Linear Optics Measurements and Corrections

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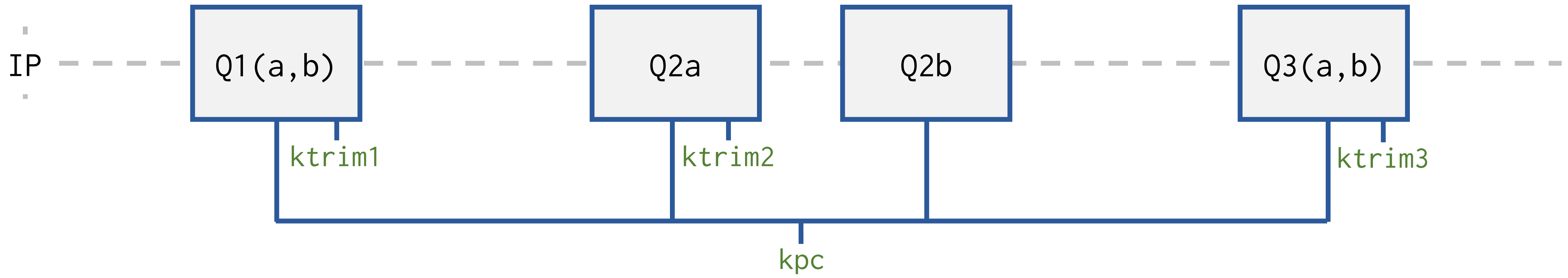
Introduction

- Linear optics corrections are vital in the LHC as them:
  - Ensure that no aperture issues coming form β-beating happen.
  - Guarantee performance making the beams collide at the designed β*.
  - Ease the operation of the machine.

- HiLumi is expected to be more challenging than the current LHC
  - 6 strong sources of errors per side per IR (as opposed to 4 in the LHC).
  - Lower beta-star -> very high β in the triplets, amplifying the errors.
  - The powering scheme lets less degrees of freedom (4 trims for 6 magnets):

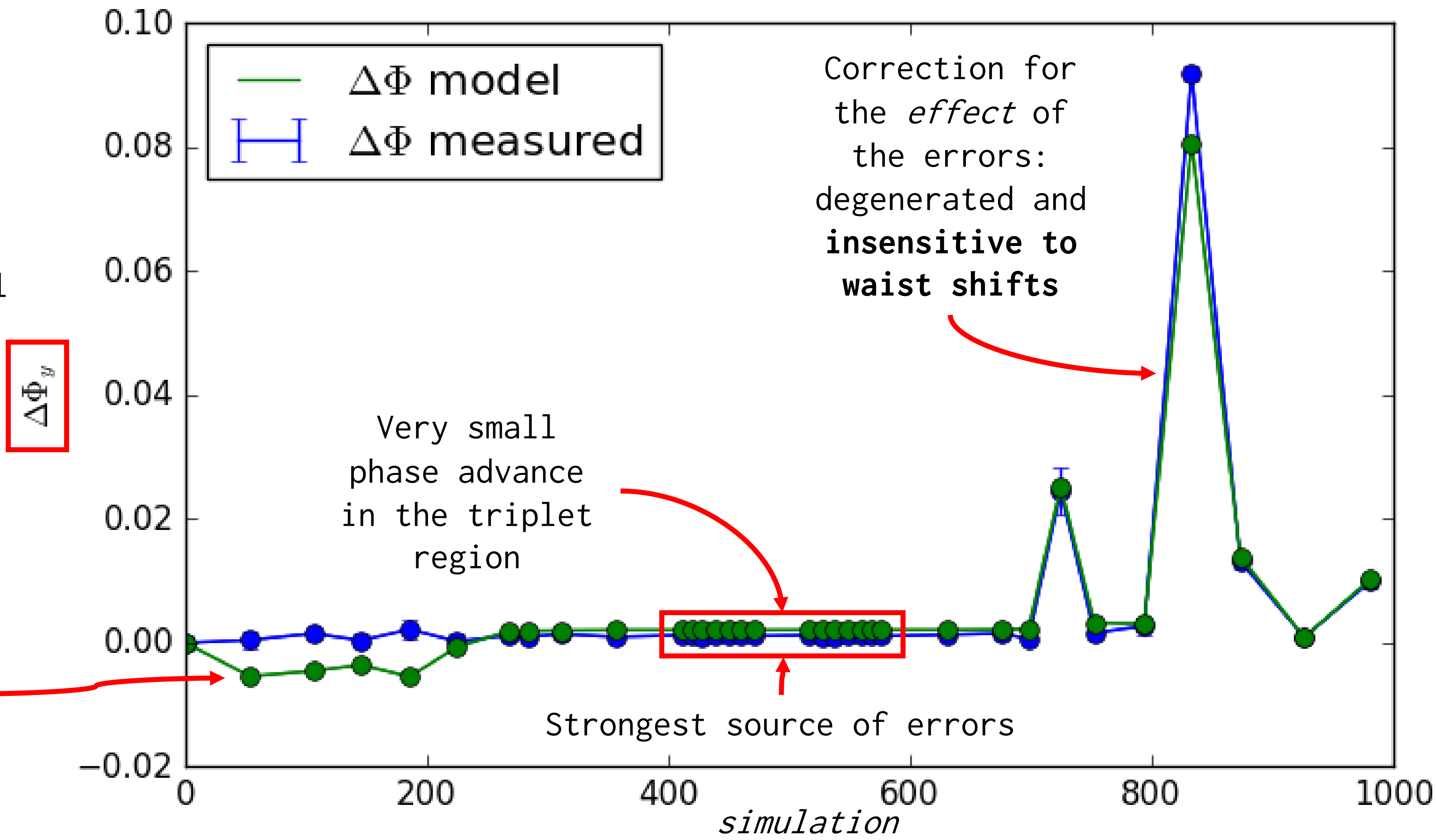


Phase advance:

- It is model and BPM calibration independent.
- Traditionally, has been the observable used to compute local corrections.

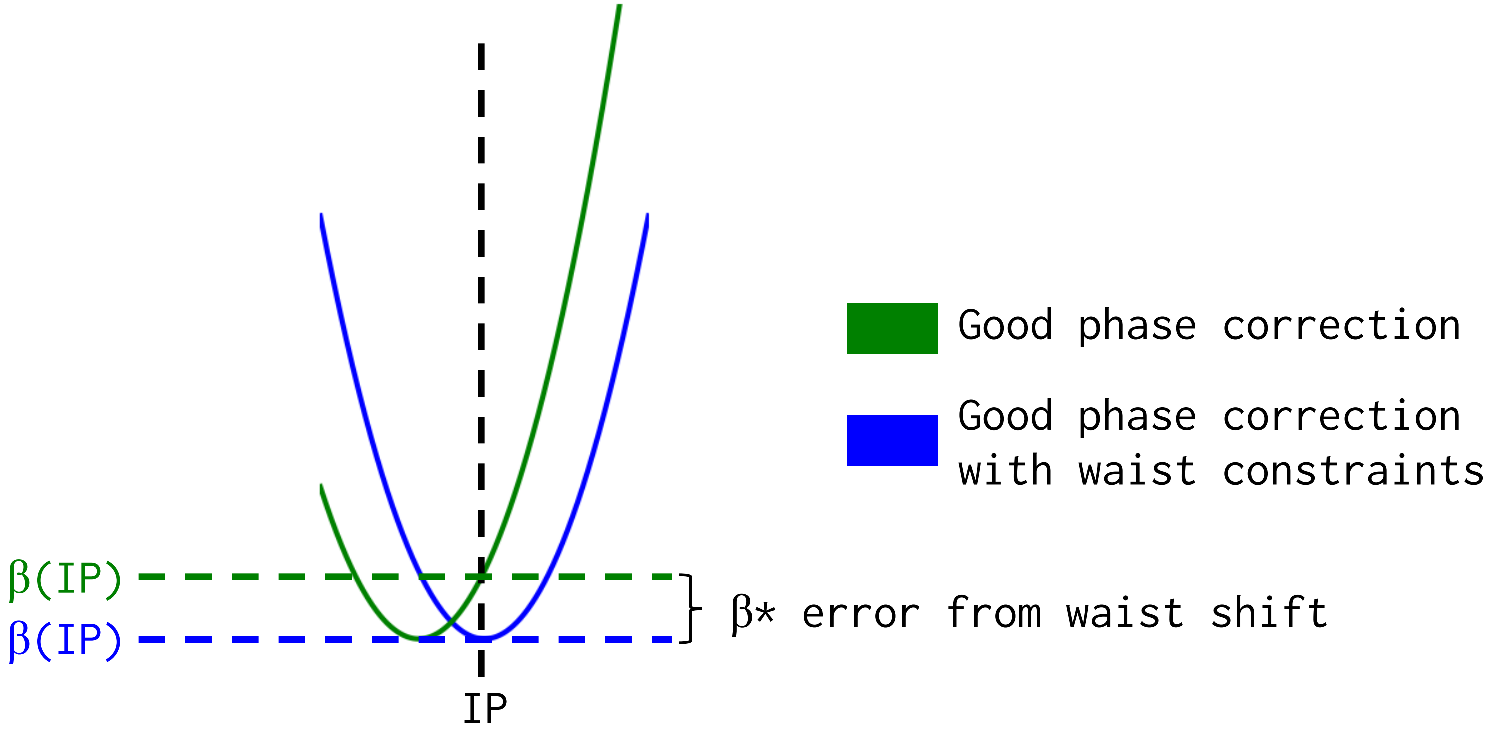
Segment-by-segment:

