

Lessons learned from LHC optics control in view of HL-LHC



On behalf of the OMC team:

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Anticipate HL-LHC will strongly push optics parameters influencing the commissioning strategy

- β^* , levelling, flat-optics, ATS factors, crossing angles, aggressive optics reduction in first years

Run3 LHC commissioning also placed similar (if less extreme) demands

- Commissioning straight away to low β^* , β^* levelling, higher ATS factors, multiple commissioning of new optics

Aim of this talk is to look at Run3 experience and particular challenges/developments relevant to HL

- Local/global correction experience
- RDT compensation
- Local arc errors
- Energy errors
- Dispersion
- Collimator hierarchy and beam-beam optics measurements
- High-order errors
- Commissioning time

Reduction in β^* increasing ATS factor, better understanding of OMC limitations over time has driven increasing complexity of optics commissioning:

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Proton beams were successfully stored through the entire ring of the CERN Large Hadron Collider (LHC) on September the 10th of 2008. A reasonable lifetime was achieved for the counterclockwise beam, namely beam 2, after the radiofrequency capture of the particle bunch was established. This provided the unique opportunity of acquiring turn-by-turn betatron oscillations for a maximum of 90 turns right after injection. Transverse coupling was not corrected and chromaticity was estimated to be large. In this largely constrained scenario, reliable optics measurements have been accomplished. These measurements together with the application of new algorithms for the reconstruction of optics errors have led to the identification of a dominant error source.

The LHC is currently operating with a proton energy of 4 TeV and β^* functions at the ATLAS and CMS interaction points of 0.6 m and 0.55 m, respectively. The high luminosity operation is a challenge for various aspects of the commissioning. An improvement of the optics commissioning was achieved in a high energy hadron collider.

In circular machines, nonlinear dynamics can impact parameters such as beam lifetime and could result in a decrease of the performance reach of the machine. Studying these effects in experiments is essential to confirm the accuracy of the models used to improve the machine performance. A direct measurement of the nonlinear errors of insertion elements is an important step in the dependency of optics time as a function of the amplitude of the oscillations. This is achieved as amplitude detuning. The conventional technique is to excite the beam with a single kick and derive the tune from turn-by-turn data acquired with beam position monitors. Although this provides a very precise tune measurement it has the significant disadvantage of being destructive. An alternative, nondestructive way of exciting large amplitude oscillations is to use an AC-dipole. The perturbation in the presence of an arc dipole excitation shows a distinct behavior compared to the free beam which should be correctly taken into account in the interpretation of experimental data. The AC-dipole for direct amplitude detuning measurement requires careful data processing allowing us to observe the natural tunes of the machine; the feasibility of such a measurement is demonstrated using experimental data from the Large Hadron Collider. An experimental proof of the theoretical notions based on measurements performed at injection energy is provided as well as an application of the technique at top energy using a large number of excitations on the same beam.

Nonlinear magnetic errors in the LHC insertion elements are not only detrimental to detuning with amplitude, linear and nonlinear chromaticities, but also to the beam lifetime and beam lifetime. As such, the commissioning of nonlinear errors of insertion elements can be of critical significance for successful operation. The LHC is currently operating with a proton energy of 4 TeV and β^* functions at the ATLAS and CMS interaction points of 0.6 m and 0.55 m, respectively. The high luminosity operation is a challenge for various aspects of the commissioning. An improvement of the optics commissioning was achieved in a high energy hadron collider.

The LHC has a beta-beating tolerance lower than any other previous hadron collider. Table 1 shows the LHC beta-beating tolerances from Ref. [1], as derived from its tight mechanical aperture. To achieve the required control of the beta beating, the use of the most accurate numerical

High energy colliders have not traditionally required precise optics measurements. The maximum relationship between the interaction points and the model of the machine is a challenge for various aspects of the commissioning. An improvement of the optics commissioning was achieved in a high energy hadron collider.

The recent start-up of the Large Hadron Collider (LHC) triggered renewed interest in nonlinear diagnostics for high-energy operation. Nonlinearities can be the source

As a function of the amplitude of oscillations. The conventional technique is to excite the beam to large amplitudes with a single kick and derive the tune from turn-by-turn data acquired with beam position monitors (BPMs). Although this provides a very precise tune measurement it has the significant disadvantage of being destructive. An alternative, nondestructive way of exciting large amplitude oscillations is to use an AC-dipole. The perturbation in the presence of an arc dipole excitation shows a distinct behavior compared to the free beam which should be correctly taken into account in the interpretation of experimental data. The AC-dipole for direct amplitude detuning measurement requires careful data processing allowing us to observe the natural tunes of the machine; the feasibility of such a measurement is demonstrated using experimental data from the Large Hadron Collider. An experimental proof of the theoretical notions based on measurements performed at injection energy is provided as well as an application of the technique at top energy using a large number of excitations on the same beam.

Utilizing the N beam position monitor method for turn-by-turn optics measurements
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 (Received 20 March 2016; published 21 September 2016)

LHC optics commissioning: A journey towards 1% optics control
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 (Received 1 February 2017; published 19 June 2017)

Analytical N beam position monitor method
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First operational dodecapole correction in the LHC
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The N beam position monitor method (N-BPM) which was recently developed for the LHC has significantly improved the precision of optics measurements. The main improvement is due to the consideration of correlations between the different sources, as well as increasing the amount of BPM combinations with a single location. We present how this technique can be applied at high energy and other methods.

Since 2015 the LHC has been in a regime of high luminosity operation. The interaction points of ATLAS and CMS were upgraded to 0.6 m and 0.55 m, respectively. The high luminosity operation is a challenge for various aspects of the commissioning. An improvement of the optics commissioning was achieved in a high energy hadron collider.

Measurement and correction of focusing errors is of great importance for performance and machine protection of circular accelerators. Furthermore, LHC needs to provide equal luminosities to the experiments ATLAS and CMS. High demands are also set on the speed of the optics commissioning, as the forward progress with leveling on luminosity will require many operational optics. A fast and accurate method for measuring the focusing errors is usually done by using the measured phase advance between two beam position monitors (BPMs). A recent extension of this established technique, the N-BPM method, was successfully applied for optics measurements at CERN, ALBA, and ESS. We present here an improved algorithm that uses analytical calculations for both random and systematic errors and takes into account the presence of quadrupole, sextupole, and BPM misalignments, in addition to quadrupole field errors. This new scheme, called the analytical N-BPM method, is much faster, further improves the measurement accuracy, and is applicable to very pushed beam optics where the existing numerical N-BPM method tends to fail.

In 2017, optics commissioning strategy for low- β^* operation of the CERN Large Hadron Collider (LHC) underwent a major revision. This was prompted by a need to extend the scope of beam-based commissioning at high energy, beyond the exclusively linear realm considered previously, and into the nonlinear regime. It also stemmed from a recognition that, due to operation with crossing angles in the experimental insertions, the linear and nonlinear optics quality were intrinsically linked through potentially significant feed-down at these locations. Following the usual linear optics commissioning therefore, corrections for (normal and skew) sextupole and (normal and skew) octupole errors in the high-luminosity insertions were implemented. For the first time, the LHC now operates at top energy with beam-based corrections for nonlinear dynamics, and for the effect of the crossing scheme on beta-beating and dispersion. The new commissioning procedure has improved the control of various linear and nonlinear characteristics of the LHC, yielding clear operational benefits.

A4 RDT correction from the phase information
 Linear coupling correction from the phase information of the betatron oscillation

I. INTRODUCTION
 The 2012 optics commissioning of the LHC reached a milestone when the beta* at the ATLAS and CMS experiments, located in

I. INTRODUCTION
 In recent years the field of optics measurement and correction is growing in interest with the design of pushed optics like the high-luminosity LHC (HL-LHC) upgrade

I. INTRODUCTION
 them is too close to arc, errors in the phase measurement get strongly enhanced. In order to measure the transversal displacement of the beam as accurately as possible, in the LHC the beam is excited by an AC-dipole [3].

Coupling co-linearity
 Phase advance constraint in K-modulation

Prospects for beam-based study of dodecapole nonlinearities in the CERN High-Luminosity Large Hadron Collider
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Rigid waist shift: A new method for local coupling corrections in the LHC interaction regions
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First operational dodecapole correction in the LHC
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A precise determination of the β function at different locations in an accelerator is essential to allow accurate optics correction and to ensure high machine performance. The usual linear optics commissioning technique, however, this technique presents some limitations when the phase advance between the modulated quadrupole and the K-modulation algorithm. In this paper, the improvement of the β measurement uncertainty is quantified for different optics configurations for both, the LHC and the proton synchrotron (PS) booster. The new algorithm is used to reanalyze measured data during van der Meer scans for luminosity calibration providing significantly more accurate results than obtained previously. Moreover, in the PS booster, this improvement has also reduced the uncertainty of the β function at different locations of the machine.

Abstract: Nonlinear magnetic errors in the LHC insertion elements are not only detrimental to detuning with amplitude, linear and nonlinear chromaticities, but also to the beam lifetime and beam lifetime. As such, the commissioning of nonlinear errors of insertion elements can be of critical significance for successful operation. The LHC is currently operating with a proton energy of 4 TeV and β^* functions at the ATLAS and CMS interaction points of 0.6 m and 0.55 m, respectively. The high luminosity operation is a challenge for various aspects of the commissioning. An improvement of the optics commissioning was achieved in a high energy hadron collider.

Successful operation of large-scale particle accelerators depends on the precise correction of magnet field or alignment errors present in the machine. In the Large Hadron Collider (LHC), transverse linear coupling has been shown to have a significant impact on the beam dynamics. However, current measurement methods are not sufficient for precise local coupling measurement at the interaction point. In this paper, an approach to determine interaction region local coupling corrections with a rigid waist shift based on correlated global variables such as the closest tune approach [C] is presented. The validity of the method is demonstrated through simulations and experimental measurements taken during the LHC Run 3 commissioning in 2022, where determined corrections were applied and led to a measured luminosity increase of 9.7% and 3.5% at the ATLAS and CMS detectors, respectively.

Amplitude detuning measurements in the LHC have shown that a significant amount of detuning is generated via feed-down from high-order multipoles. This undesired effect can be detrimental to the machine performance. In this study, we investigate the high-order errors in detail, performing amplitude detuning measurements during the commissioning of the LHC Run 3 and insertion regional corrections via feed-down, using for the first time the dodecapole correctors in the insertion region.

