Outlook for HL-LHC optics commissioning

The LHC **O**ptics **M**easurement and **C**orrection Team

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HL-LHC has ambitious optics commissioning plan for first years of operation:

- **Injection commissioning / polarity checks**
- **commissioning of multiple special optics** (e.g. ballistic for BPM calibration)
- **Measure virgin machine to** $\beta^* = 0.3\,\mathrm{m}$
- **Local optics corrections in IR** (linear coupling and $\Delta\beta/\beta$)
- **Interleaved linear / nonlinear corrections**
  - $\rightarrow$ Correct IR sextupole and octupole errors ($\mathrm{a}_3, \mathrm{b}_3, \mathrm{a}_4, \mathrm{b}_4$)
  - $\rightarrow$ Correct $\Delta\beta/\beta$ to $\leq 2.5\,\%$ at IP and $\leq 20\,\%$ globally
- **Decapole and dodecapole corrections to come in later years**
- **Commissioning to smaller** β^* **in later years**

This year commissioned LHC to $\beta^* = 0.3\,\mathrm{m}$ from scratch

$\rightarrow$ **first time taking virgin LHC to such low-**β^*

$\rightarrow$ **first time commissioning LHC with large ATS factor** $(= 2)$

$\rightarrow$ **condensing years of Run 2 iterative developments into single step**

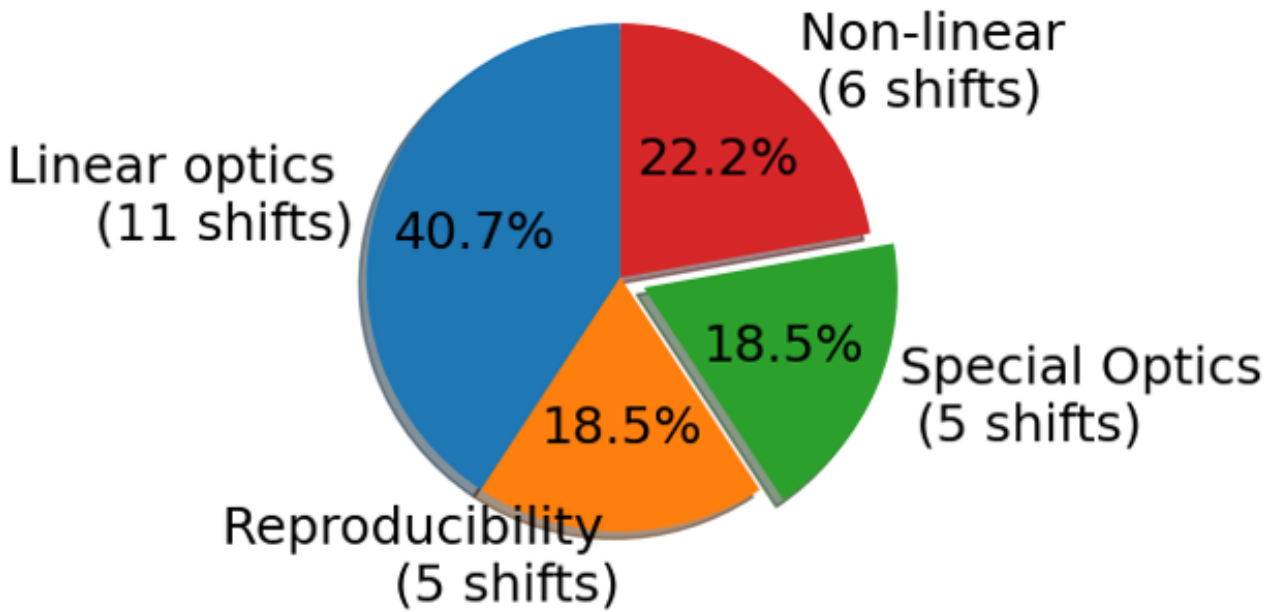
based on 2022 experience what is outlook for HL-LHC commissioning?

Overview

- **2022 commissioning overview**
  → shifts, team, and software requirements
- **Linear optics commissioning**
  → achieved β-beat
  → sensitivity to machine setup
  → K-mod challenges
  → Local corrections in arcs
- **Nonlinear optics commissioning**
  → how successful?
  → b_4 deterioration
  → sextupole hysteresis
  → first b_6 corrections in LHC
- **AC-dipole**

2022 was extremely long and challenging optics commissioning!

- **27 shifts of optics measurement and correction** (+3 extra OP-development shifts)
  → factor ≈ 2× increase vs higher-β^* / iterative commissioning in Run1-2
  → from Day 2 (22nd April) until start of stable-beams (2nd July)



- **Successfully commissioned linear optics of nominal cycle plus multiple special optics**
  T.H.B. Persson, '*Linear Optics Measurements and Corrections*' LMC, 6 July 2022
- **Could not achieve same quality of NL-optics correction as Run2 or HL-LHC targets**
  E.H. Maclean, '*Non-linear Optics Measurements and Corrections*' LMC, 6 July 2022

Only possible thanks to large, well motivated, team!

- ≈ 15 people directly contributing to optics measurements and corrections
- relying on contributions from external collaborators plus other projects/machines (injectors, FCC, muon...)

Software status

Basic OMC functionality implemented in extensively used control room tools

- β-beat measurement
- linear coupling
- global and local corrections

Over Run 2 significant diversification of OMC tasks during commissioning
$\rightarrow$ new capabilities not well integrated into general OMC tool-set/experience