- A model of the segment is used to match the measured errors in the machine.



Local corrections: Waist shifts

- In the past, just the phase advance was used to correct local errors in the IRs. The phase advance can be insensitive to waist shifts.

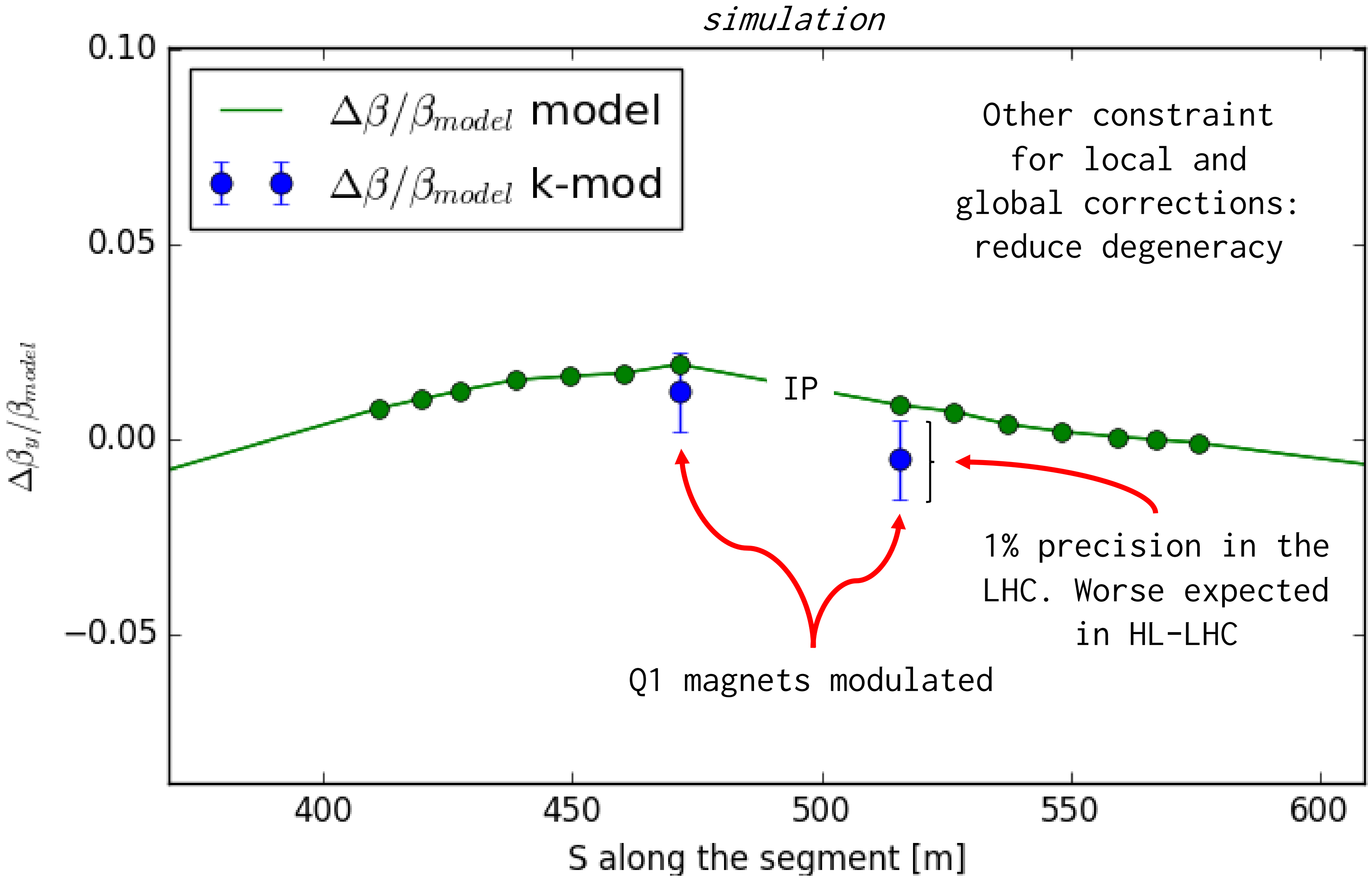


- K-modulation has been used in the current LHC with good success to refine the correction removing the waist shifts.

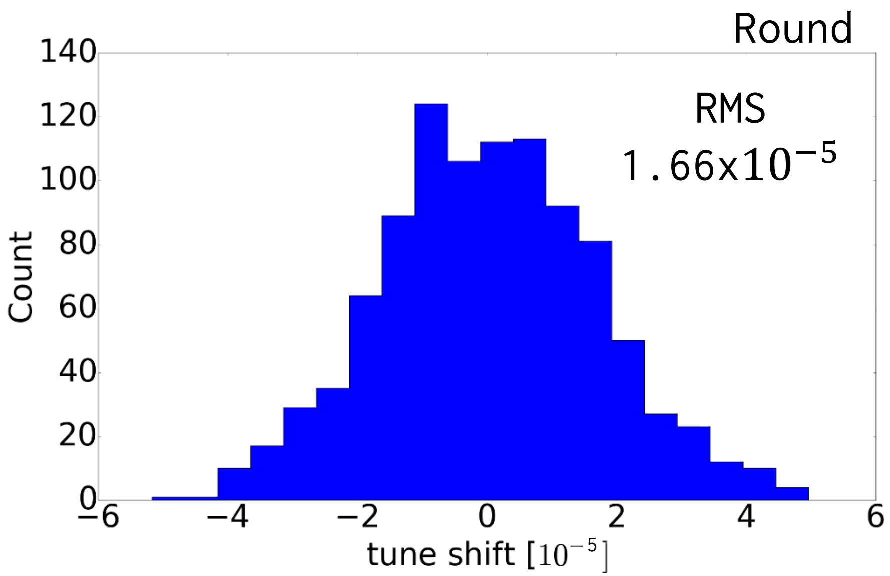
β from k-modulation corrections

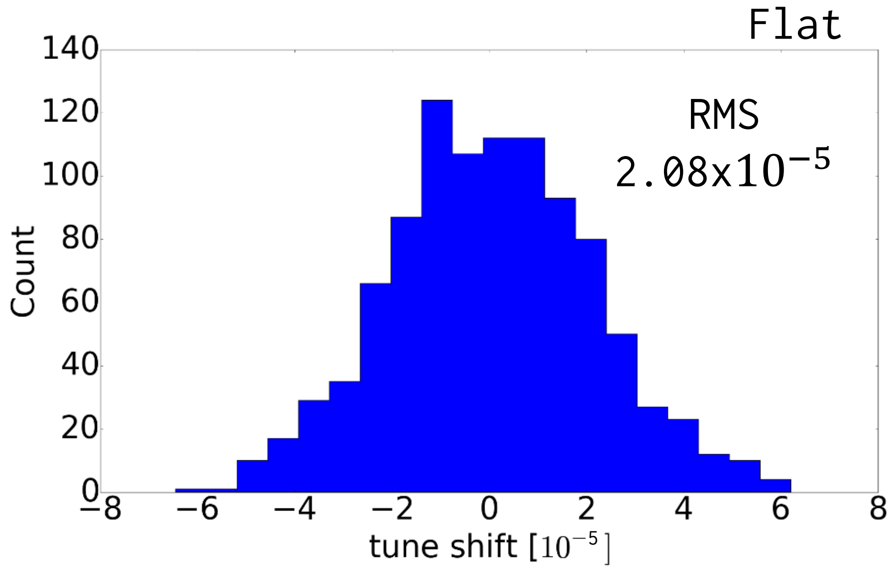
K-modulation:

- The average β-function in the triplet computed from the change in tune produced by the modulation.
- Its precision depends critically on the precision on the measurement of the tune.

