Optics commissioning

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

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Particular thanks to N. Magnin, P. Hagen, R. De Maria, S. Fartoukh, and to the Collimation team, OP group and EICs and BI experts supporting OMC commissioning and MD!

2022 had an extremely ambitious optics commissioning plan

$\rightarrow$ **commission virgin machine straight away to $\beta^* = 0.3\,\mathrm{m}$!**

- **First time commissioning virgin machine since 2015**
- **First time taking virgin machine to such low-β^***
- **First time commissioning LHC with large ATS factor ($= 2$)**
- **Attempting to condense years of Run 2 iterative developments into single step**

Aim of this talk is to review optics experience from 2022

$\rightarrow$ **Overview of 2022 commissioning**

$\rightarrow$ **Some particular advancements & challenges this year**

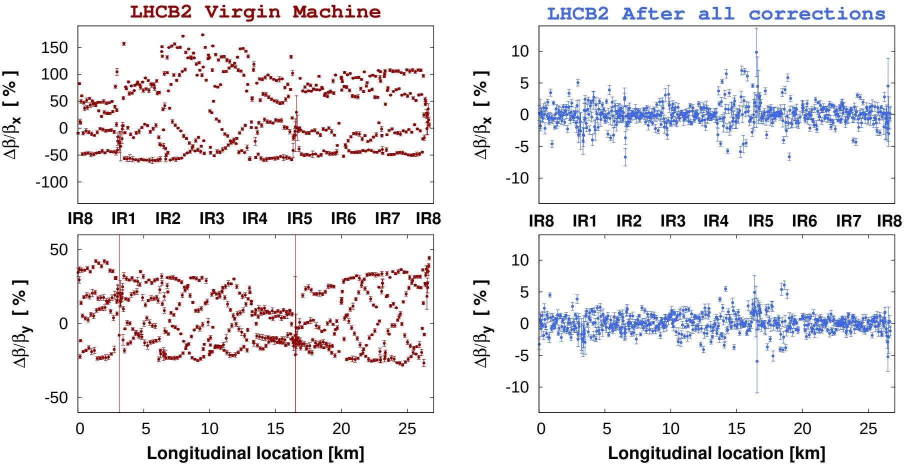
$\rightarrow$ **what will 2023 look like?**

Ultimately 2022 was extremely successful optics commissioning!

→ **achieved HL-LHC/Run3 target optics quality starting from record high β-beat!**

→ **Final estimated luminosity imbalance due to optics within $1\,\%$**

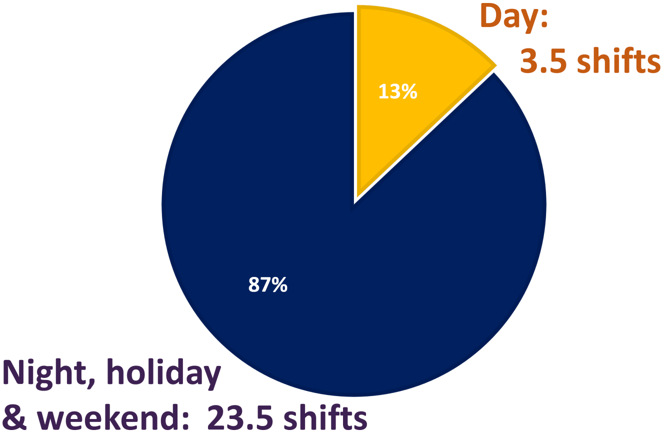
→ **key demonstration that we can commission directly to very pushed optics (challenging optics commissionings on the horizon: HL-LHC...)**



2022 was an extremely challenging commissioning for the OMC team!

Team photo post-commissioning...

27 shifts of optics commissioning in 2022

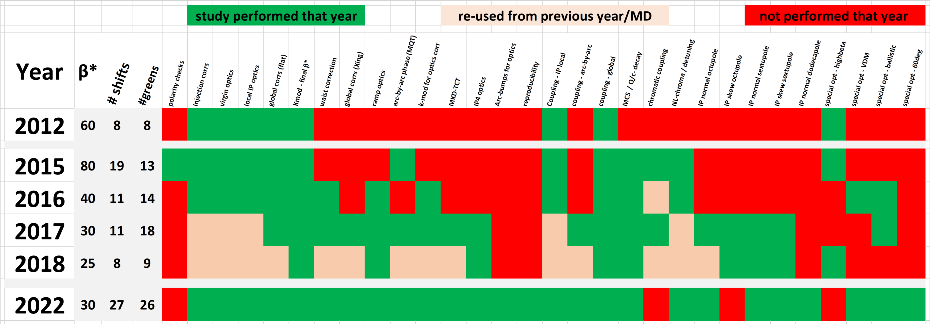


- 1 SHIFT $\neq$ 1 DAY: numerous occasions of two OMC shifts in 1 day
- OMC requires single-pilot: majority of shifts slotted in during night+weekend/holiday when other beams/teams not ready/available