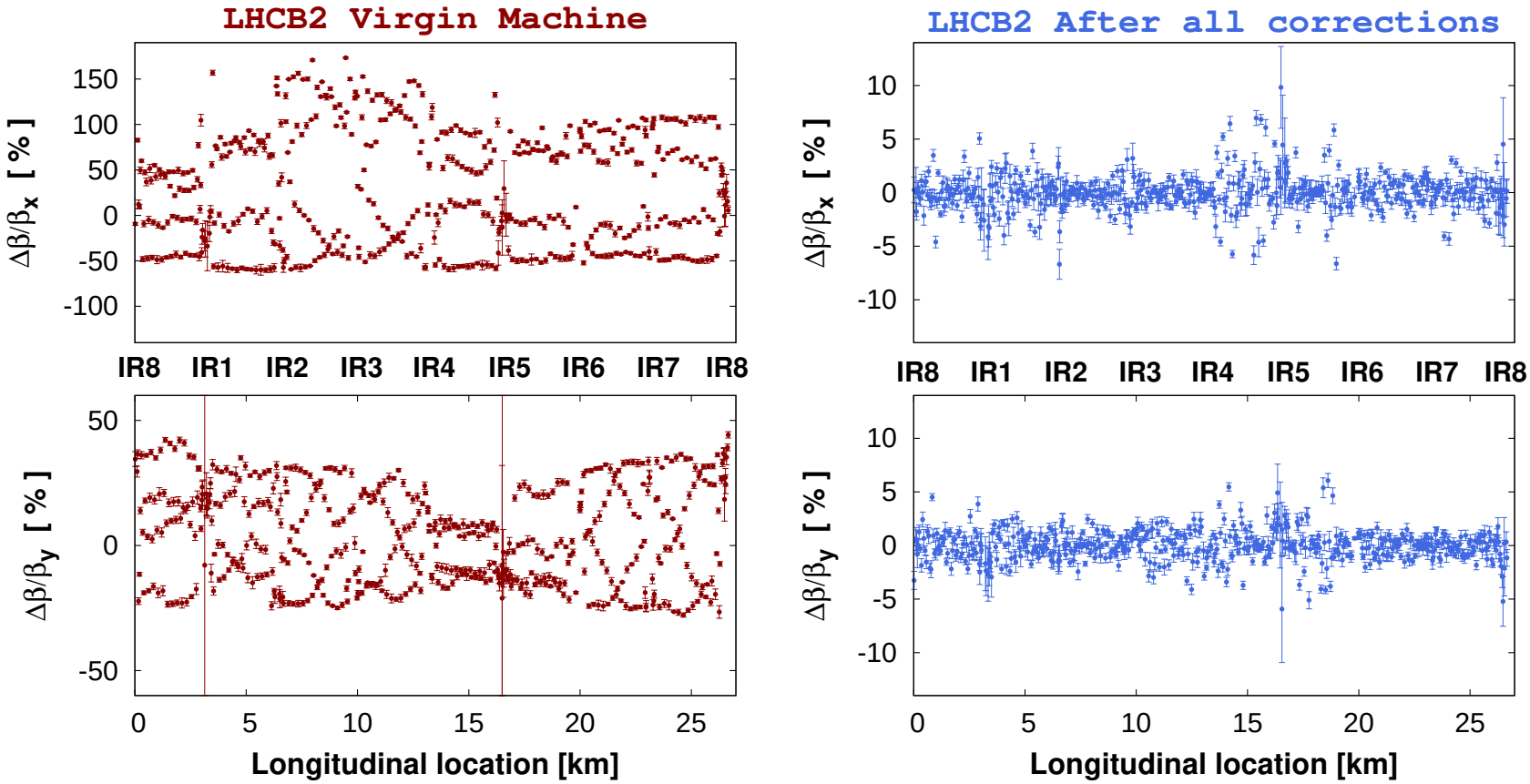
- Machine Learning for bad-BPM detection
- Action Phase Jump local corrections
- Online model creation
- MKD - TCT phase advance correction
- Manual correction of waist shifts
- local coupling at IPs
- nonlinear optics measurement and correction
- ...

Key task for Run 3 is to update OMC control-room tools with user-friendly functionality needed for HL-LHC

Ultimately very successful linear optics commissioning

→ achieved HL-LHC target optics quality starting from record high β-beat!

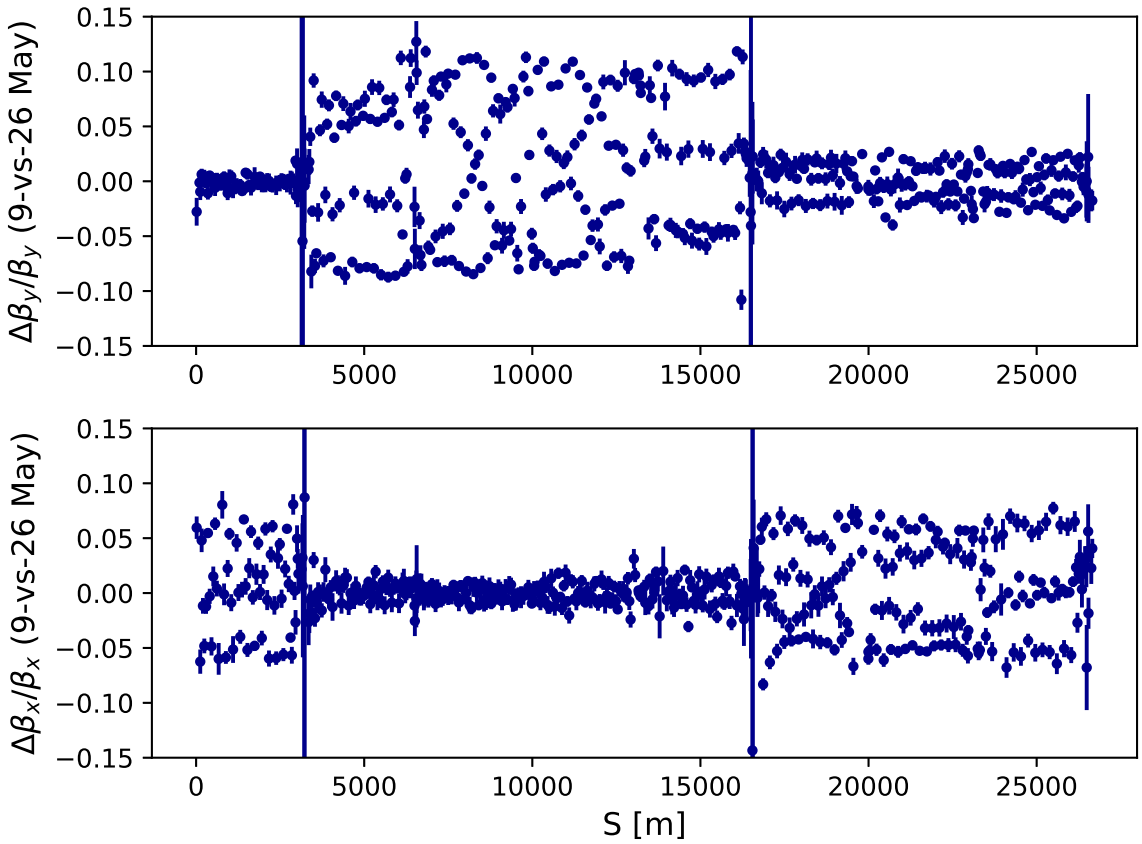
→ Final estimated luminosity imbalance due to β-beat within 1 %



W.R.T. linear optics HL-LHC plan to go straight to 30 cm in Year 1 appears achievable → still very challenging and 2022 was not straightforward...