I. INTRODUCTION

scans, an optics configuration with $\beta^* = 19$ m in IP1 and

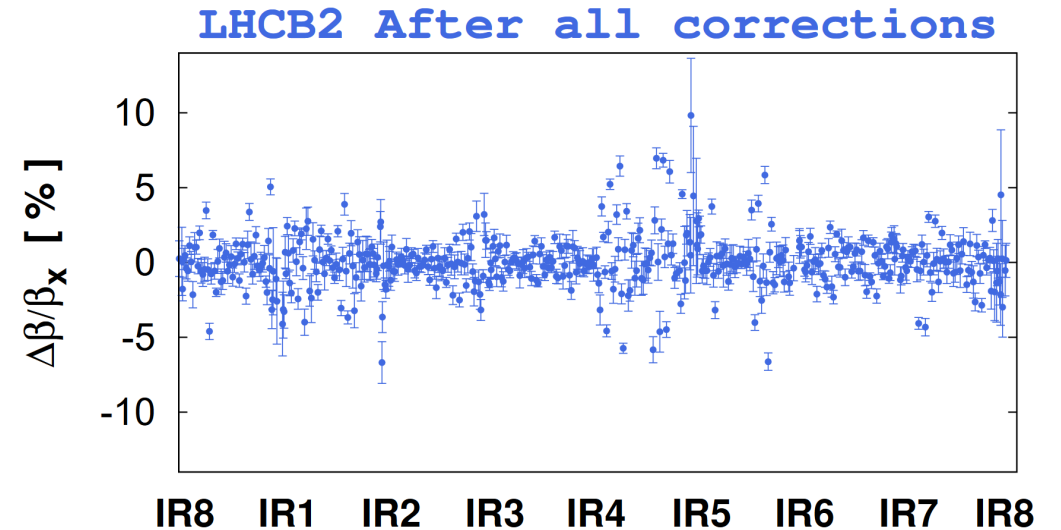
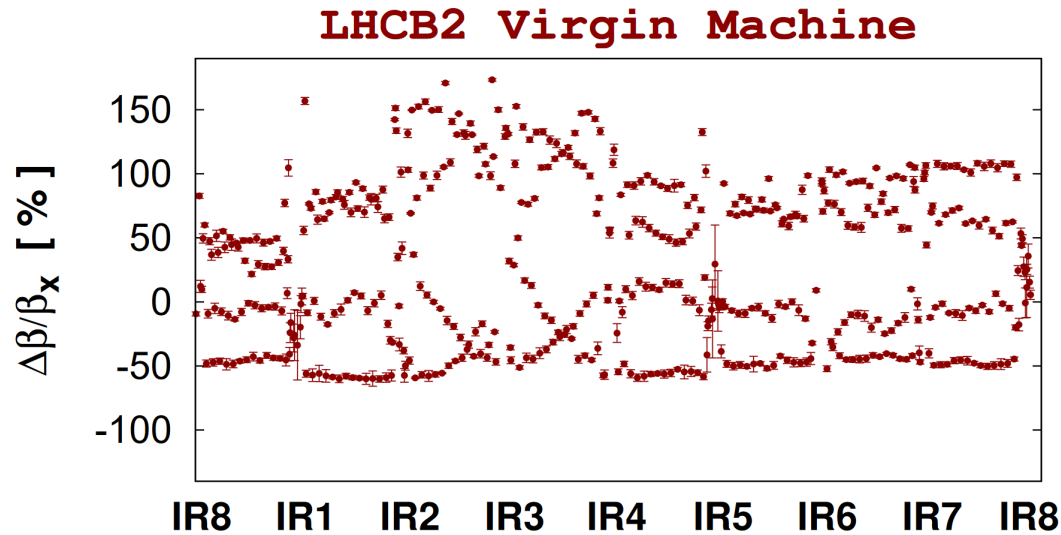
scans, an optics configuration with $\beta^* = 19$ m in IP1 and

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Successfully commissioned optics straight-away to 30cm in first year of Run3

- In 2022 achieved target β -beat quality, and luminosity imbalance from optics within 1%.
- Key demonstration can commission directly to very pushed optics (same β^* expected in first years of HL-LHC)

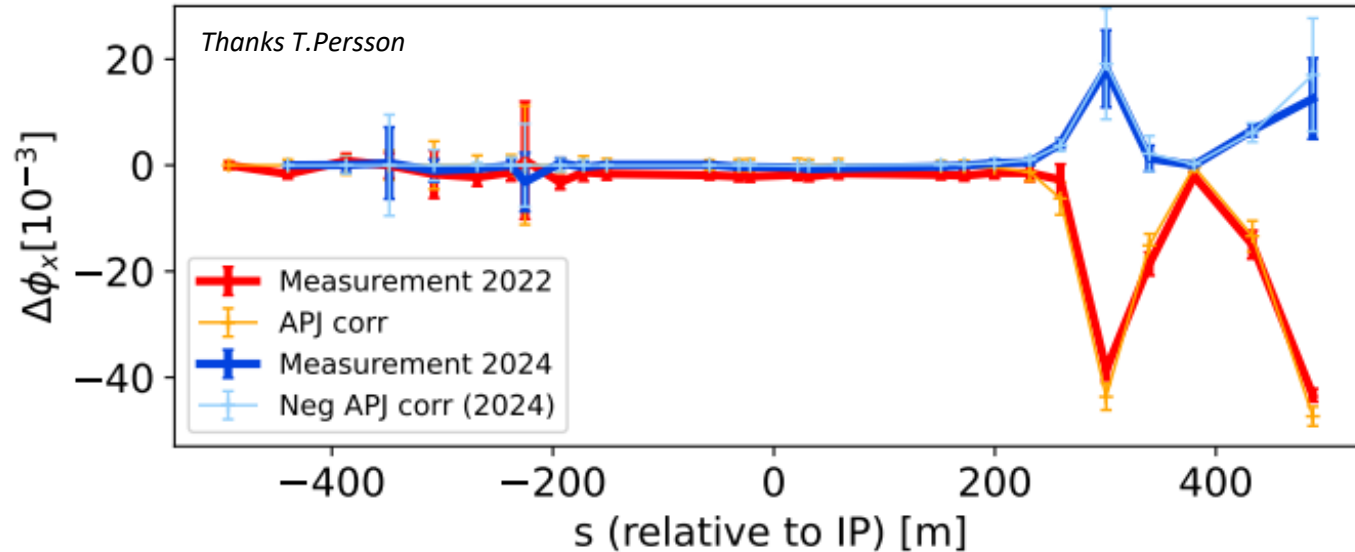


- Significant time reduction for local corrections
 - In 2015 took ≈ 5 shifts / 2 weeks to reach point where local IR corrections were incorporated
 - **achieved online in Run3 !**

In 2024 triplet polarity of IR1 was reversed

It was possible to extrapolate local IR1 corrections from previous year to the new triplet polarity

→ Began 2024 commissioning with initial guess corrections for IR1 simply inverting 2022/23 knobs



Success of this approach reflects good understanding of local errors in IR

→ Knowledge that has been developed over many years, over commissioning of many different optics

HL-LHC commissioning will be performed with new triplets, new errors

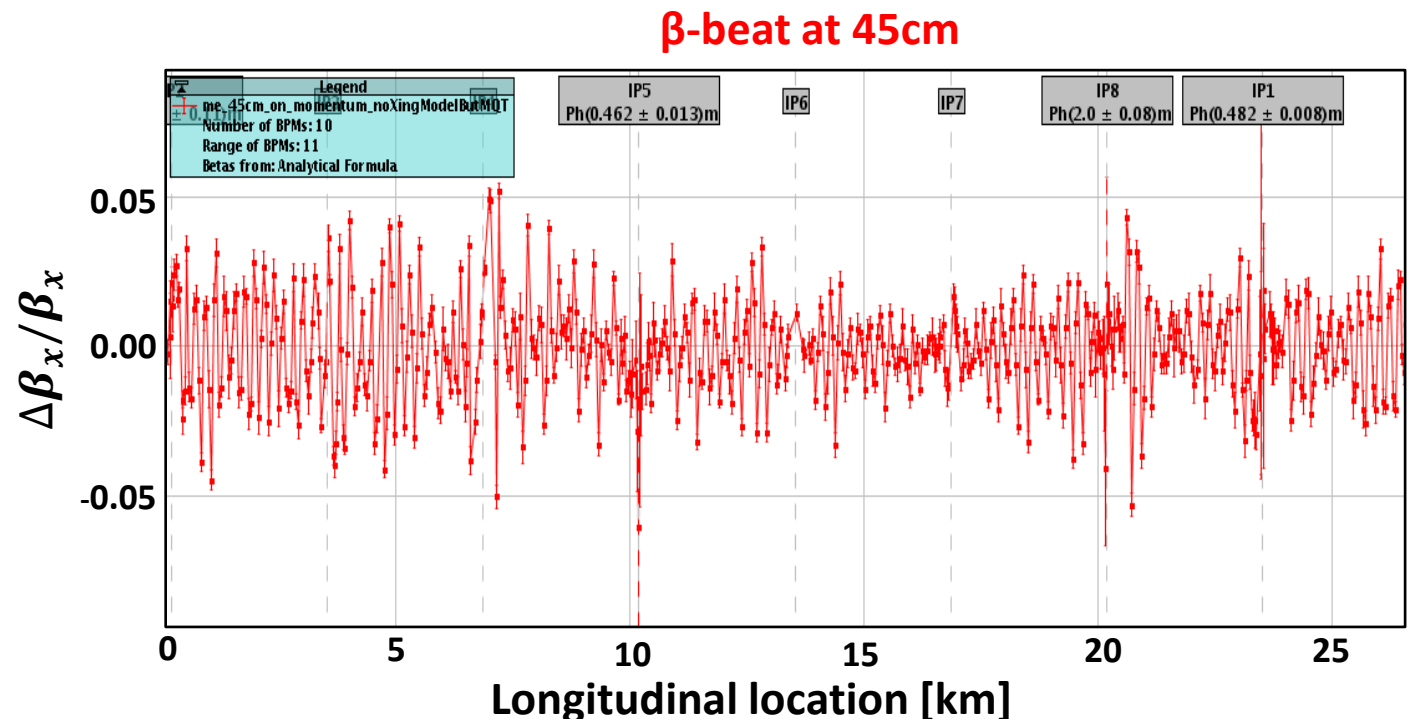
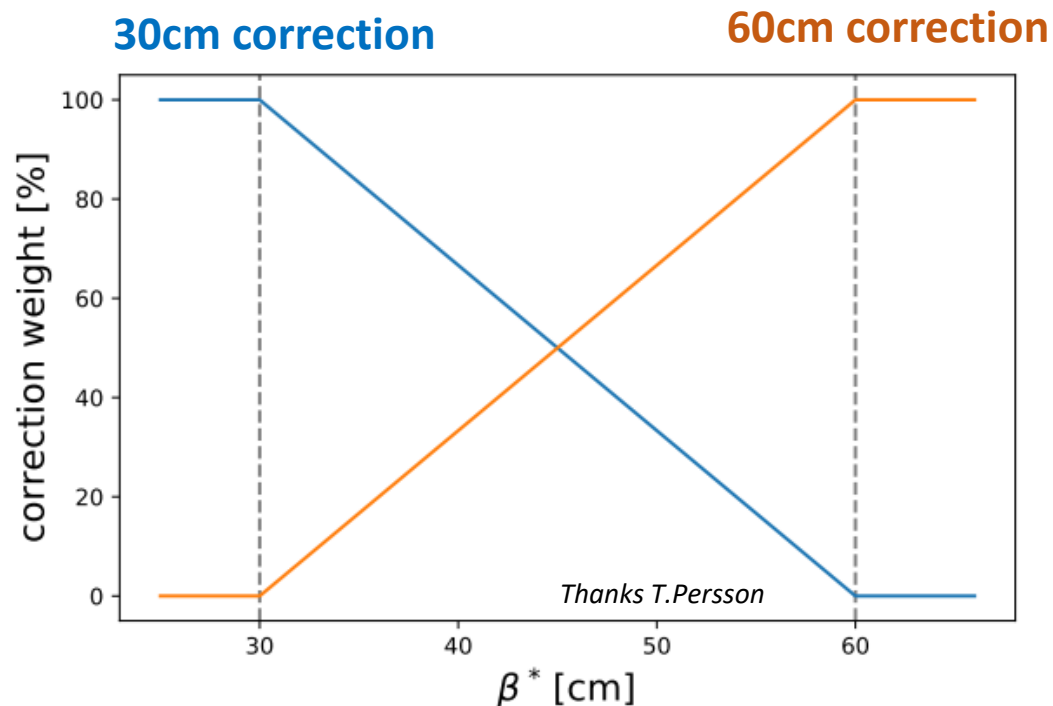
- In Run3 have been developing and testing multiple complementary methods to help correctly identify local IR errors Segment-by-segment, Action-Phase-Jump, ML-based error reconstruction: aim is that consistency between different methods can help identify best possible local errors and corrections

After correction of strong local errors, generally perform global correction to optimize final β -beat and β^*

→ In Run 2 performed single global optimization for final β -beat and β^* at end-of-squeeze.