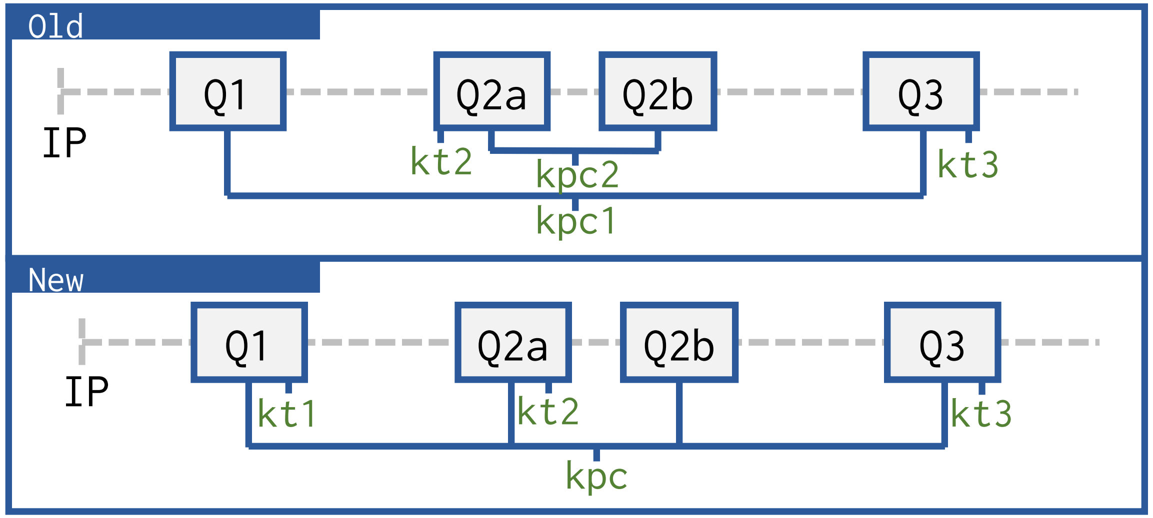


Tune noise from current ripple





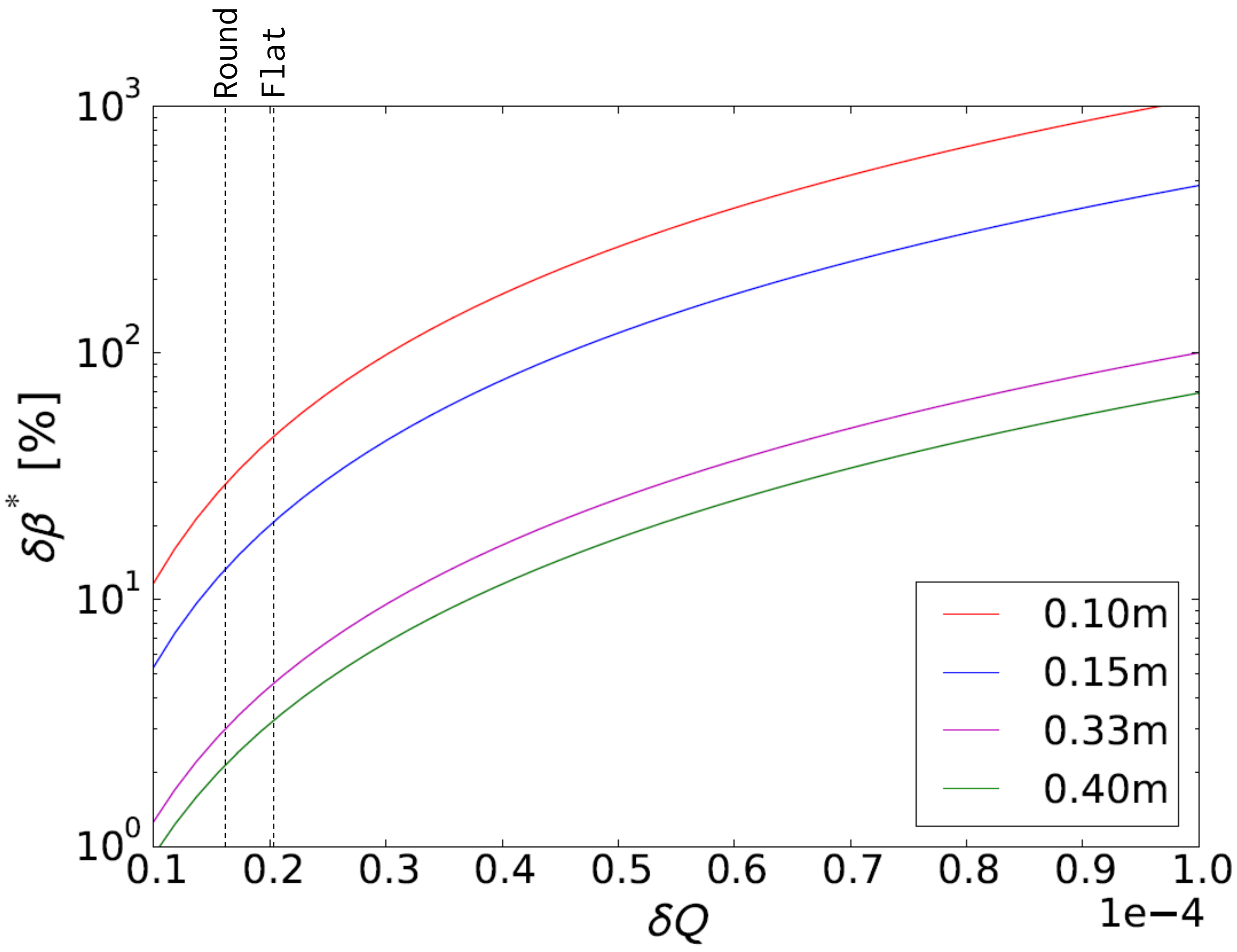
- The ripple was reduced in the specification from 1ppm to 0.1ppm*.
- No important effect on β-beating was found.
- Moving to the new powering scheme allowed for better compensation of the current ripple:



Private communication from Miguel Cerqueira Bastos

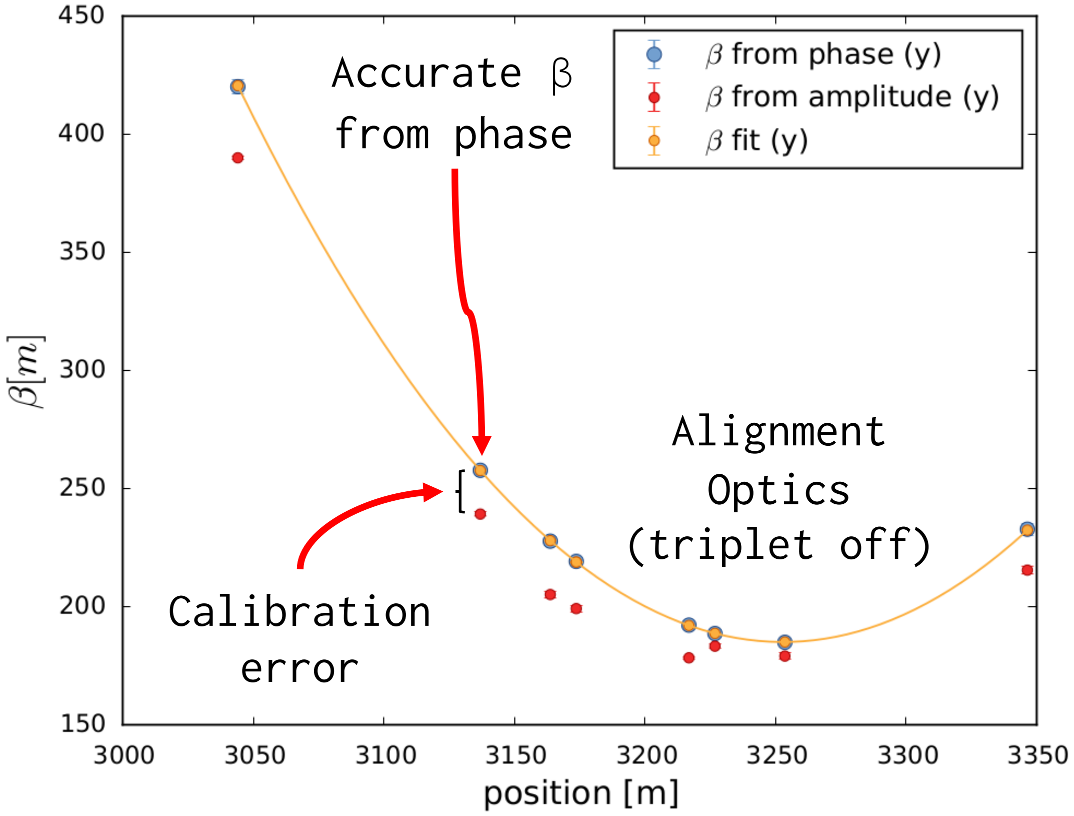
β from k-modulation corrections

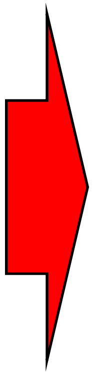
- The tune noise will limit the performance of k-modulation.
- Simulations show a considerable error in the measurement with such uncertainty in the tune, but the modulation should improve the measurement.
- In the current LHC we get results compatible with $\delta Q \leq 10^{-5}$.
- Flat optics will be slightly harder to measure with K-modulation.

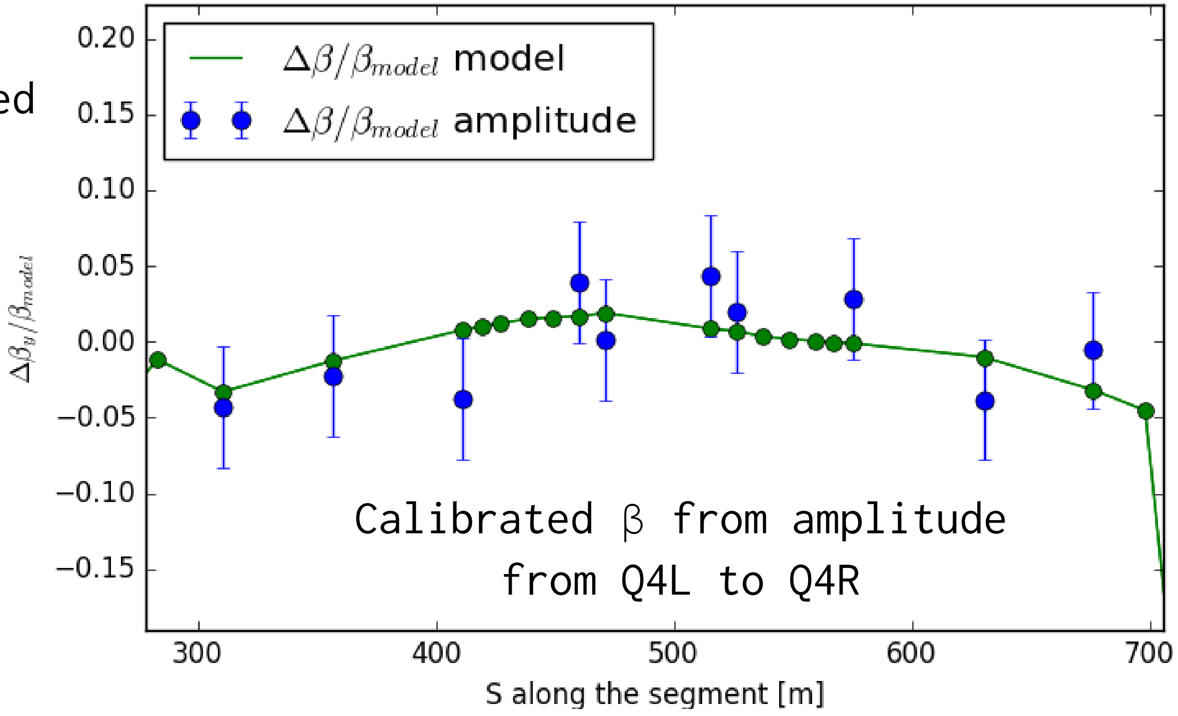


β from amplitude corrections

- β from amplitude can be another source of precise measurement of the β function.
- Problem: it is strongly BPM calibration dependent.
- Now it deviates about 3% rms* with respect to K-modulation measurements.

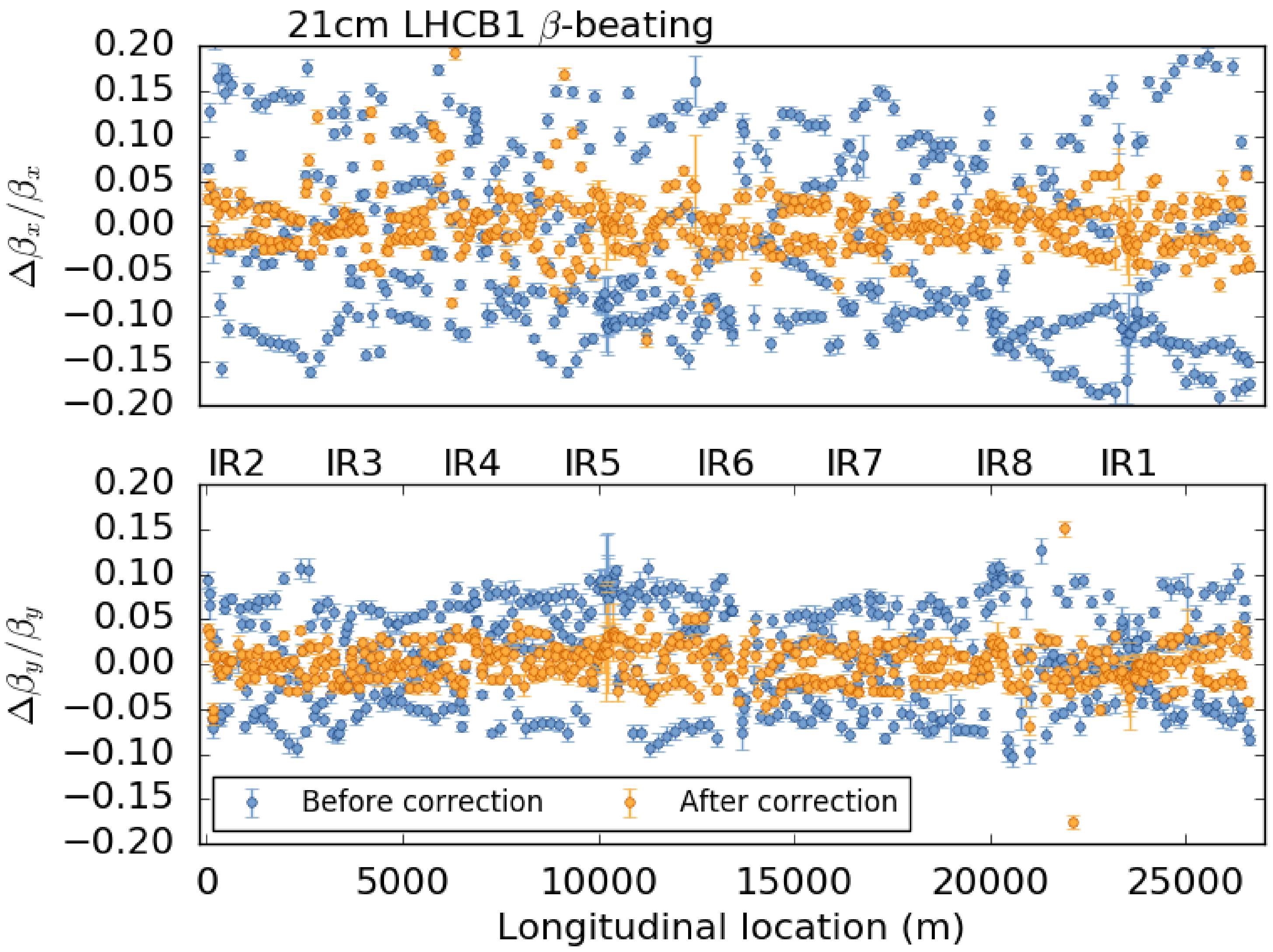






Beam 1	β* [m]
IP1 horizontal	0.184 ± 0.002 (-14%)
IP1 vertical	0.213 ± 0.001 (1%)
IP5 horizontal	0.22 ± 0.02 (4%)
IP5 vertical	0.26 ± 0.01 (19%)