At 30 cm we are extremely sensitive to small changes in the machine setup!

- orbit settup in 2022 was performed part-way through optics commissioning
- resulted in path-length change for closed-orbit and introduced $\Delta E/E \approx 1 \times 10^{-4}$
- caused 10 % relative β shifts and needed iteration of IP1/5 local corrections
  (relevant to orbit setup - not behaviour expected from orbit feedback)

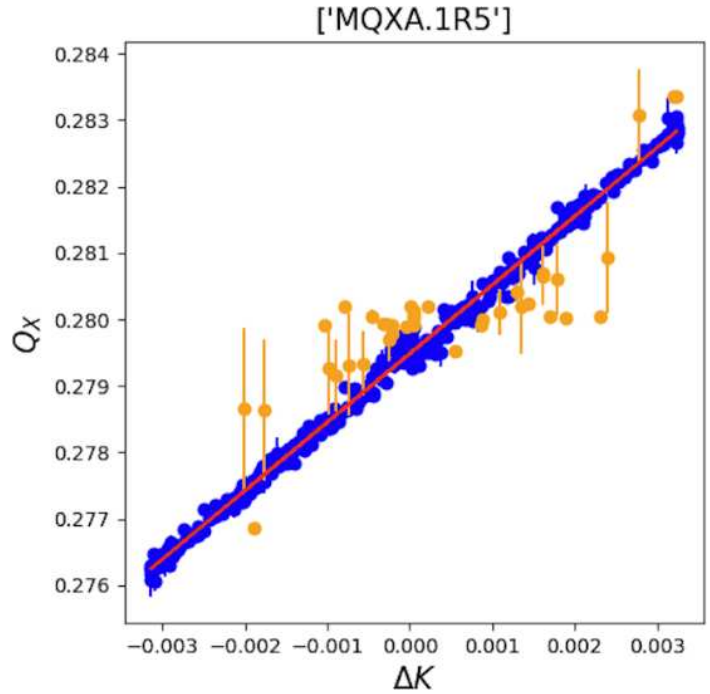


Optics shifts due to changes in machine state will need more careful consideration/planning for future years → especially going to smaller β^*

K-mod becomes more challenging at low-β^*

- **increased sensitivity to tune jitter**
- **increased sensitivity to alignment errors**
- **worse orbit leakage**
- **...**

substantial challenge for $\beta^* \leq 20\,\mathrm{cm}$ in HL



Main K-mod issue in 2022 was poor reliability of BBQ data quality at $30\,\mathrm{cm}$

→ **Not understood. Some shifts obtain good quality K-mod data, others very poor. Seems less reliable at end of squeeze.**

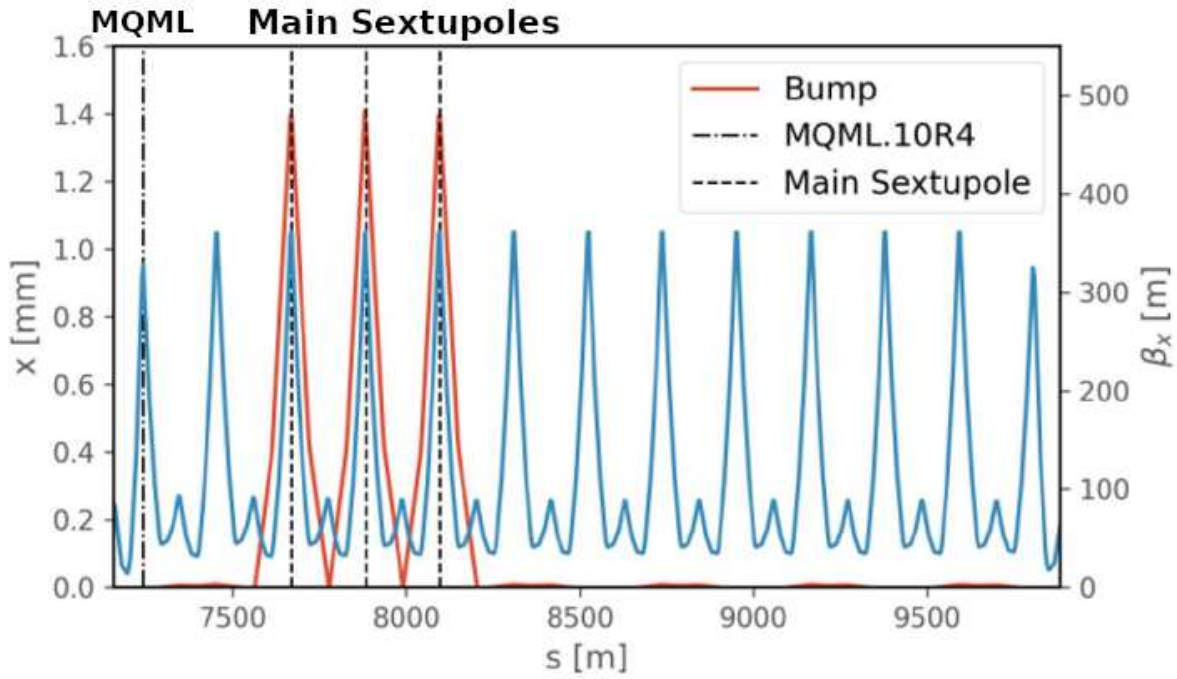
→ **NL-optics corrections influence BBQ quality, maybe in conjunction with beam quality.**

→ **Not a fundamental problem this year, but significantly influenced OMC efficiency**

Key objective for Run 3 is to improve and test K-mod measurement and analysis techniques

Larger ATS factor meant local errors in the ARCs became significant to operation for the first time

- After local optics corrs in IRs, still struggled to find global corrections for LHCB1
- Due to local errors in Arc45 & Arc81: corrected by orbit bumps through main sextupoles
- Previously had been problem in Run2 flat-optics MD
- 2022 corrections agreed very well with those found in Run 2



Key objective for Run 3 is to achieve good understanding of local arc errors/corrections, ready for implementation at start of Run 4

