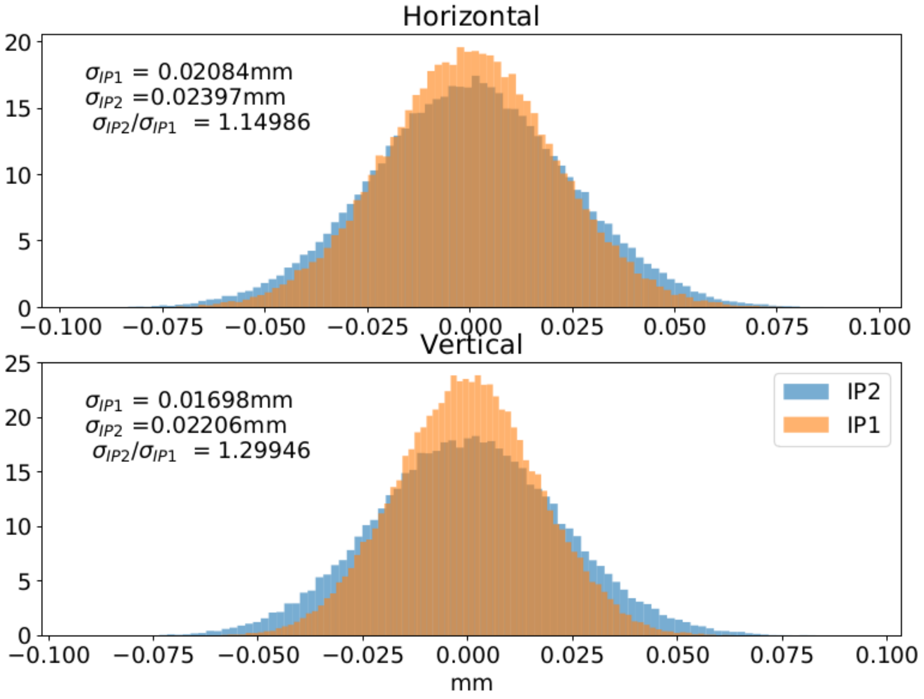
Limitations of K-modulation

- As the β* is squeezed further the K-modulation measurements cannot constrain the β* to the desired level
  - Limited by:
    - Tune jitter
    - Misalignment
    - Mispowering

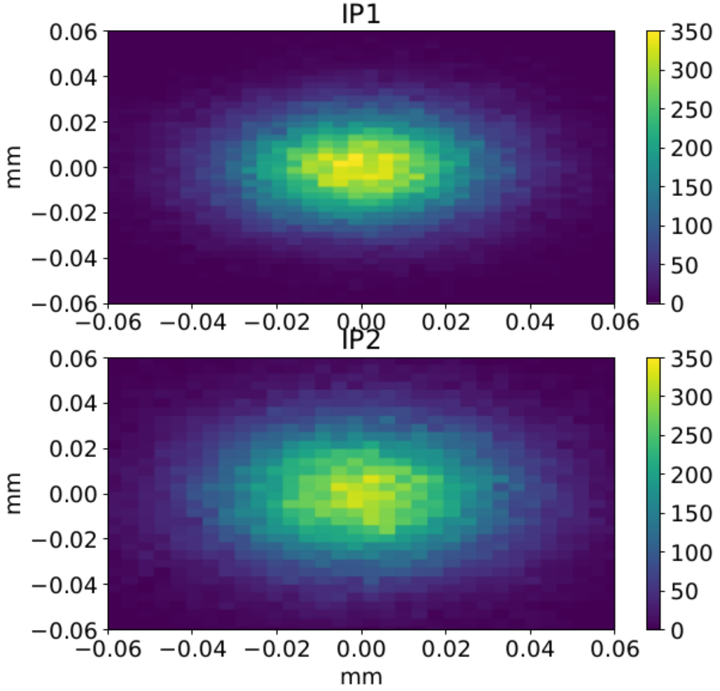


β* = 15 cm

Simulation of the local coupling error



2d histogram x-y



Tracking simulation: Ideal machine (beam 1) + trim of the **colinearity knob = 10** (MQSX.3L2 = 10^{-3} m^{-2} and MQSX.3R2 = -10^{-3} m^{-2})

→ **Beam size is 15% larger in horizontal and 30%** in vertical in IP2 compared to IP1

→ **33% lower luminosity** (neglecting effect from crossing angles) compared to the 50% that was observed in the machine

→ Almost identical beam size increase for beam 2 (less than 1% difference)

Commisiong strategy 2017