Beam 1 K-modulation ***results before global corrections****.*

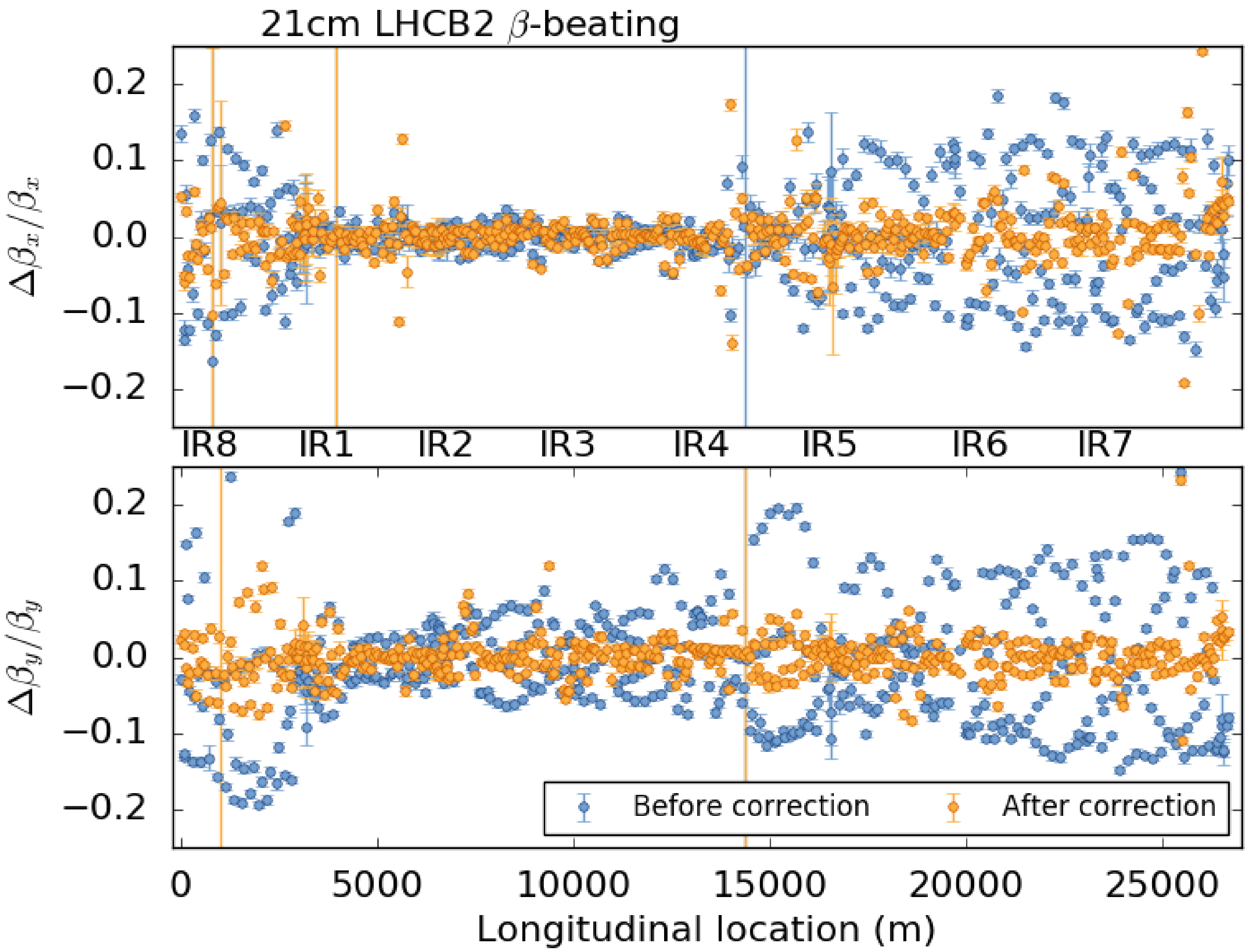


- Local corrections from the normal commissioning used.
- These corrections are the result of 7 years of iterations, it is hard to achieve for an automatic local correction with no human intervention.
- Before global corrections: RMS β-beating 9% and peak 24%.

Beam 2	β* [m]
IP1 horizontal	0.213 ± 0.006 (1%)
IP1 vertical	0.212 ± 0.003 (1%)
IP5 horizontal	0.219 ± 0.009 (4%)
IP5 vertical	0.214 ± 0.002 (2%)

Beam 2 K-modulation ***results before global corrections***.

- K-modulation performed only before global corrections.
- Final β-beating ~5% -> errors from the arcs are under control. We may expect a bit more in HL-LHC as the pre-squeeze β* is 50cm.