Non-linear optics commissioning in 2022 only partly successful

→ **Did not achieve target goals for year 1 HL-LHC commissioning**

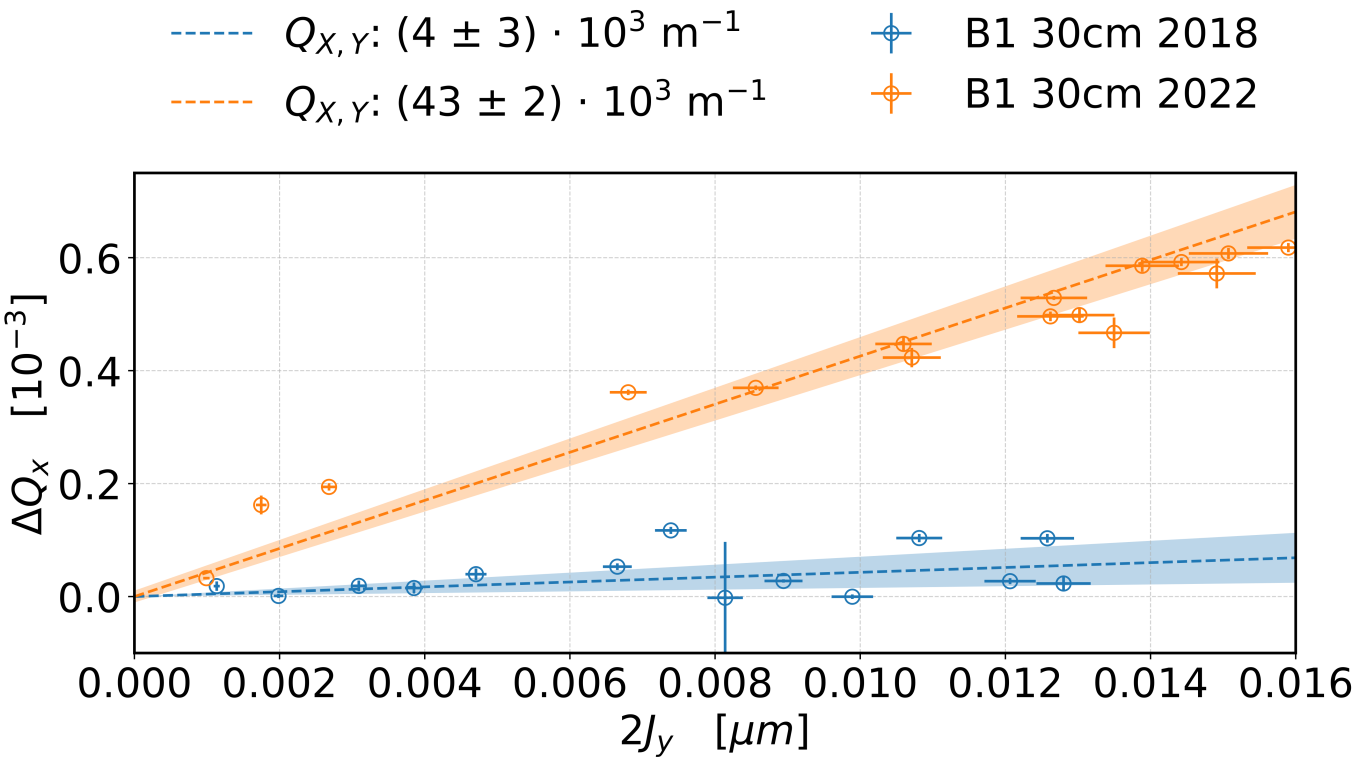
→ **Did not match quality achieved iteratively over course of Run 2**

multipole order	2017/18	2022
normal-sextupole	✓	✓
skew-sextupole	✓	✓
normal-octupole	✓	✓ ✗
skew-octupole	✓	✗
normal-dodecapole	✗	✓

Obtain only a partial correction of the normal-octupole errors

→ **Expected to be able to re-use Run 2 b_4 corrections (previously consistent)**

→ **observe significant degradation of amplitude detuning since Run 2**



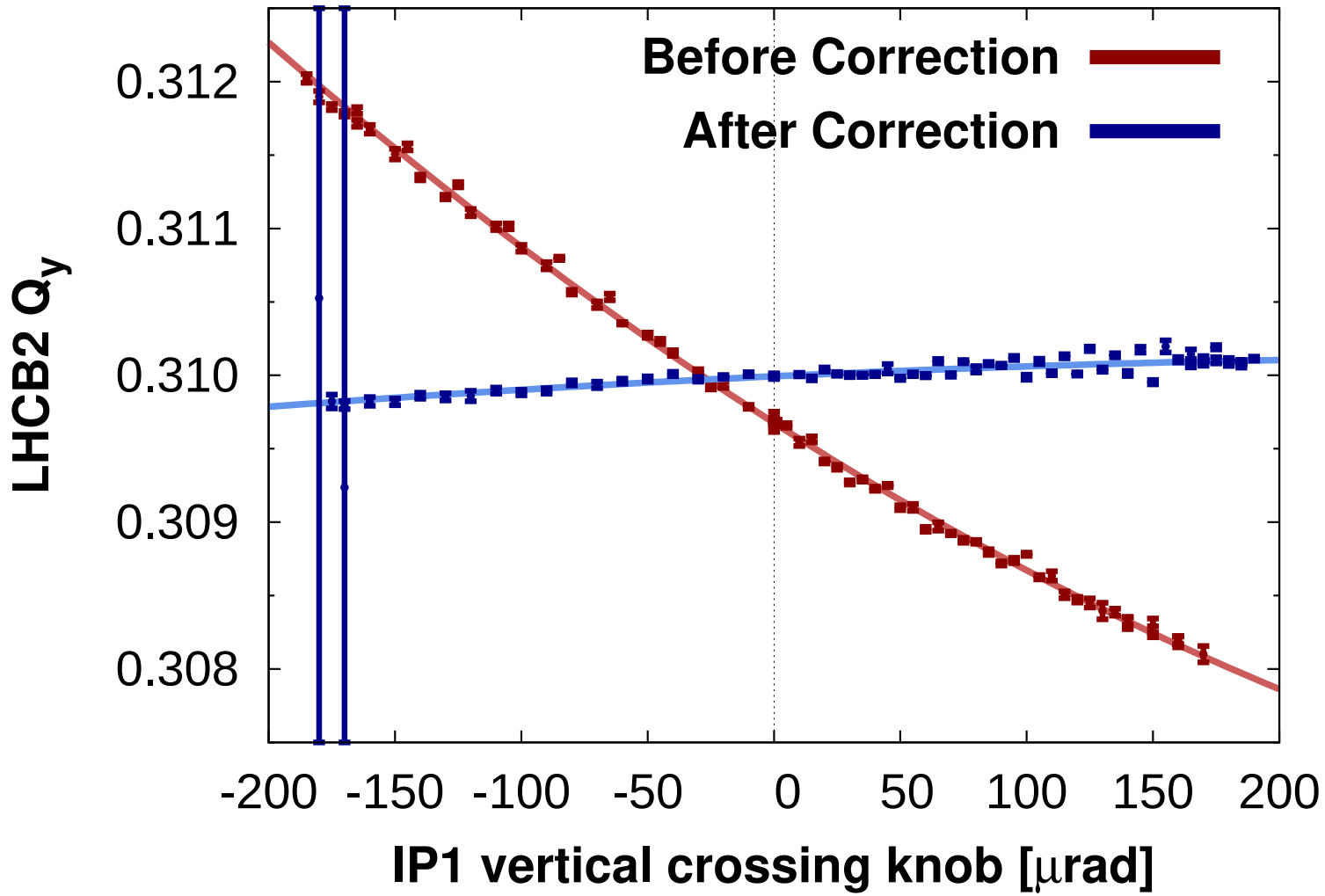
Effectively loose 20 % of available LHCB1 MO strength at 30 cm due to residual b_4