Switch to luminosity levelling required tight optics control throughout the squeeze

- Not practical to measure/correct at every match point or levelling-step (recent HL-LHC optics MD had >20 matched points!)
- Strategy adopted is to correct at a few β^* and trim in/out global corrections during squeeze steps, validating at intermediate points
- Works well so far in LHC – being studied in HL-LHC MDs with higher ATS factors

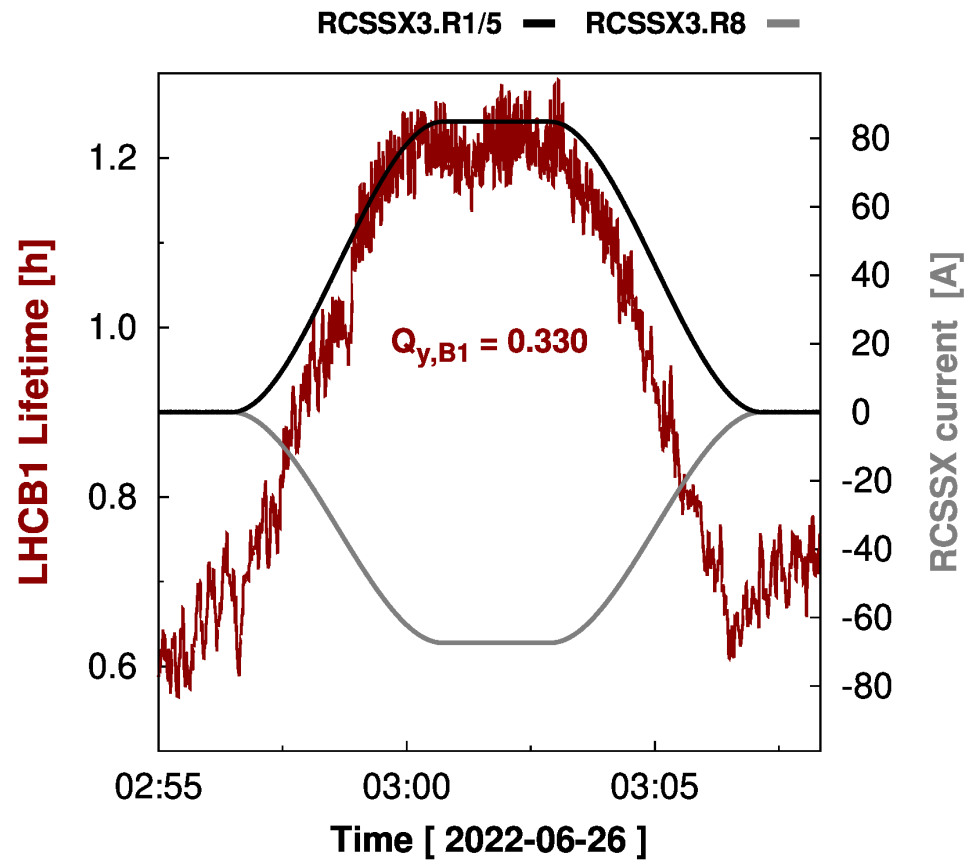
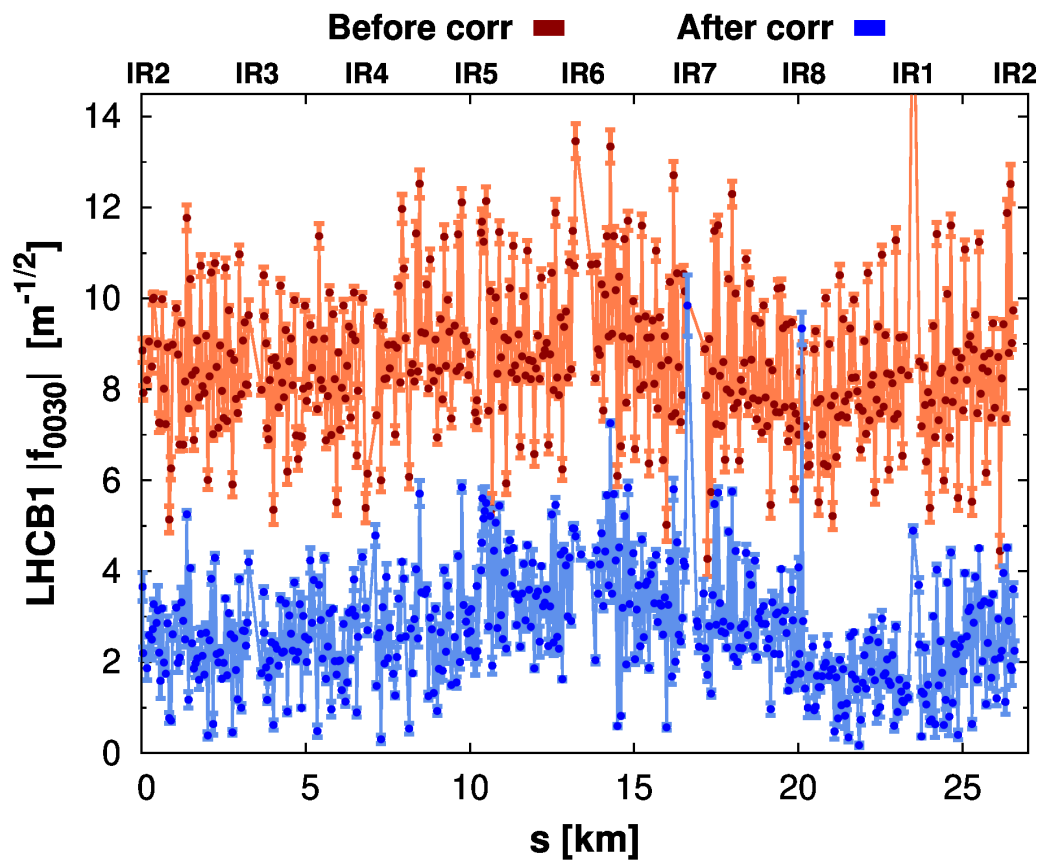


Significant progress towards making direct RDT corrections for nonlinear optics corrections routine in LHC

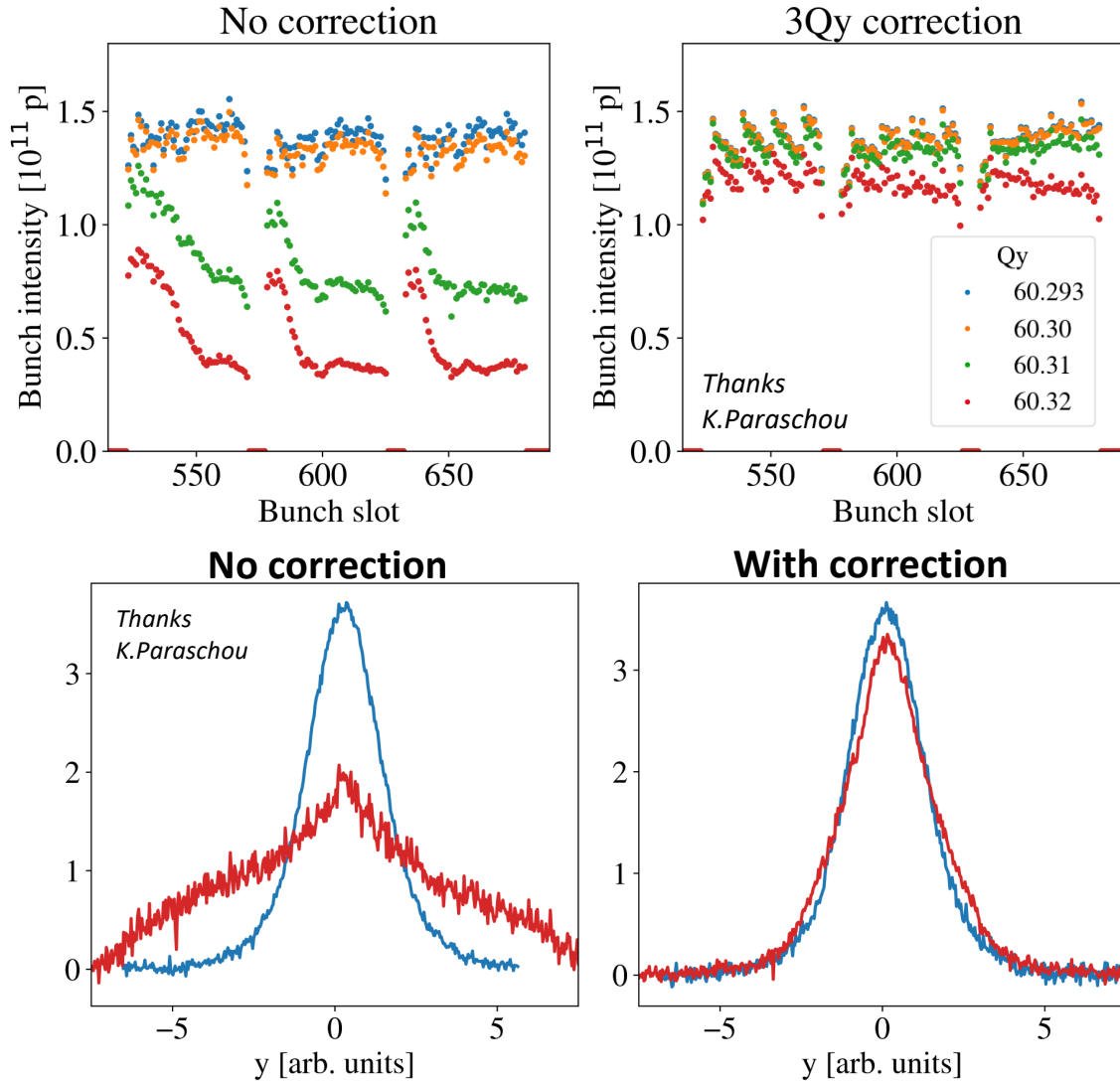
→ effort which has been ongoing since first studies of sextupole resonances back in 2010!

Particular focus during Run3 has been optimization of resonances at injection

- In many cases corrections never intended in baseline LHC strategy e.g. 3QY → demonstrates good flexibility of the corrector packages