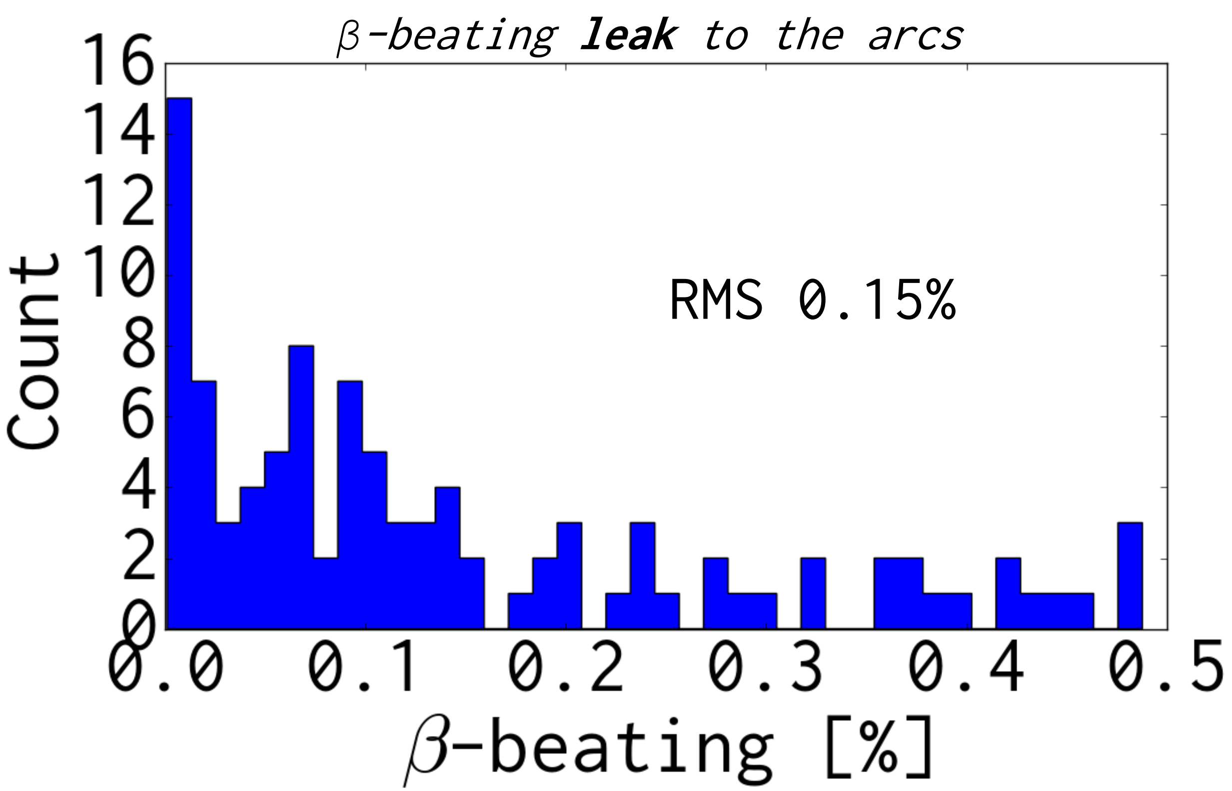
HL-LHC local corrections

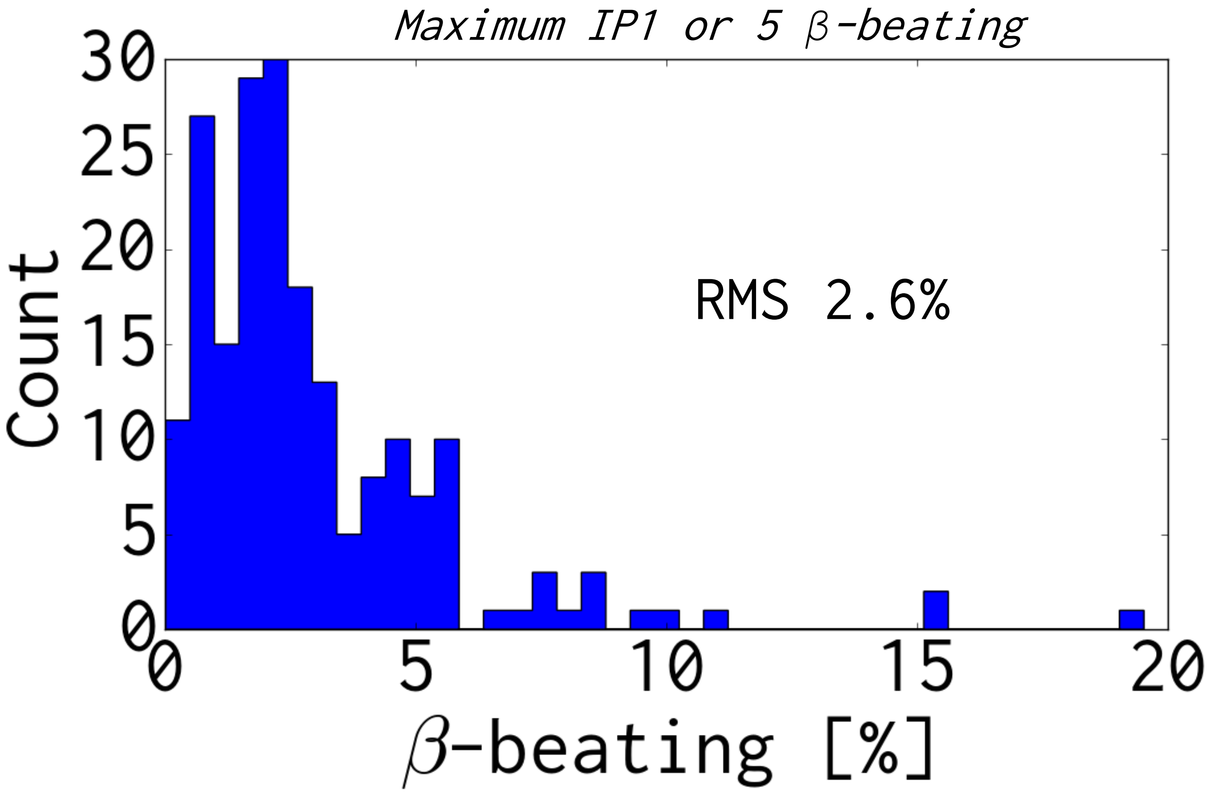
- To have statistics for the HL-LHC, 100 of possible "machines" are generated.
- Each of them will have 10 units of quadrupolar errors in **every quadrupole of the triplet**.
- $0.7 \cdot 10^{-3}$ rms uncertainty in phase (current precision in the LHC*) assumed in the arcs focusing quadrupoles, and extrapolated to the rest of the points.
- An **automatic** correction of the local errors is performed only in the relevant segments, using only the triplet itself.
- The resulting errors and corrections are applied into the full ring.
- A global correction using non-common magnets is then performed for refinement.

**P.K. Skowronski et al., "Limitations on Optics Measurements in the LHC", Proc. IPAC'16*

LHC simulations of current situation

- LHC at β*=40cm simulations.
- 1% precision on K-modulation.