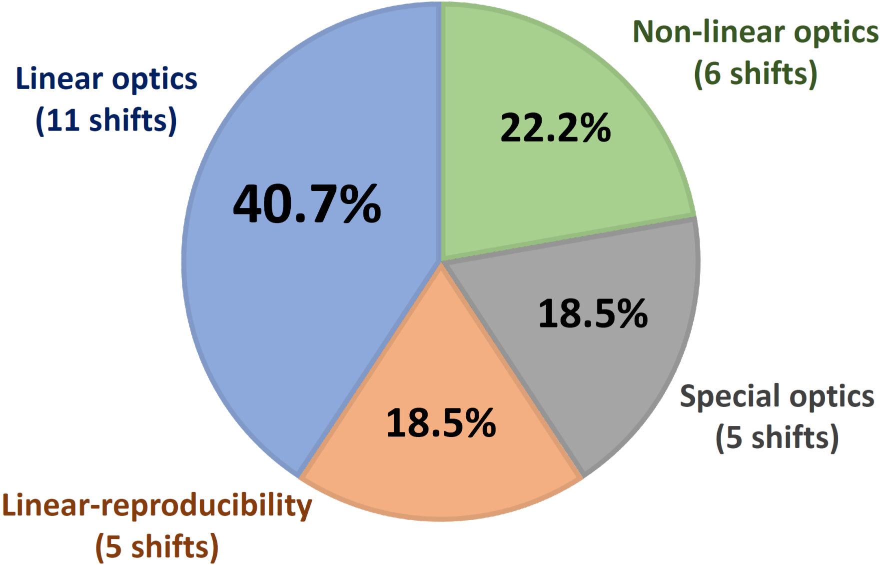
Only possible thanks to large, well motivated, team!

- ≈ 15 **people directly contributed to 2022 OMC: rely on contribution from external collaborators plus other projects/machines (injectors, FCC, muon...)**

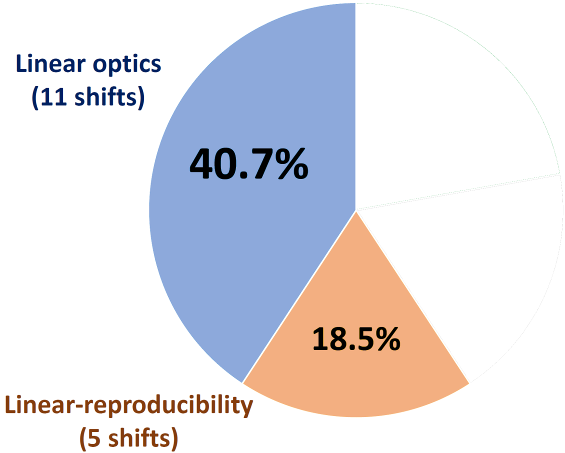
OMC activities through the ages:



- increasing complexity of optics commissioning over time as we push to smaller β^* and ATS optics
- reduce commissioning load later in run by re-using previous corrections
- 2022 was most complex commissioning to date!



- For 2022 collimation team provided dedicated optics measurement sequences
  → hugely beneficial to OMC studies this year!

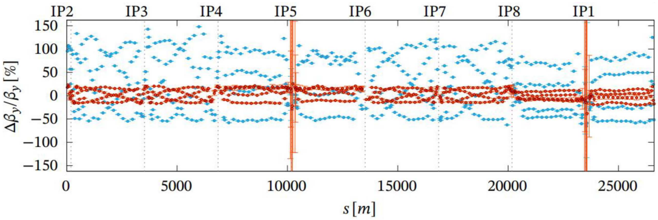


- **Majority of 2022 commissioning spent on linear optics**
  → **11 shifts divided ≈ equally between:**
  Injection/Ramp (β,coupling), **local corrs** (β), **global corrs** (β), **coupling** (local,arc-arc,global), **various other** (β-waist, final K-mod, IP4...etc...)