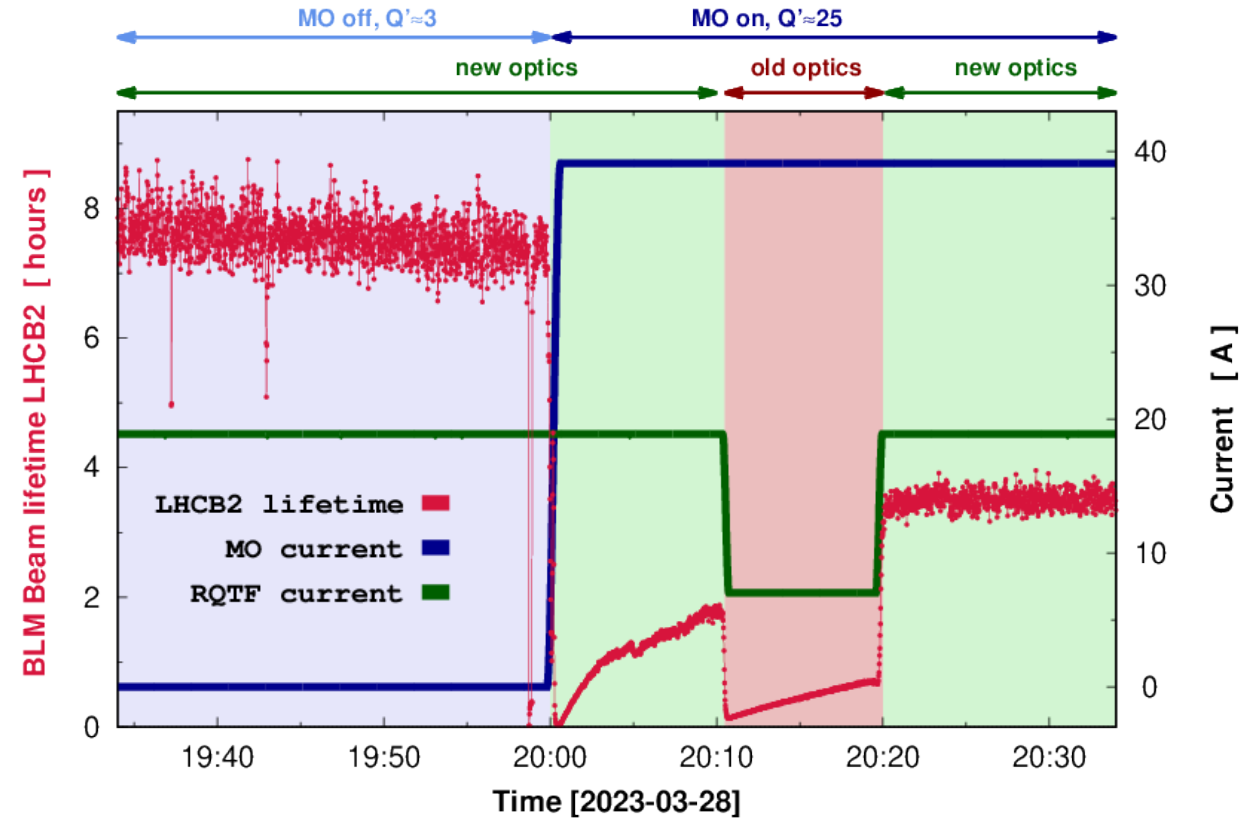


Normal/skew sextupole resonance corrections aim to improve good WP region → particularly relevant for reversed MO polarity



New optics design at injection used to help suppress resonances driven by Landau octupoles

→ being incorporated directly into HL-LHC optics design

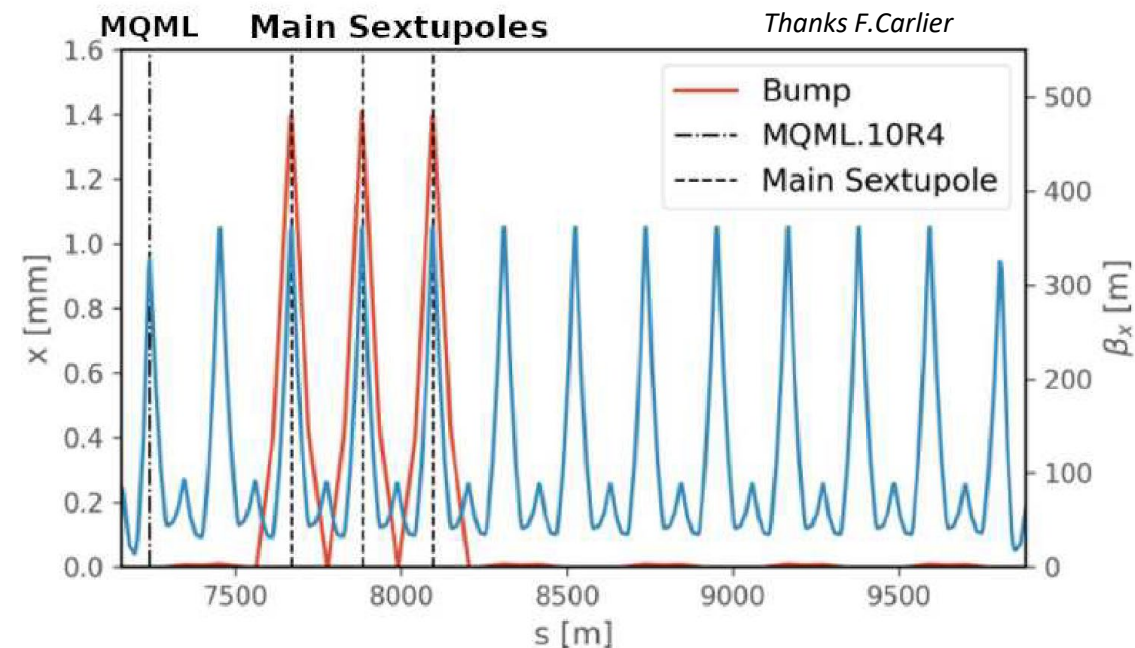
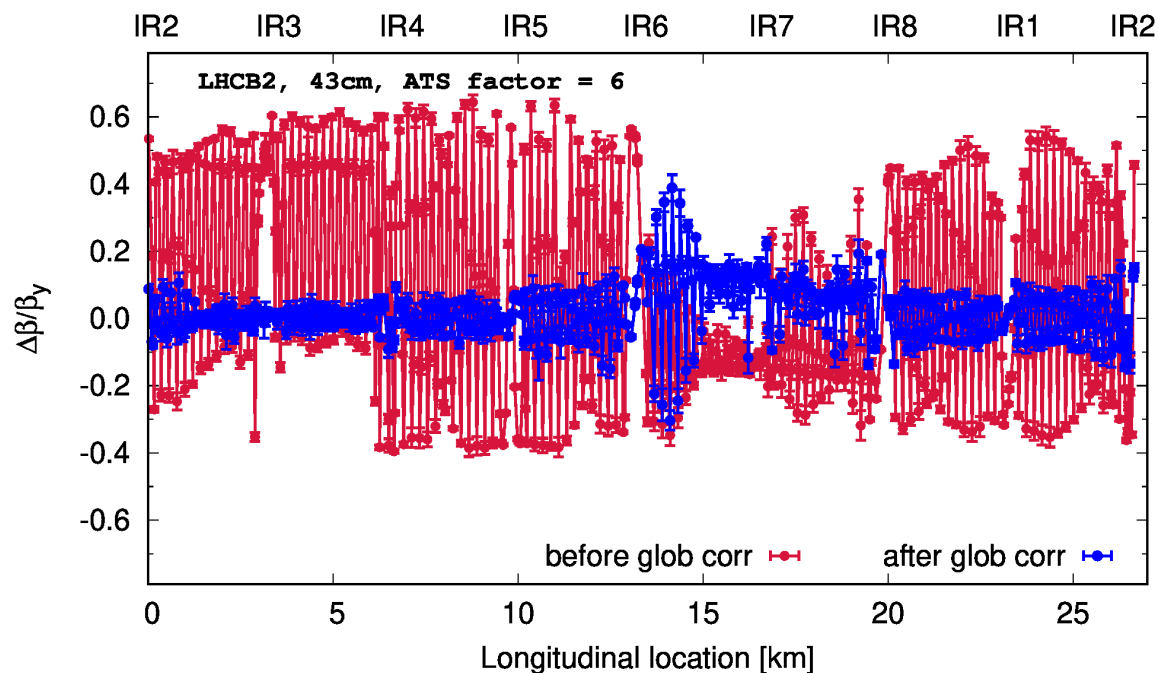


Lots of good news!

→ **but also some issues/challenges emerged for first time in Run3**

With increased ATS factors local errors in the arcs become a challenge for optics commissioning

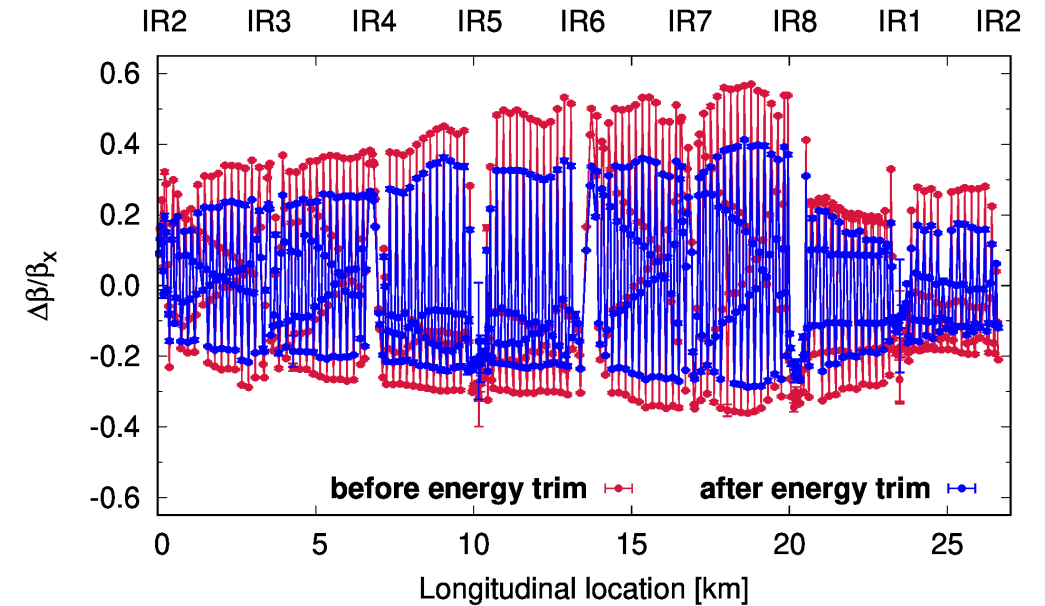
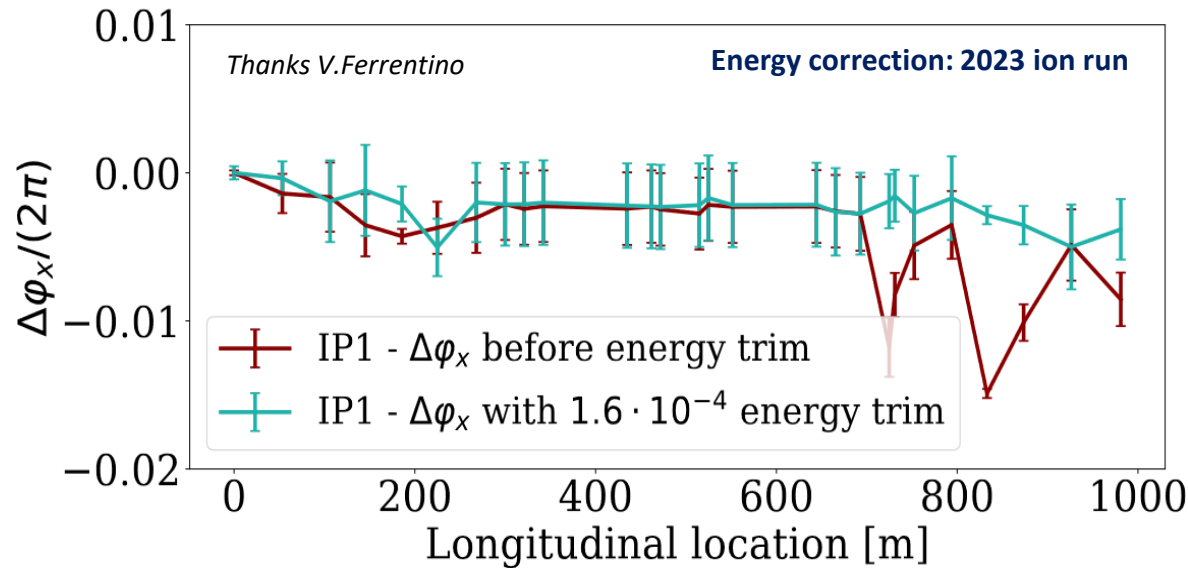
- Traditional OMC used local corrections in IRs to reduce β -beat to $\approx 10\%$ - 20% , followed by global corrections
- HL-LHC optics MD tested up to ATS factor = 6 \rightarrow saw up to 60% β -beat even with IR-corrections applied
- Attempts to correct residual with basic global corrections (even multiple iterations) failed to achieve required β -beat