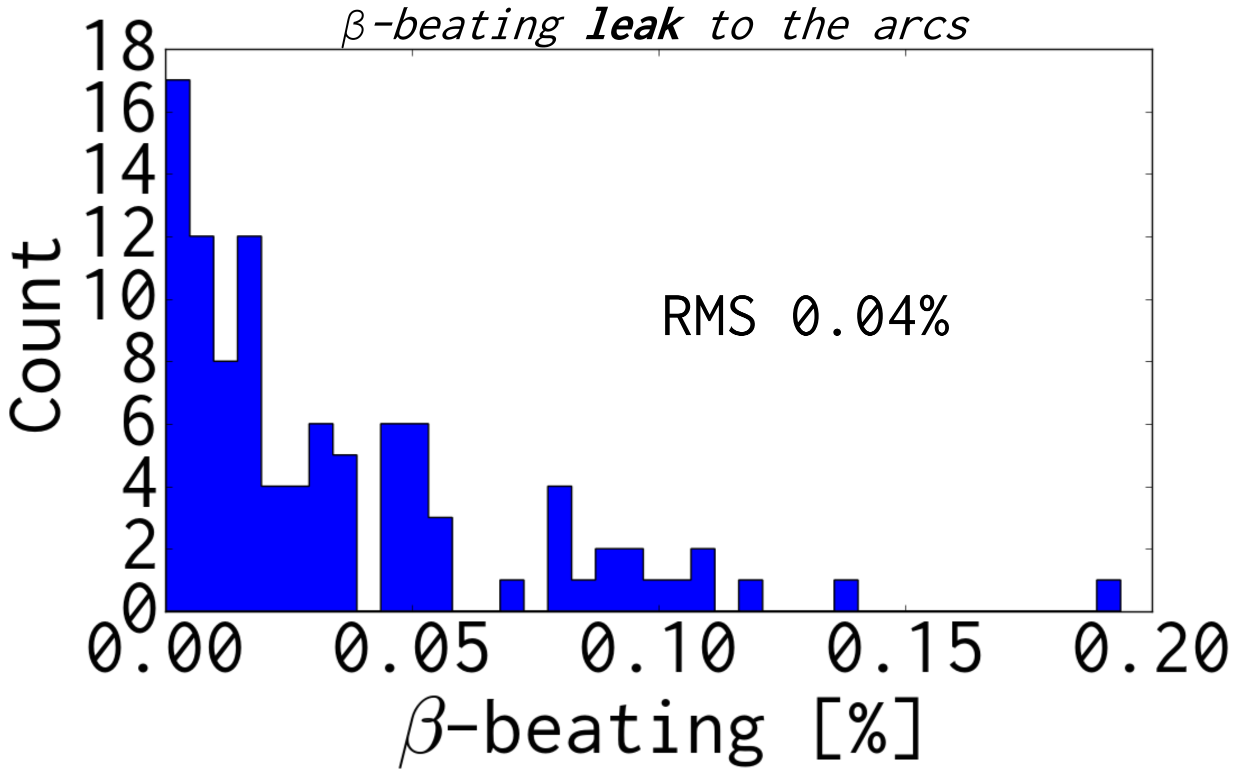


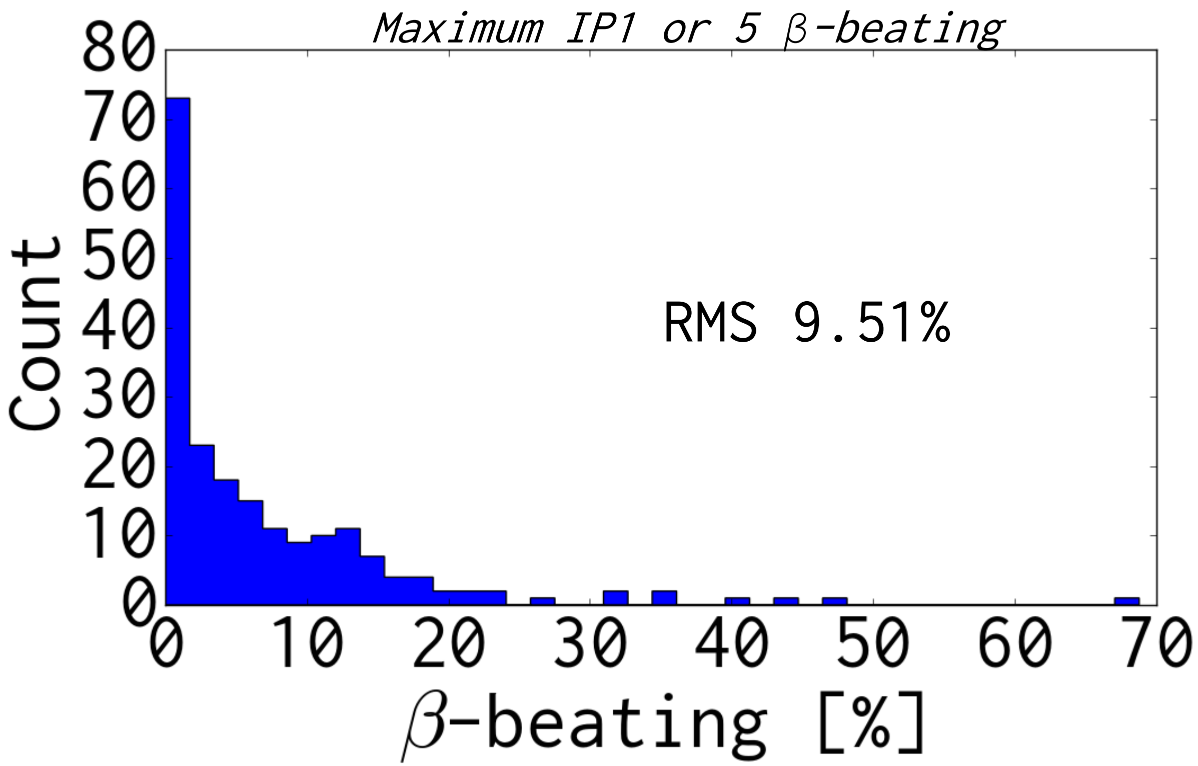


- The β-beating in the IP is the expected one understanding that it is an automatic correction.

HL-LHC “LHC-like” scenario

- HL-LHC at β*=20cm.
- 1% precision in K-modulation.

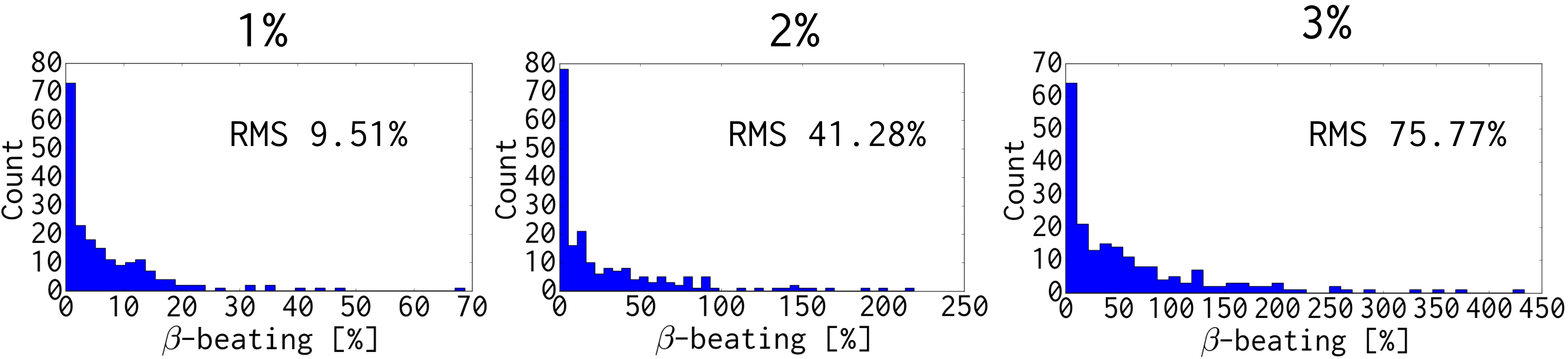




- The correction is always well closed.
- The β-beating in the IP looks good enough but can become a performance issue, with and RMS of ~9% and peak around ~70% β-beating. Human intervention will help.

HL-LHC errors progression

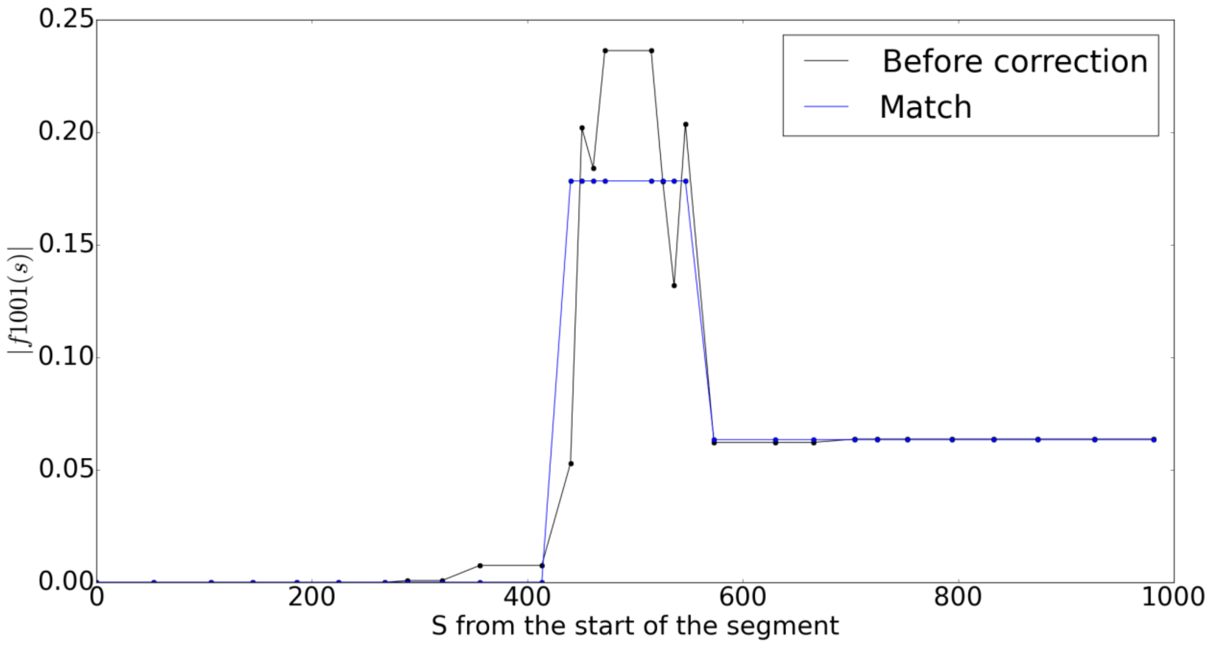
- HL-LHC at β*=20cm.
- Progression of the β*-beating with decreasing K-modulation precision:

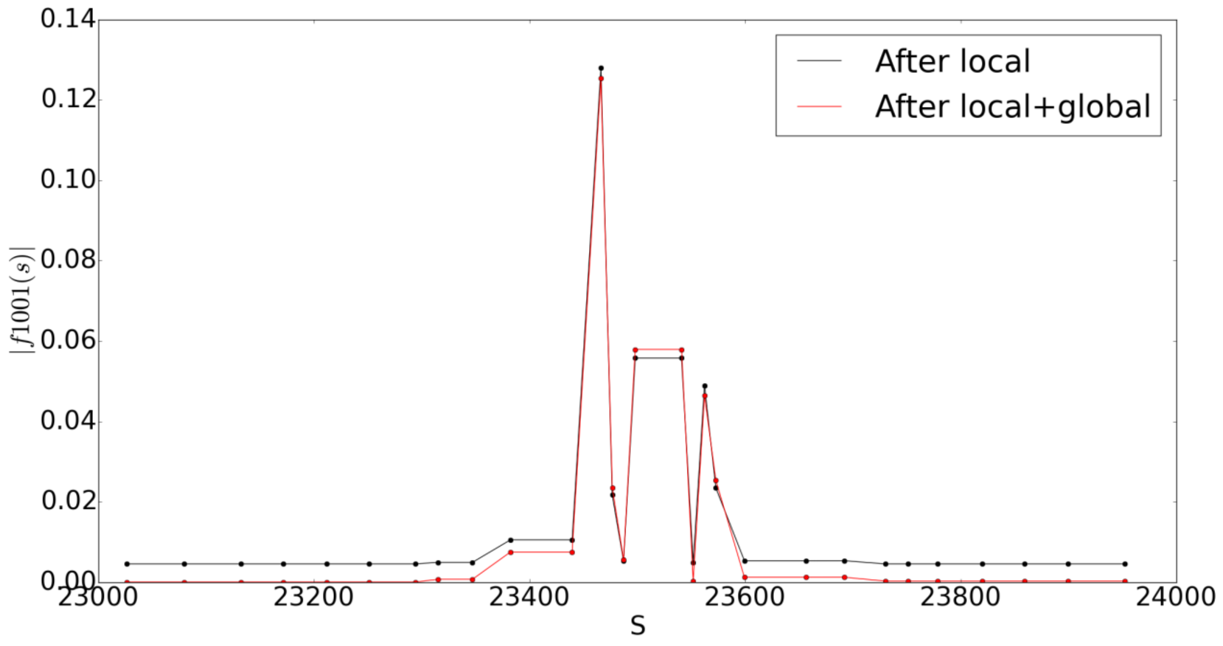


- **It will be critical to have a precise measurement of the β function close to the IR.**

Local coupling correction in the HL-LHC

- The tilts on the triplet quadrupoles can be a strong local source of coupling.
- The Segment-by-segment technique is also suitable to find and correct local coupling sources.
- Local coupling peaks are unavoidable as there are only 2 correctors for 12 sources of error in each IR.

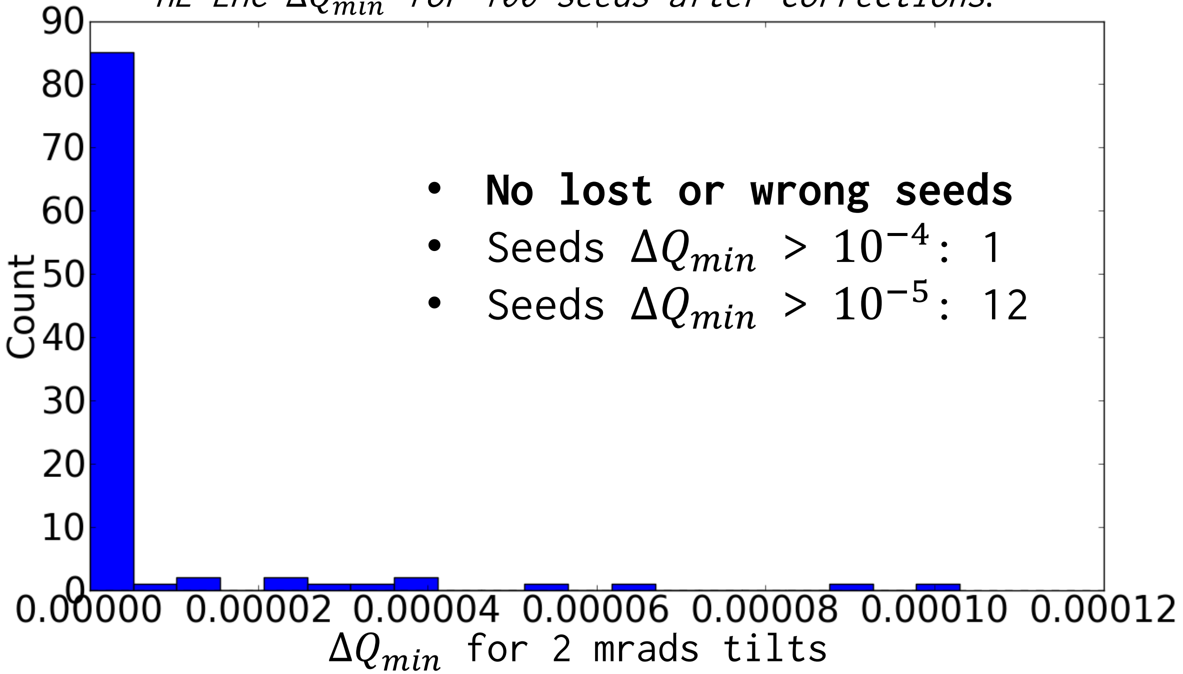




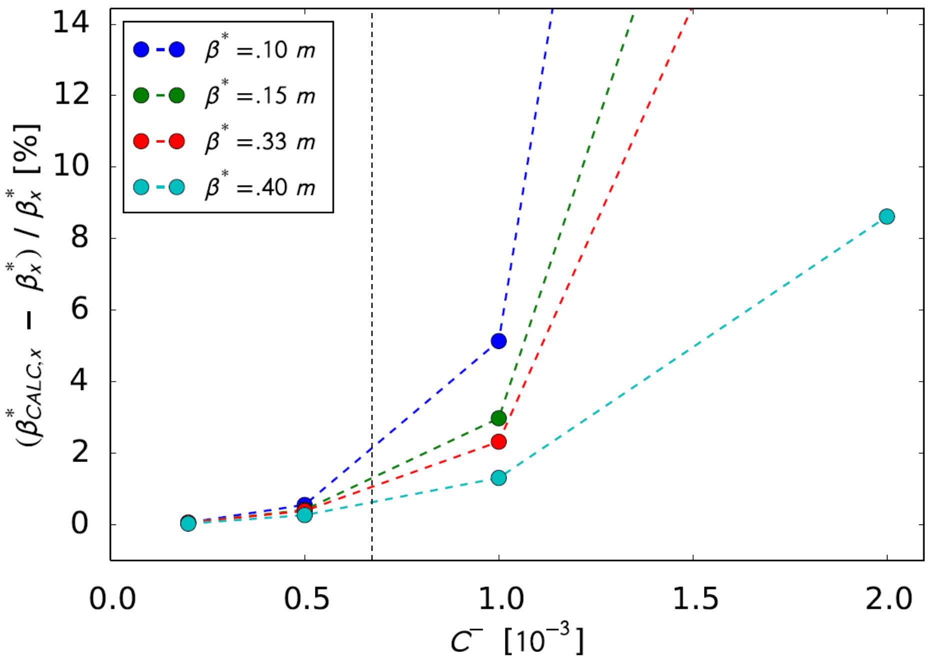
Local coupling correction in the HL-LHC

- K-modulation requires ΔQ_{min} below ~$6x10^{-4}$ to get to the 1% precision level.
- Coupling corrections of ΔQ_{min} below 10^{-3} have already been demonstrated in the LHC*.
- Simulations show that the coupling coming from the Hilumi triplet tilt can be corrected to this level.
- **Improved MAD-X coupling treatment -> way better results.**

HL-LHC ΔQ_{min} for 100 seeds after corrections.



Expected K-modulation error from C^- for the HL-LHC



Conclusions

- An accurate β-function measurement in the interaction region will be critical to correct the β*-beating and guarantee the machine performance.

- K-modulation may no reach the needed precision in Hilumi, we need backup plans:
  - β from amplitude?
  - Luminosity scans?

- The errors coming from the arcs don’t seem to be a problem -> tested in ATS MD.

- Coupling looks correctable to the levels needed to guarantee K-modulation performance.

Challenging situation foreseen for Hilumi local optics…

…and more challenges from non-linear optics now.