Local corrections in IRs vital to obtain acceptable $\Delta\beta/\beta$

→ **Historically done with SbS and a main time sink in commissioning**

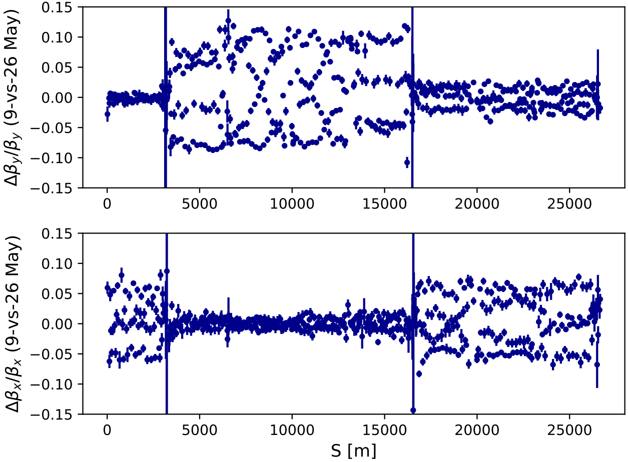
→ **(5 shifts, ~ 2 weeks, at 6.5TeV in 2015 to have local corrs incorporated)**



- **In Run3 majority of local corrs could be determined online!**
  - → **LHC IP SbS corrections determined/tested online**
  - → **Cable swap of RQTL7.L3.B1/B2 identified online**
  - → **Local error in IP7 collimation MD identified in 30 minutes**
- **For first time devoted 1 shift to comparing alternative methods**
  - → **Action-Phase-Jump (J.Cardonna et. al.) used for IR1 correction!**
  - → **First time employing non-SbS method in operation!**
  - → **APJ needs incorporation in OMC toolset to also be used online**

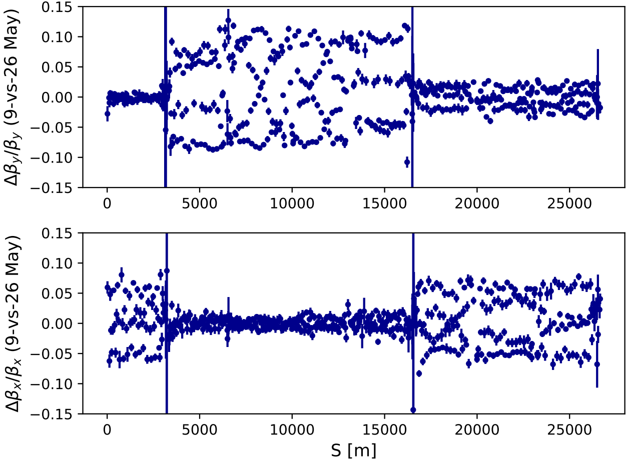
At 30 cm we are extremely sensitive to machine setup!

- **Had a scare part way through commissioning when observed $\delta(\Delta\beta/\beta) \leq 13\%$ appearing before/after LHCb velo stop**
- **Concern was this represented issue with optics stability which could hit MP targets**
- **Prompted multiple shifts to study linear optics stability & understand change**
  OMC team meeting 2nd June 2022, T.H.B.Persson & E.H.Maclean, '*Beam1 stability*', '*Beam2 stability*'



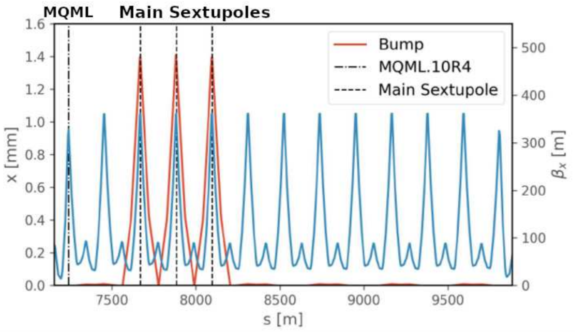
At 30 cm we are extremely sensitive to machine setup!

- orbit setup in 2022 was performed part-way through optics commissioning
- resulted in change to integrated dipole field, causing $\Delta E/E \approx 1 \times 10^{-4}$
- **Added $\approx$ 6-shifts (5 for reproducibility, 1 to iterate local-corrections)**
- Relevant to orbit setup this year (not feed-back). **To watch out for in future years!**

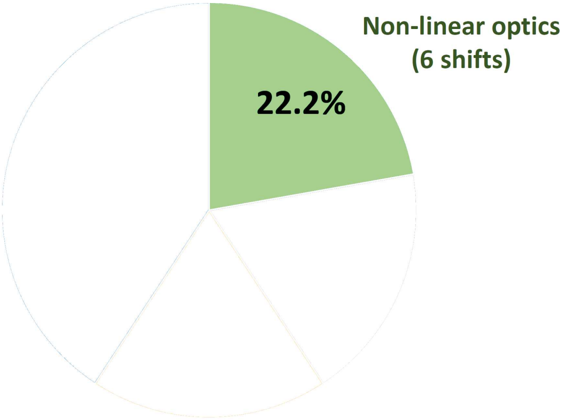


Larger ATS factor meant local errors in the ARCs became significant to operation for the first time