- Solution is local corrections in arcs via feed-down from orbit bumps in MS \rightarrow beneficial for LHC B1 during HL-LHC MDs at ATSF=3,6
- Still far from online corrections \rightarrow LHC B1 corrections for high-ATS factor tests determined over ~ 1 month between MDs
- \rightarrow hope that corrections found in Run3 can help in Run4, but no experience of stability of local arc errors over LS (local IR errors known to vary)

At low- β^* optics becomes sensitive to slight changes in energy from orbit setup during commissioning

- First noticed during 2022 commissioning, where influenced optics reproducibility
- During 2023 ION commissioning able to identify energy errors from local IR optics corrections



Energy correction: 2024 commissioning

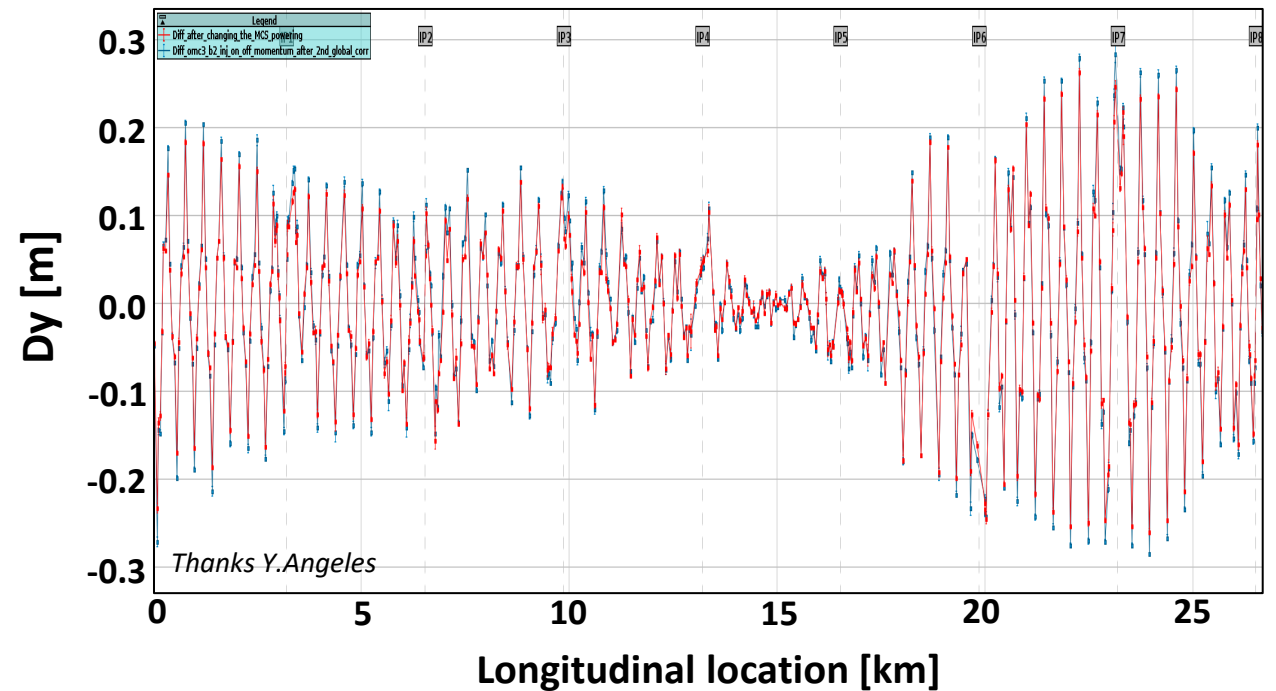
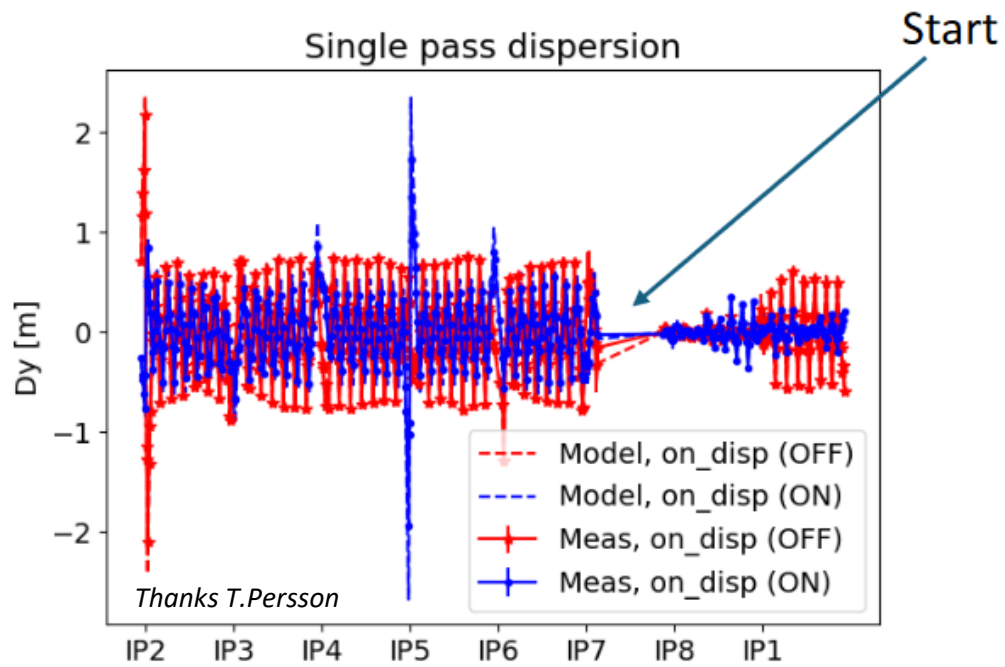
- During 2024 commissioning had to perform 4 separate re-corrections of energy via optics tools following changes in orbit setup, causing beta-beat shifts in range 10-20%
- Corrections performed online, but still relatively time consuming
- Only become more challenging for HL-LHC: **aim to develop automated checks/corrections to simplify commissioning**

Vertical dispersion never considered a priority for optics commissioning

→ Several occasions now in Run3 where starts to cause or identify problems

- 2023 ION run suffered from large ALICE background
- Mitigated by increasing IP1 on_disp knob to modify vertical dispersion at collimators
- New procedures to determine single pass dispersion from conventional optics measurements being studied

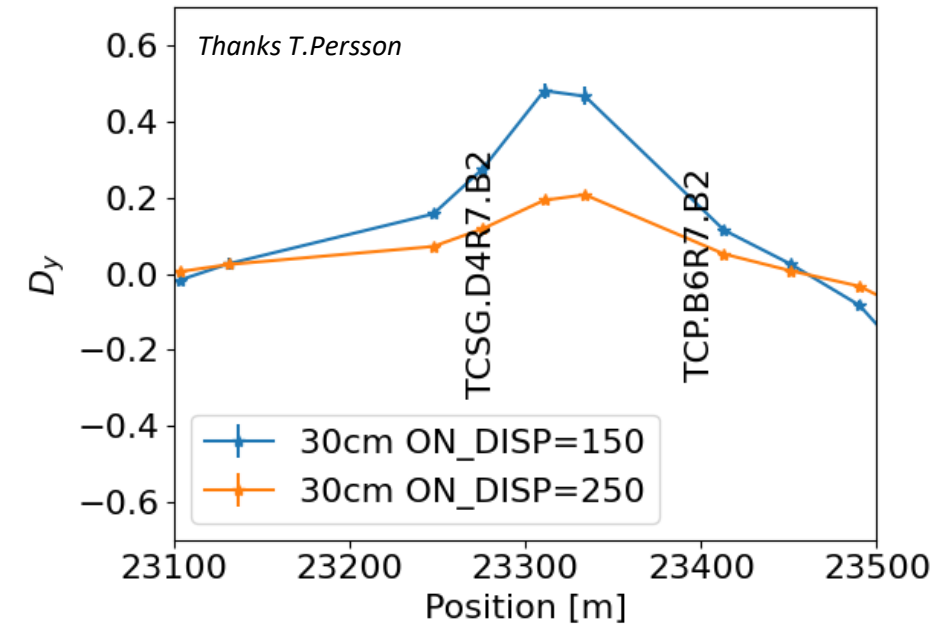
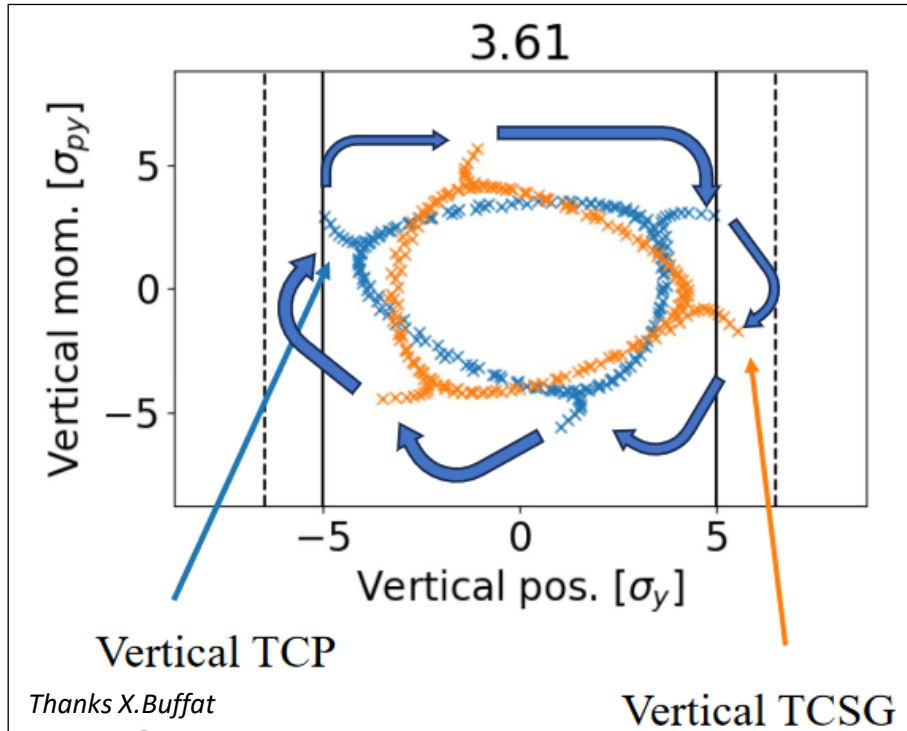
- Studies of vertical dispersion throughout Run3 consistently show very large D_y error
- Seems to indicate very large skew quad error around BPM.26R5.B2 to BPM.30R5.B2: e.g. large MQ tilt



During 2024 intensity ramp up breakage of collimator hierarchy of LHC B2 was seen

Once again problem could be partially mitigated via increase of IP1 on_disp knob to modify vertical dispersion at collimators → $\approx 0.4\sigma$ increase in margin via D_y change