→ **could not find correction online during commissioning**

→ **source is not understood** (ruled out IR-sextupole, global-β-beat, and IP waist shift)

→ **Priority for coming year is to understand and correct**

As in Run2, normal/skew sextupole corrections were determined by minimizing linear feed-down to tune vs crossing-angle

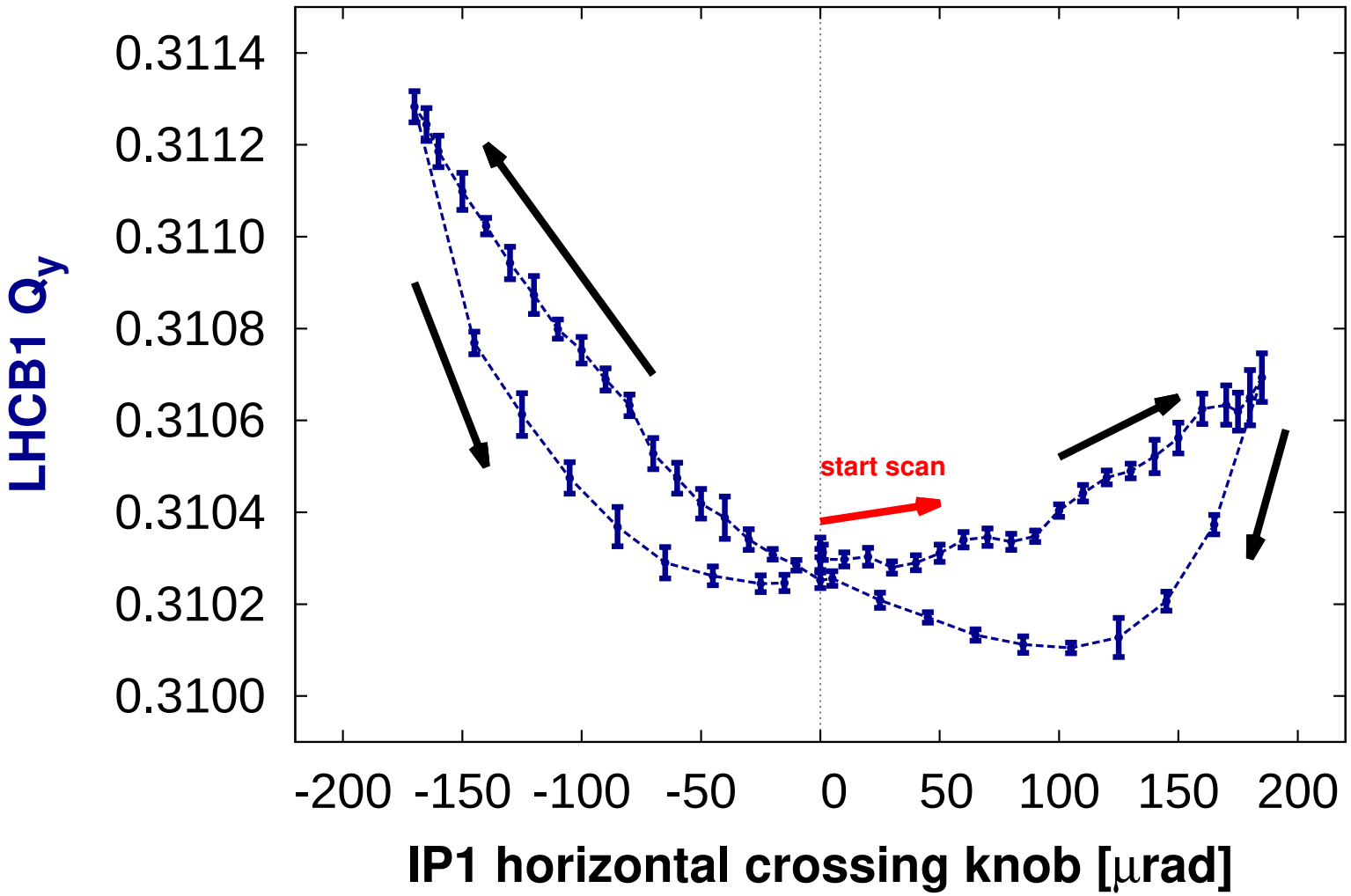


Observed tune hysteresis during crossing-angle scans (not seen/noticed in Run2)

→ **Not explained by orbit leakage or orbit hysteresis**

→ **One possibility is NL-errors generated by orbit correctors**

→ **task for Run 3 is to follow up in MD to understand and test options for correction**



Ran out of time during 2022 commissioning to attempt measurement or correction of skew-octupole errors

Key Run 3 aim is to improve the efficiency of NL-optics studies:

- **Nonlinear optics studies (detuning measurements, sextupole scans) very manual procedures in control room requiring significant beam-time**
- **Analysis of NL-measurements is still very painstaking and time consuming**
- **to be ready for (a_3, b_3, a_4, b_4) correction in Year 1 need significant improvements to control-room and analysis software tools for NL-optics**