- Need to pay more attention to vertical dispersion during optics commissioning

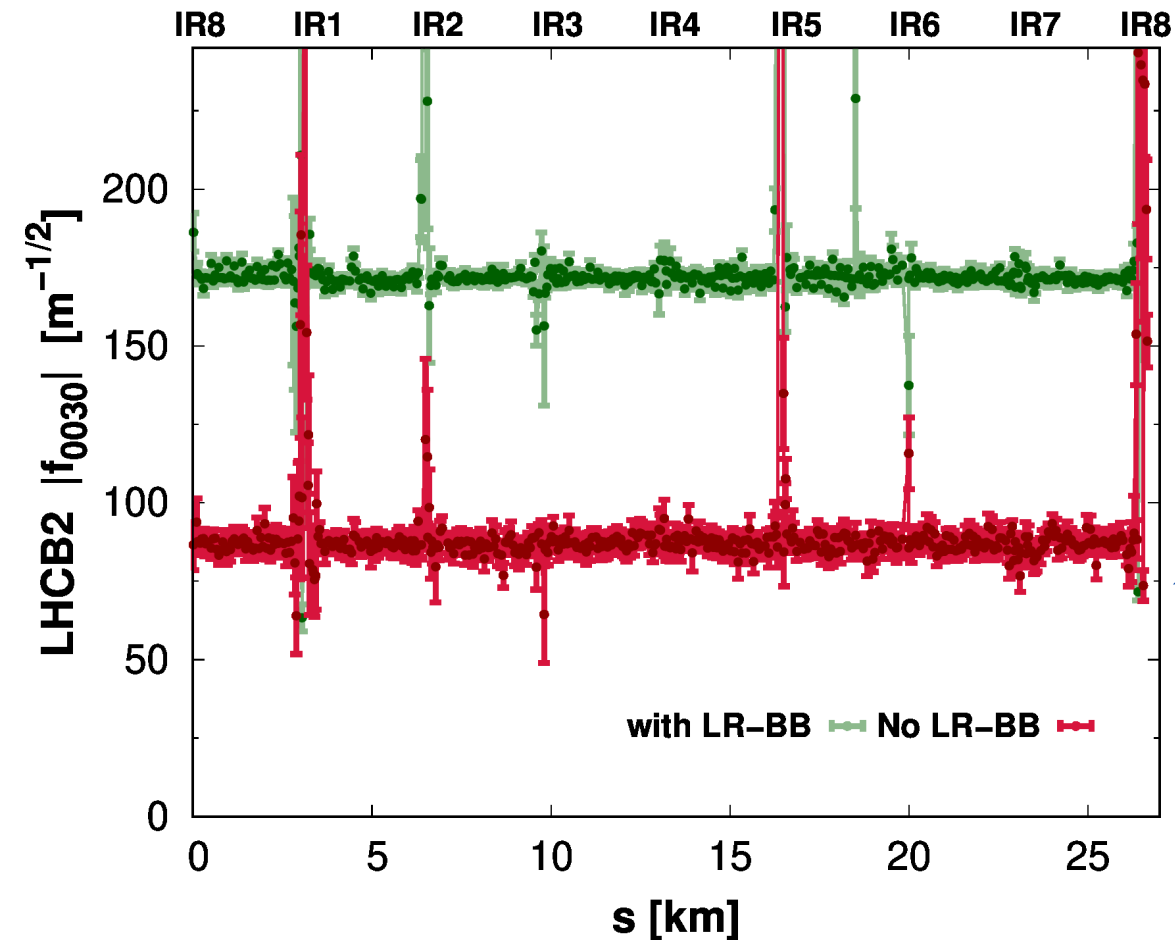


Extra sources required to explain hierarchy breakage, as didn't appear for single-beam → X.Buffat + K.Paraschou proposed 3Qy resonance

- Off momentum particles can approach the 3Qy resonance: deterioration of change of 3Qy from beam-beam due to switch to RP optics could distort phase space differently at TCP/TCSG contributing to breakage
- Reduction in Q' to stop off-momentum particles hitting 3Qy gave $\approx 0.2\sigma$ margin
- Applying partial a3 correction for lattice errors gave $\approx 0.2\sigma$ margin
- Report on mitigation gains: D.Mirarchi, LBOC 4/06/24 <https://indico.cern.ch/event/1420698/>

During 2024 intensity ramp up breakage of collimator hierarchy of LHC B2 was seen

→ Appears that 3Qy resonance can also contribute to the breakage



Large contributions to measured 3Qy resonance strength from both **lattice** and **LR-beam-beam**

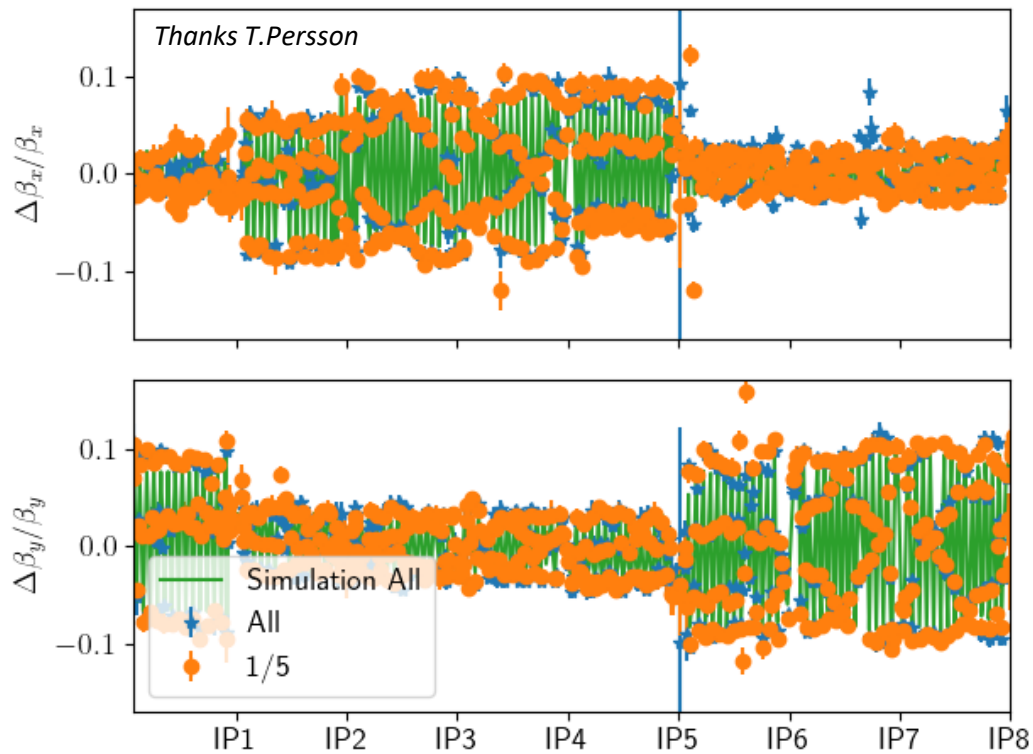
Lattice contribution is significantly worse than in previous years

- 1/3 comes from a3 errors directly (now mitigated)
- 2/3 comes from skew octupole feed-down (didn't manage to find a4 correction in 2024)
- 2/3 of lattice 3Qy still uncorrected: need new correction strategy for a4 in 2025 & HL → plan to correct directly on 3Qy feed-down in future

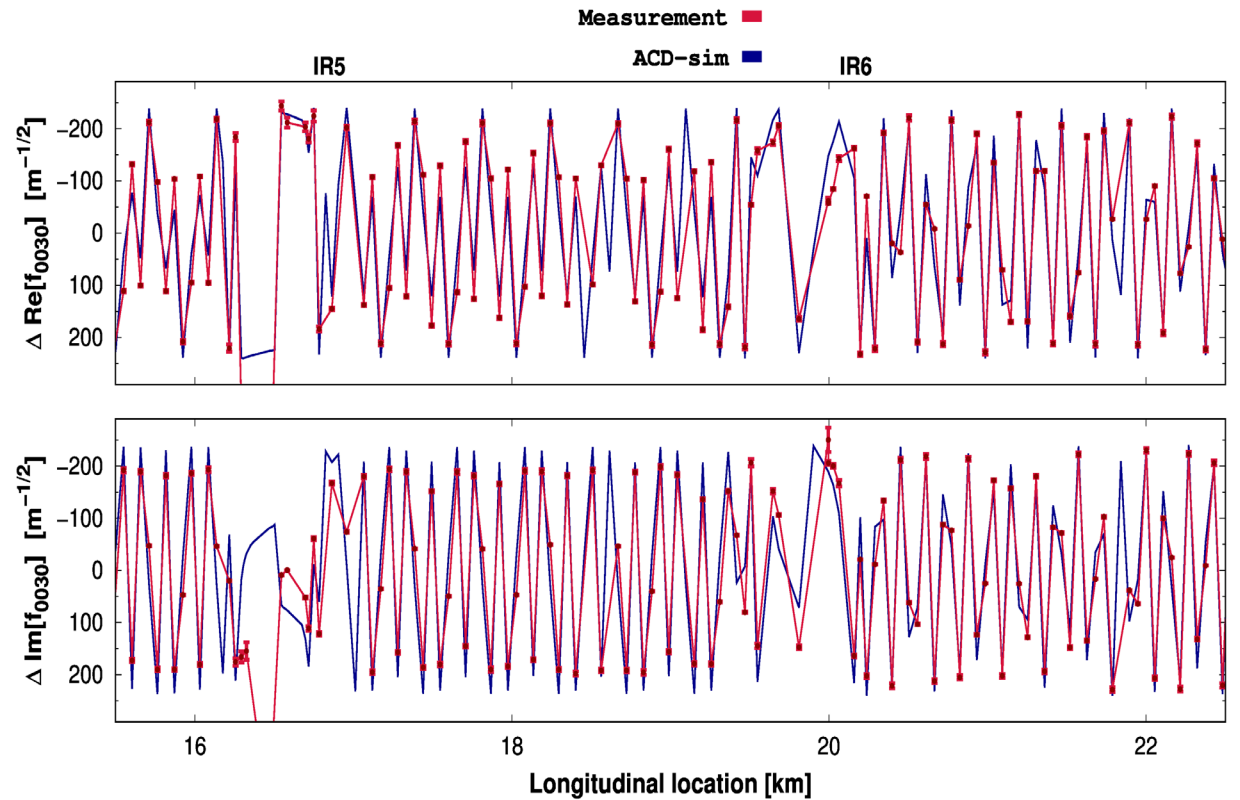
Following observations of hierarchy issue new measurement procedure used to examine optics from long-range beam-beam

- perform usual optics measurements with AC-Dipole on low-intensity pilot in collision with nominal trains
- required new dedicated measurement setup for collimators, BPMs, interlocks, developed by T.Persson

Allows direct benchmarking of linear and nonlinear optics perturbations driven by beam-beam



T.Persson, Long Range Beam-Beam investigation using Weak-Strong beams in the LHC
<https://indico.cern.ch/event/1344947/contributions/6077565/>

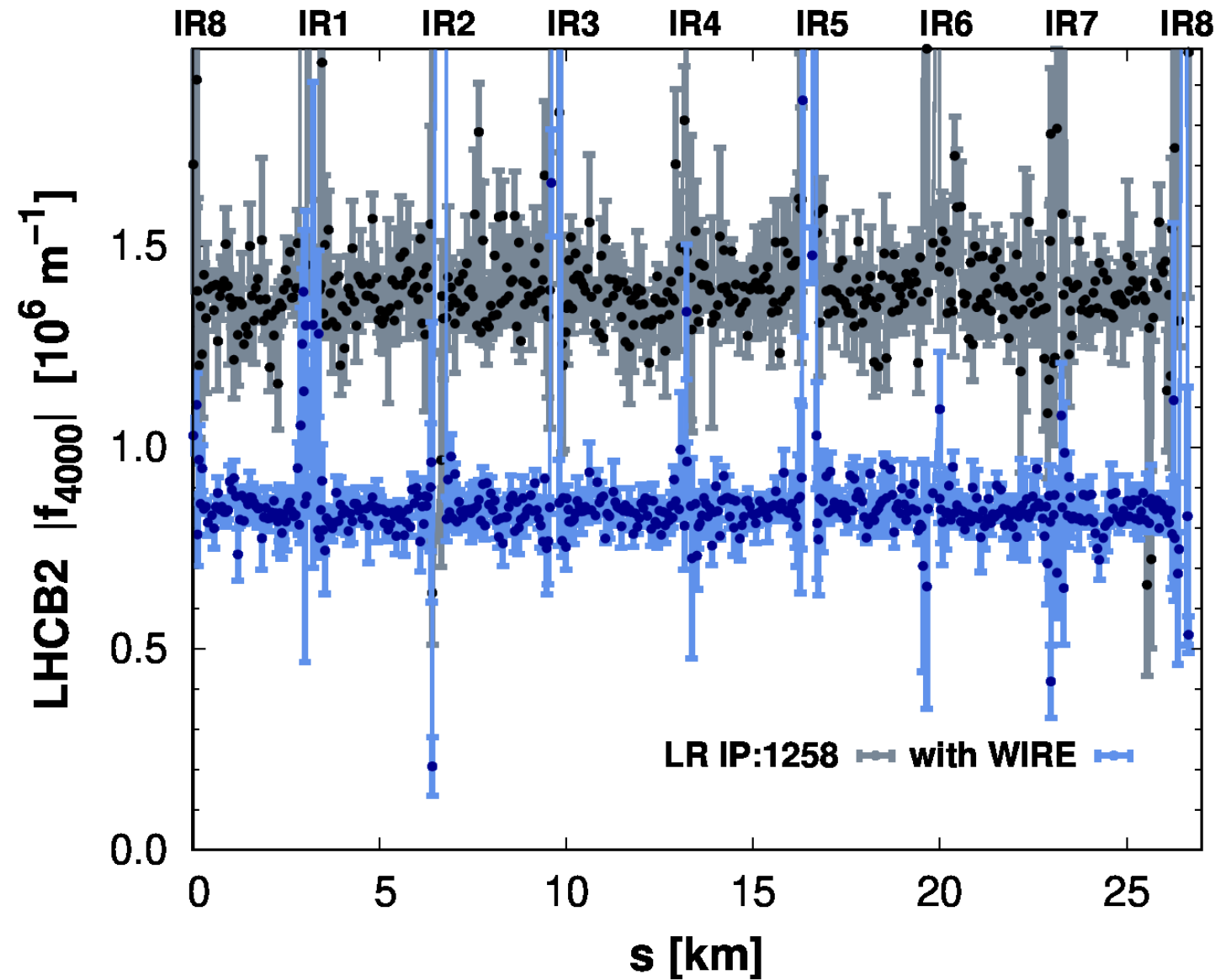


E.H.Maclean, Compensation of beam-beam driven RDTs in the LHC IRs
<https://indico.cern.ch/event/1344947/contributions/6077566/>

Correcting long-range beam-beam

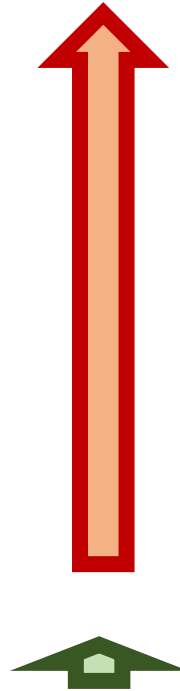
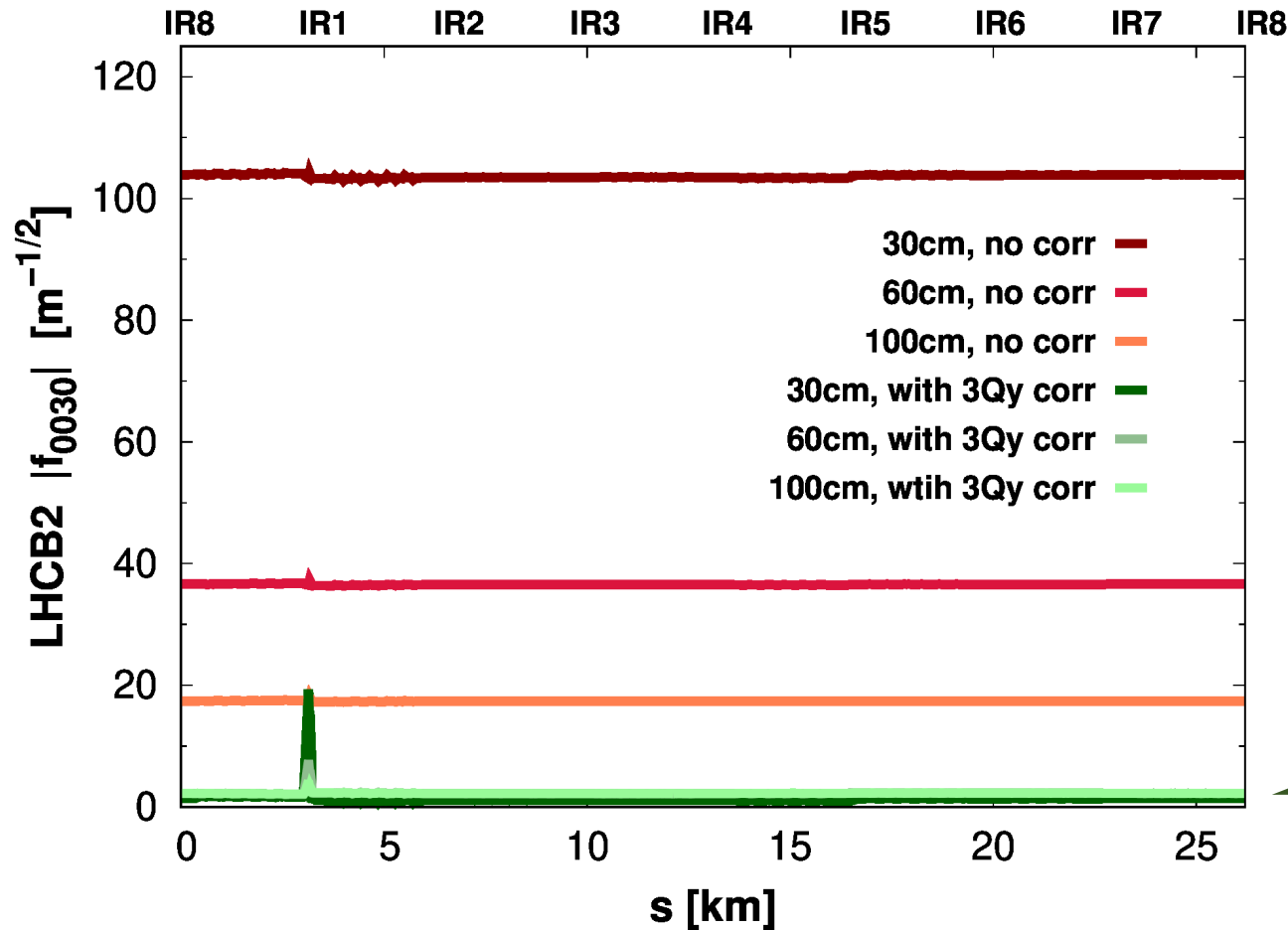
With well benchmarked models and ability to measure directly long-range beam-beam driven resonances can directly examine correction methods

Able to directly measure impact of the wire on the 4Qx resonance strength



Correcting long-range beam-beam

Using benchmarked simulations can find settings of IRNL corrector packages to suppress LRBB driven normal- and skew- sextupole resonances ($3Q_y, 3Q_x, Q_x - 2Q_y$) → application to OMC commissioning being studied

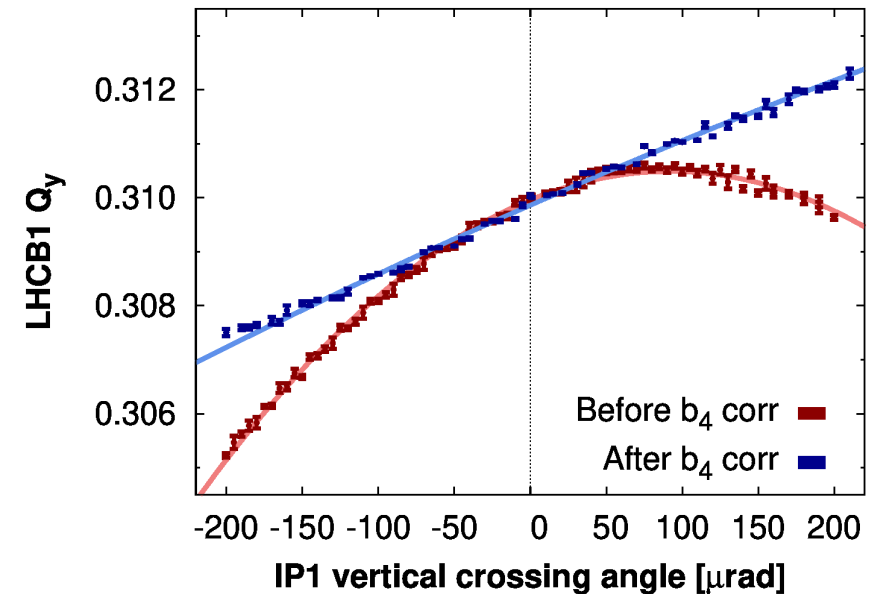
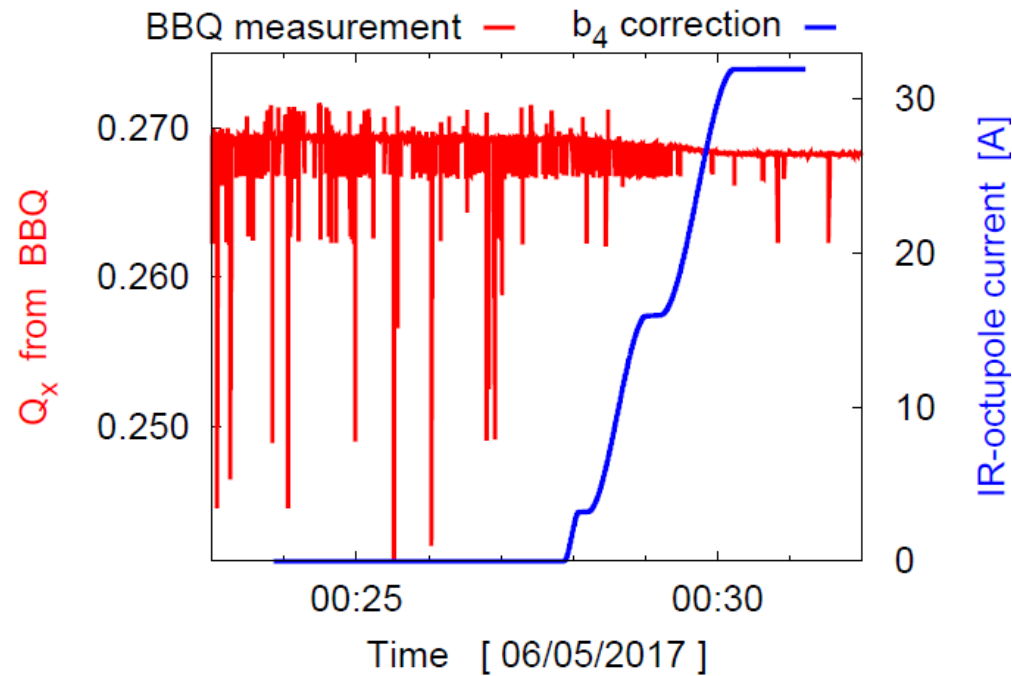


Without correction, 3Qy strength from LR-BB increases substantially through squeeze
(simulation assumes constant beam-parameters)

Skew-sextupole correction keeps LRBB 3Qy corrected through squeeze

Detuning from octupole errors in IP1/5 causes significant problems for linear optics commissioning

- Rely on K-mod for linear optics and β^* correction \rightarrow degraded by strong detuning
- Issue we have been aware of since late Run2, ran into again in 2024 as IR-b4 corrections had to be redone following polarity swap
- For 2024 ION cycle b4 corrections not initially included – no reliable K-mod data could be obtained, when attempted global corrections without K-mod data failed to achieve target β^* -beat