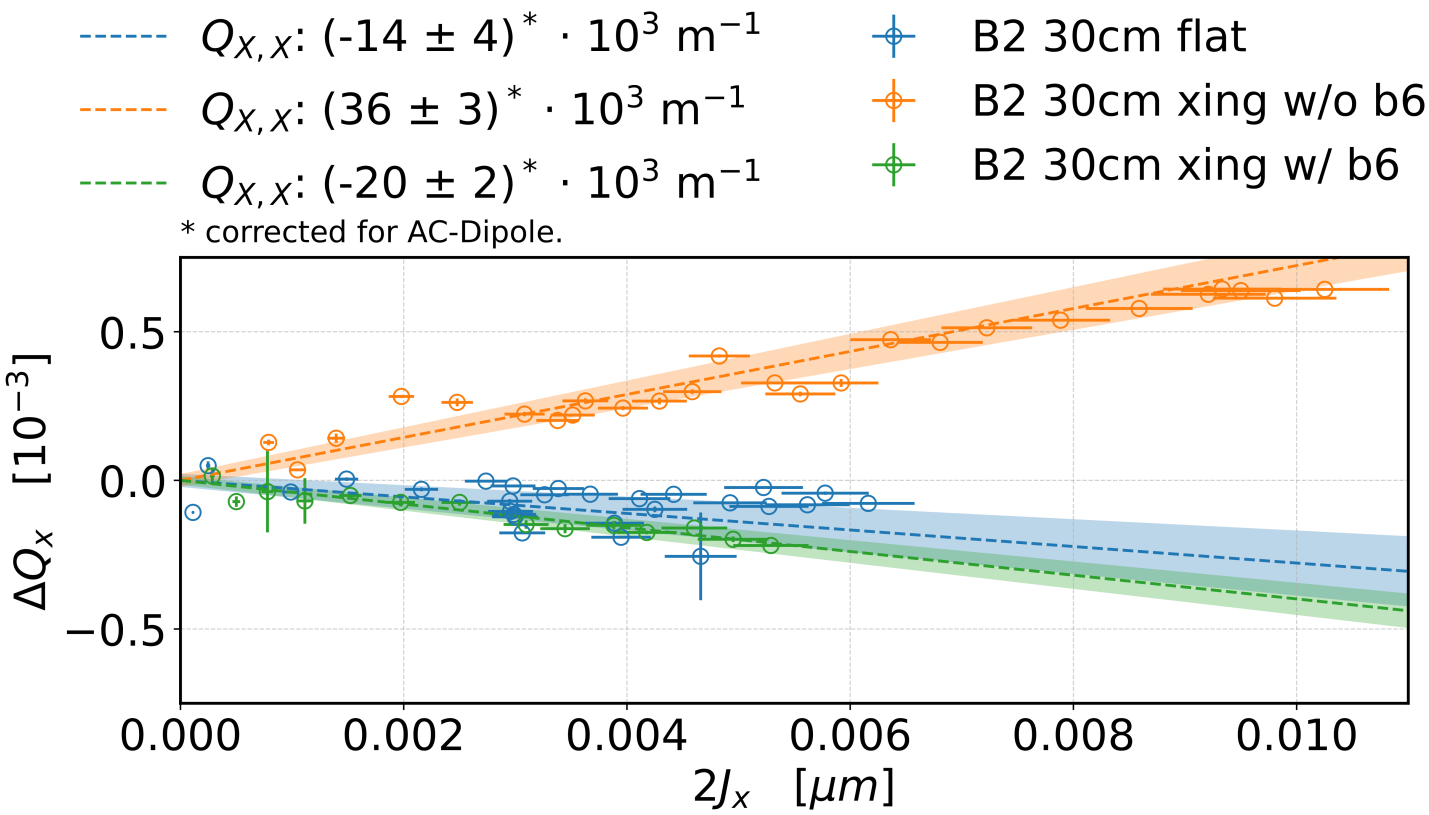
Big improvement to 2022 commissioning strategy was switch to more interleaved optics/collimation settup:

- **Collimation team performed extra measurements earlier in commissioning**
- **Prepared dedicated optics measurement collimator sequences**
- **Big benefit to efficiency of both linear and nonlinear optics studies**

For $\beta^* \leq 30\,\mathrm{cm}$ want to be able to measure and correct up to dodecapole errors

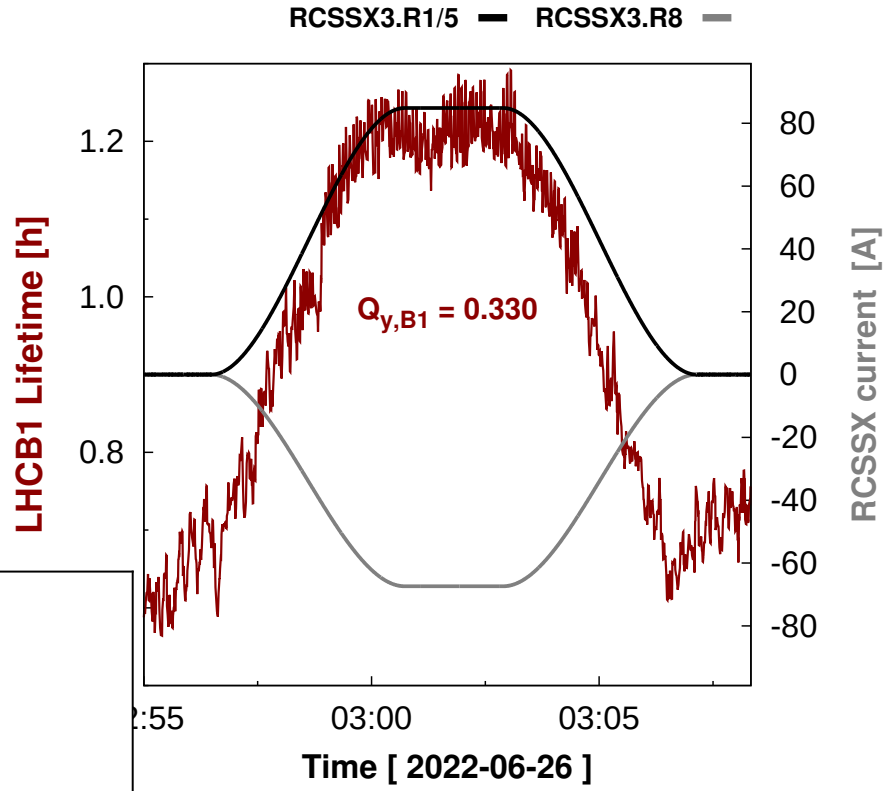
→ first correction of b_6 errors in LHC implemented operationally in 2022