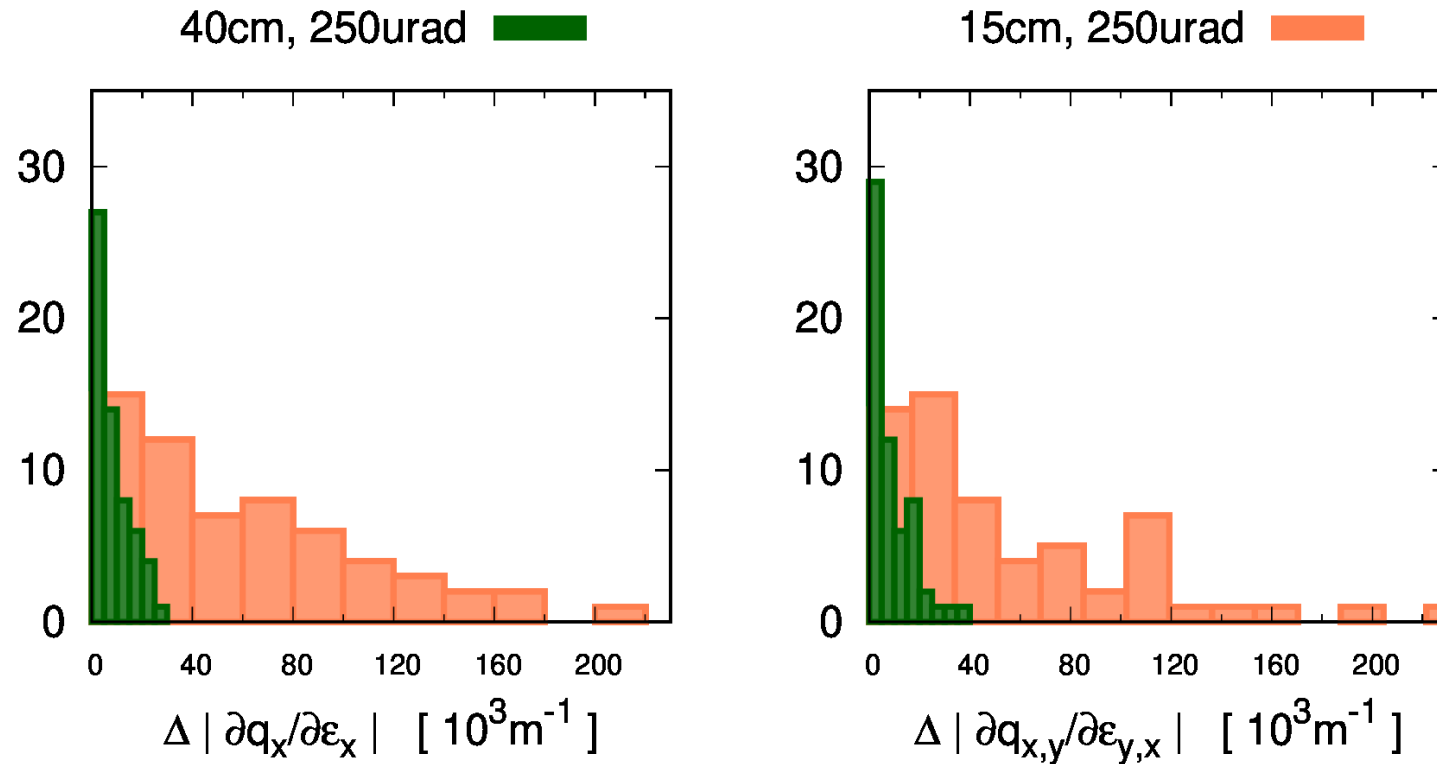
Normal octupole corrections essential for low- β linear optics commissioning: in practice well under control

\rightarrow online corrections achieved in 2024 via detuning+FD. Non-local corrections tested in case of MCOX breakage

High-order corrections in the low- β IRs

While b_4 is well under control b_6 could potentially cause similar issues in HL-LHC via feed-down with low- β^* and high crossing-angles

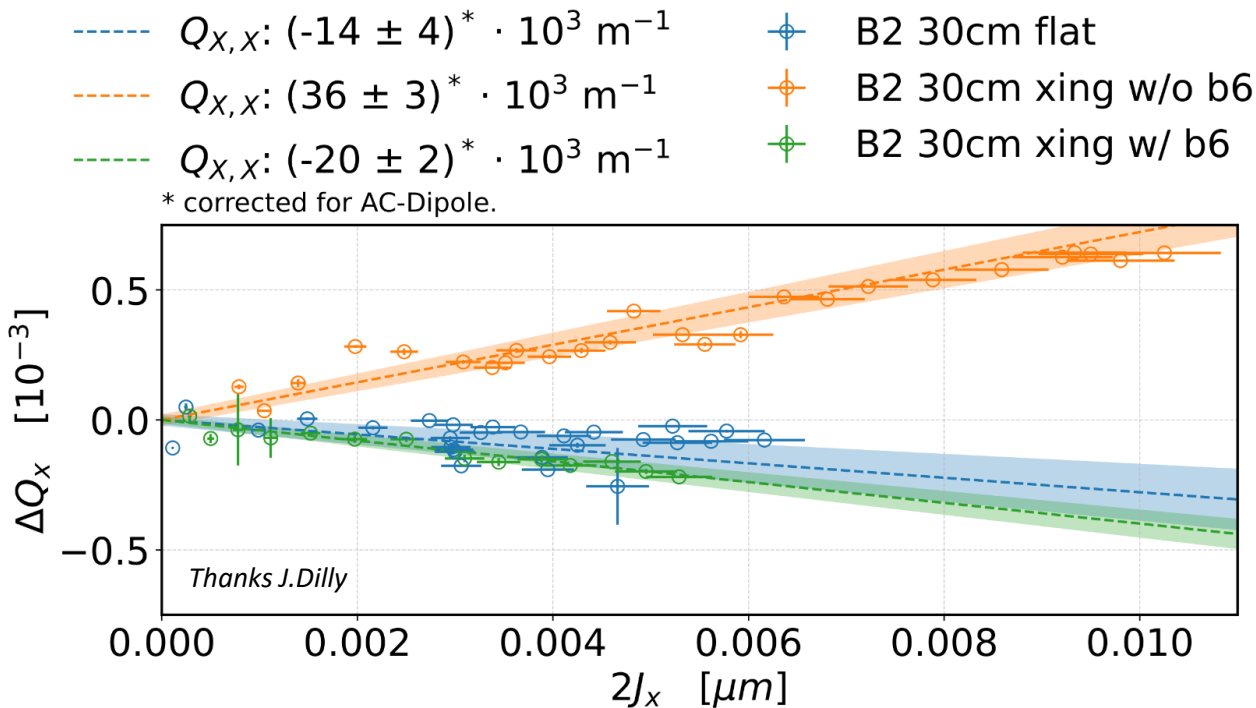
- see clear problems for linear optics commissioning when detuning is around $40 \times 10^3 [\text{m}^{-1}]$
- significantly higher tuning can degrade forced-DA to point where we struggle to excite with ACD to meaningful amplitude
- Target residual detuning for instabilities was estimated at $15 \times 10^3 [\text{m}^{-1}]$ (old numbers)



Even where b_6 errors in triplets are in-spec, can potentially pose challenges for the optics commissioning at low β^* if uncorrected

Dodecapole corrections in IP1 and IP5 achieved for first time in 2022 by correcting feed-down to detuning with X'ing

- Still very far from an online correction – compensation in 2022 required multiple measurements over commissioning period, finally implemented via follow-up studies in MD several months later
- Following triplet polarity swap in 2024 attempted to find correction of b6 during 1-2 shifts in regular commissioning
 - in practice attempts were unsuccessful (since 2024 back to running without any dodecapole corrections)
 - b6 correction required very time-consuming detuning measurements at multiple Xing configurations
 - measurement quality suffered heavily from forced-DA limitation as lower orders still only partially compensated

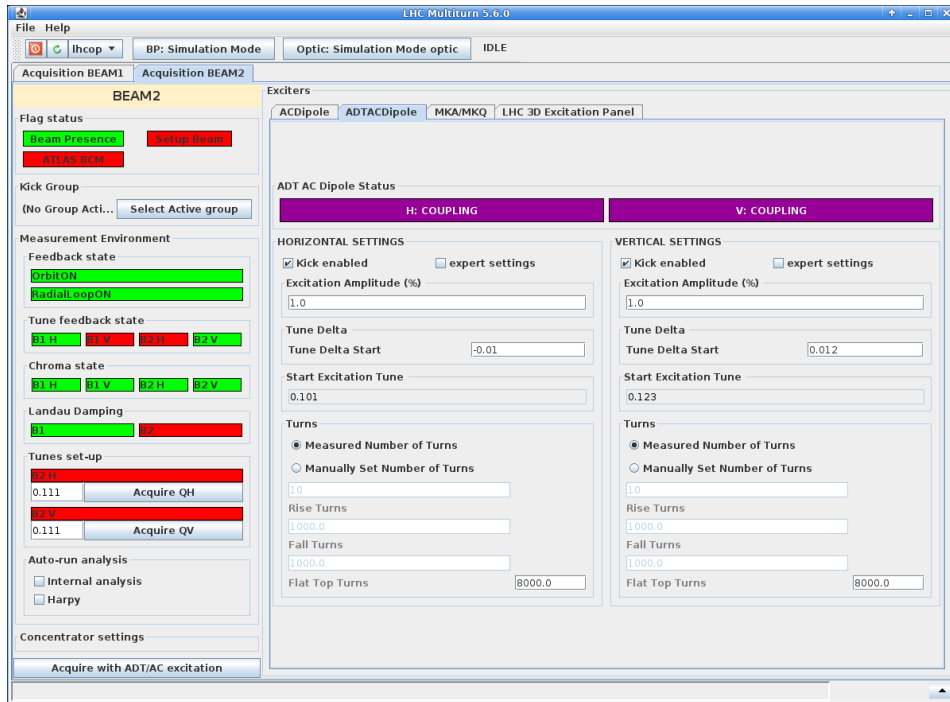


Multiple other challenges for high-order errors expected in HL-LHC

- No practical experience of beam-based correction or validation of a5, b5, a6

Commissioning time

Since trend towards increasing complexity seems likely to continue, significant effort being spent on improving OMC team tools/methods
→ nice example is switch to ADT-based coupling correction for routine monitoring without need for dedicated OMC measurements



Various efforts to make use of AC-dipole measurements & OMC tools more accessible e.g. better model creation, automatic checks of measurement setup, OP sequences for optics measurements

In practice simplification/automation of measurement process is valuable first step, but only a few shifts per year where corrections are not required

→ work should continue towards improving efficiency of corrections

Thanks U.Karr

Beam-time requirements for commissioning are significantly constrained by limitations of the AC-dipole hardware

→ Need to take a certain number of kicks to perform an optics measurement – repetition frequency of AC-dipole kicks is limited

Conclusions

- LHC commissioning so far in good state throughout Run3
 - noting that push to smaller β^* and higher ATS-factors has driven increasing complexity of the commissioning process
 - need to continue improving efficiency of OMC tasks to accommodate future challenges of HL-LHC
- A few clear challenges relevant to HL-LHC commissioning emerging during Run3
 - local arc errors become problematic at high-ATS factors: for now arc-bump compensation still far from being online correction
 - energy shifts during commissioning generate large beta-beat at low- β^*
 - high-order IR corrections still challenging & in some cases not online. Several multipoles with no experience of correction
- Learning that several aspects of the optics we have historically not worried about can potentially cause issues for operation
 - vertical dispersion → ALICE background, collimator heirarchy
 - IR skew sextupole and skew octupole → collimator heirarchy
- Very interesting application of OMC methods to study of long-range beam-beam
 - application to optics commissioning strategy being studied