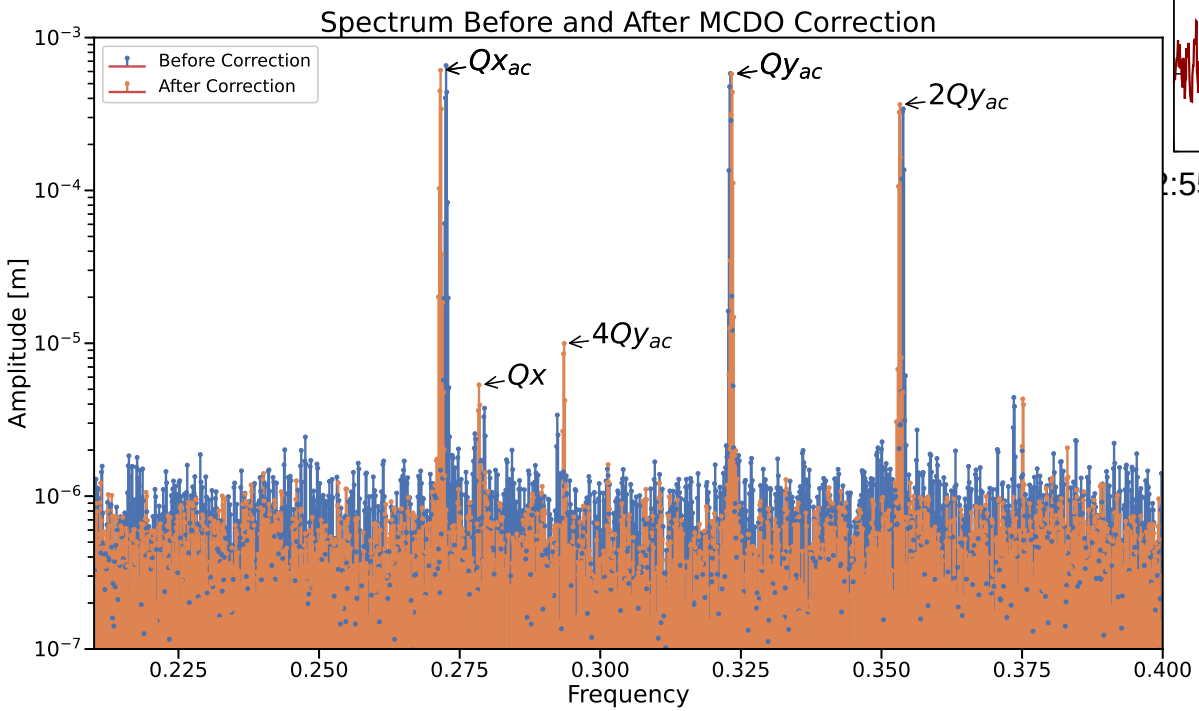
→ IP1/5 MCTX powered to minimize change in detuning with Xing-scheme



Some interesting developments for NL-optics at injection in 2022 MDs:

- First tests correcting $3Q_y$ with IR-a_3 corrs show factor 2 improvement in lifetime close to resonance
- First measurements of decapole RDT at injection suggest Run 2 beam-based corrs deteriorate $Q_x - 4Q_y$ resonance close to beam core





Performance and reliability of AC-dipole is absolutely vital

for all linear and nonlinear optics studies in LHC!

- **$\approx 20\,\%$ of OMC shifts suffered from some sort of AC-dipole fault**
  - $\rightarrow$ **AC-dipole issues didn't limit 2022 commissioning efforts**
  - $\rightarrow$ mostly solved remotely/quickly $\approx [\mathrm{hour}]$)
  - $\rightarrow$ 2 cases required access to repair
  - $\rightarrow$ issues well understood and consolidation plan in place
- **Improvements to AC-dipole capabilities over course of LS1/Run2 were fundamental to achieving high quality optics measurements we rely on today**
  - $\rightarrow$ e.g. extensive detuning and RDT measurements only possible thanks to increases in excitation length since Run1
- **Significant interest in potential for further improvements in AC-dipole capability**
  - $\rightarrow$ longer kicks, more rapid kicks, higher amplitude kicks...

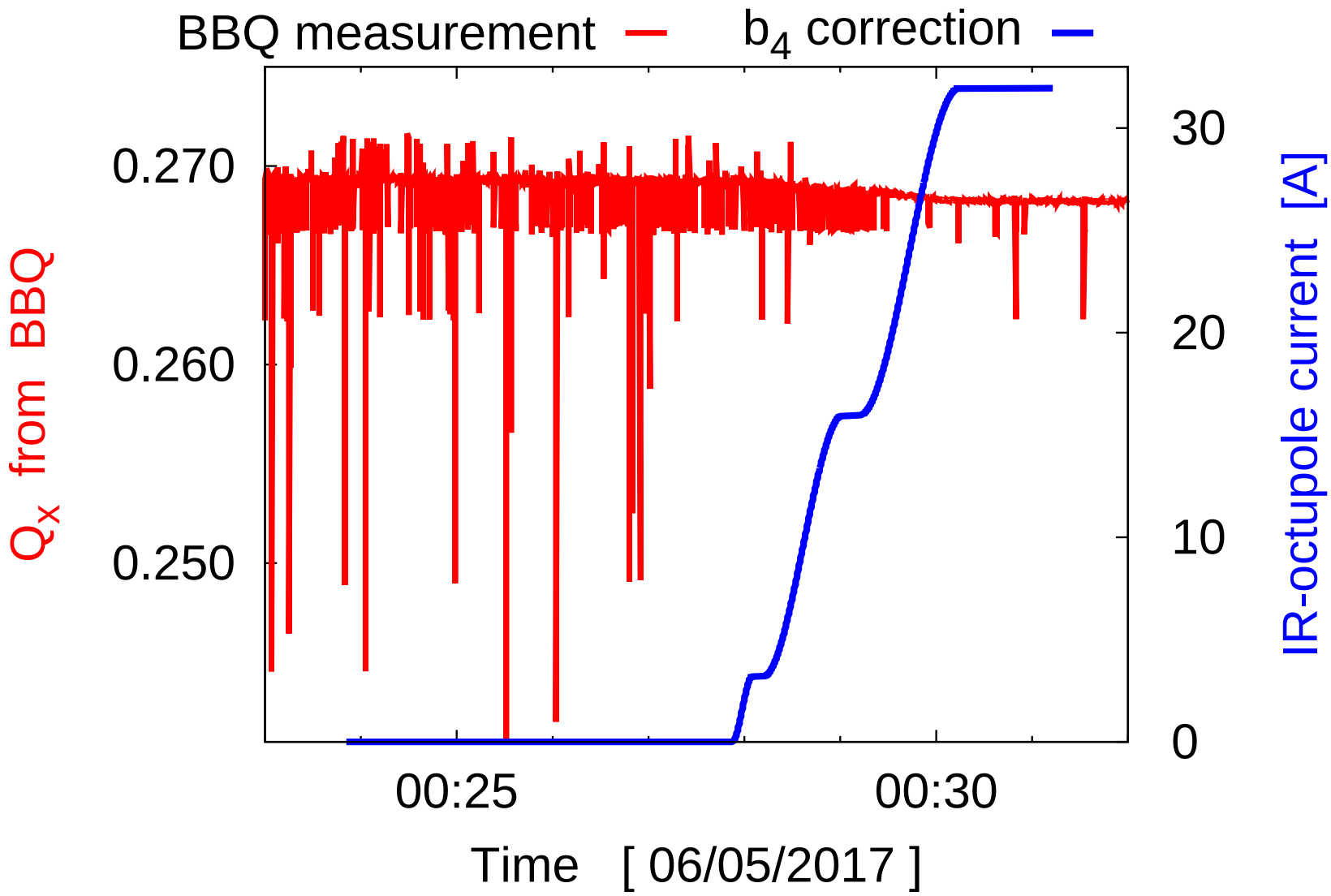
Conclusions:

- **In many ways 2022 commissioning approximates a dry run for HL-LHC**
- **Commissioning virgin optics to $30\,\mathrm{cm}$ in single year was challenging and very intensive (27 shifts!)**
- **Linear commissioning was achieved within HL-targets**

  $\rightarrow$ need to carefully consider optics stability w.r.t. machine state
  $\rightarrow$ K-mod tools and procedures need further development
  $\rightarrow$ aim to understand local arc errors by end-of-Run3
  $\rightarrow$ many specialized tasks need user-friendly implementation in OMC tools
- **Nonlinear optics commissioning had some issues $\rightarrow$ failed to achieve HL-targets or Run2 quality**

  $\rightarrow$ need significant improvements to control room and analysis tools
  $\rightarrow$ 2022 detuning residuals and crossing-scan hysteresis need to be understood
  $\rightarrow$ important demonstration of b_6 correction achieved for first time!
- **Lots of interest in potential for further upgrades to AC-dipole for Run 4**

Reserve


BBQ measurement
b4 correction
Qx from BBQ
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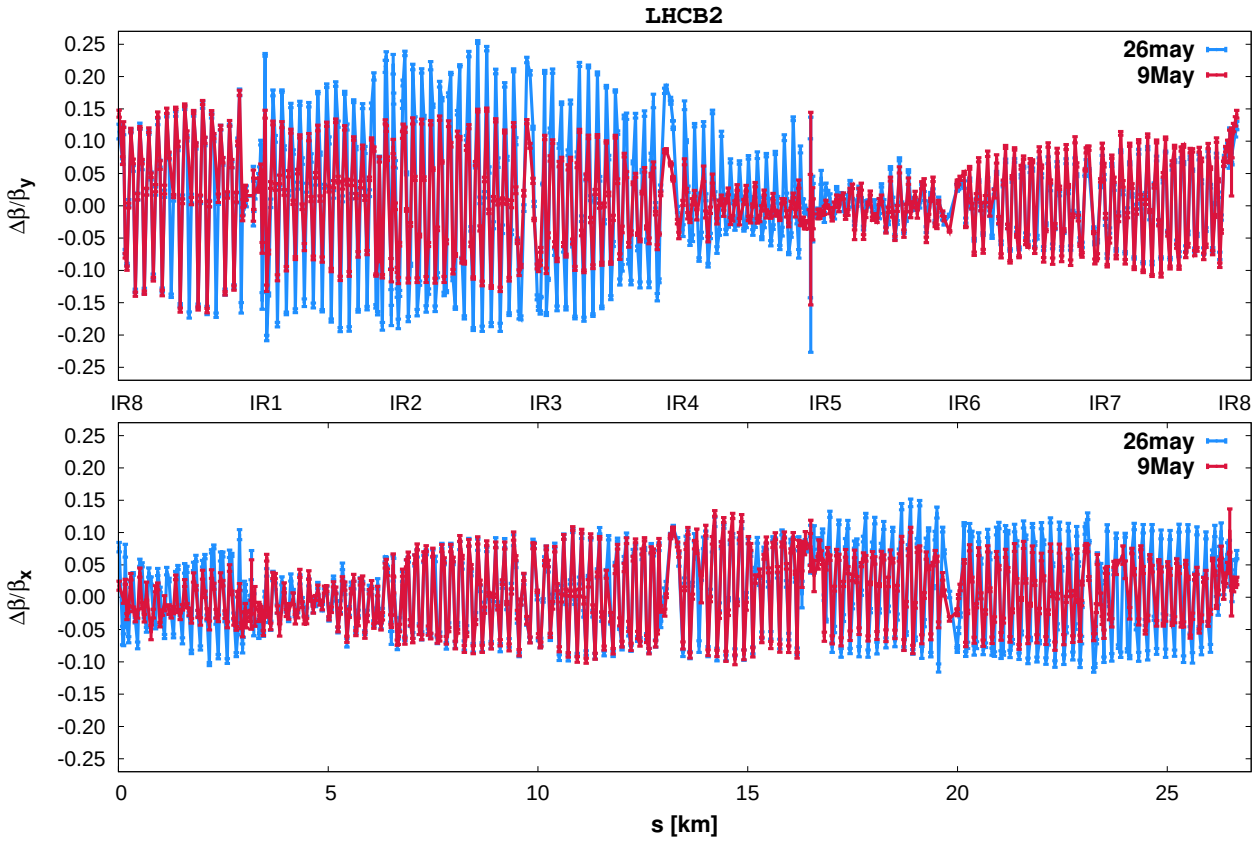
0.250
30
20
10
0
IR-octupole current [A]
00:25
00:30
Time [06/05/2017]


LHCB2
26may
9May
Δβ/βy
Δβ/βx
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
IR8
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