- **After local optics corrs in IRs, global corrections for LHCB1 failed**
- **Due to local errors in Arc45 & Arc81: corrected by orbit bumps through main sextupoles**
- **Had previously encountered similar problem during Run2 flat-optics MD**
  → able to use flat-optics corrections as starting-point for correction this year



- importance of studying pushed optics configurations in MD!
- Necessary extra component to LHC optics commissioning required from now on
- Will be important to achieve good understanding of local arc-errors during Run3

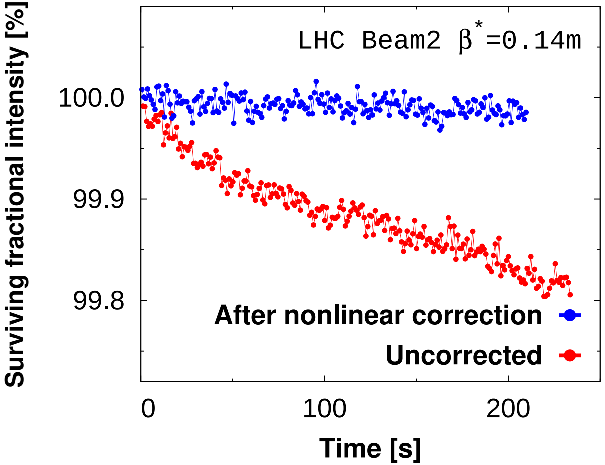


Non-linear optics
(6 shifts)
22.2%

Traditionally main concern w.r.t. NL-errors is DA

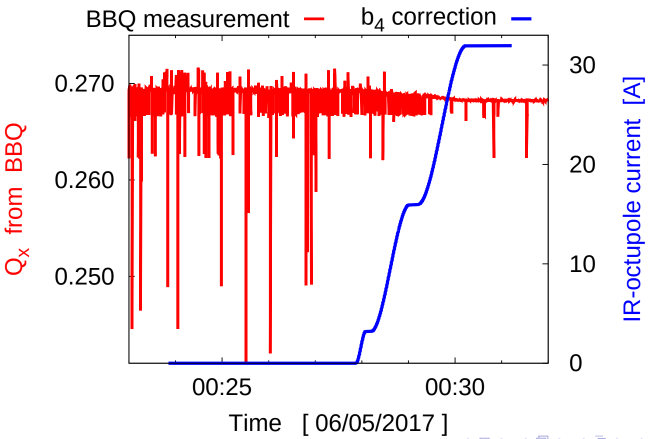
$\rightarrow$ not studied with beam for OP configuration

$\rightarrow$ pronounced effect on lifetime at very low-β^*, smaller effect at e.g. $40cm$



In practice NL-corrs also relevant to various OP or commissioning issues

- **IR-errors generate $\Delta\beta/\beta \approx 5\,\%$**
- **Feed-down to tune/coupling relevant to crossing-angle leveling**
- **Octupole correction has big impact on BBQ performance at low-β**
  $\rightarrow$ correction necessary to achieve good K-modulation data!



Non-linear optics commissioning in 2022 only partly successful

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

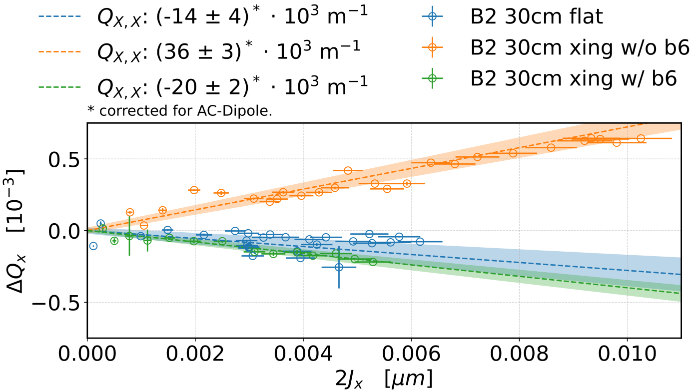
→ **Did not match quality achieved iteratively over course of Run 2**

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

Big success of NL-optics studies in 2022 was progress on measurement/correction of very high-order errors!

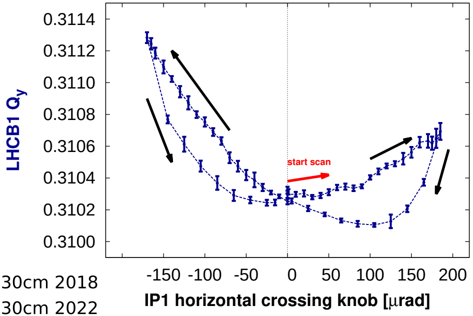
→ **First operational correction of b_6 errors in the LHC !!**

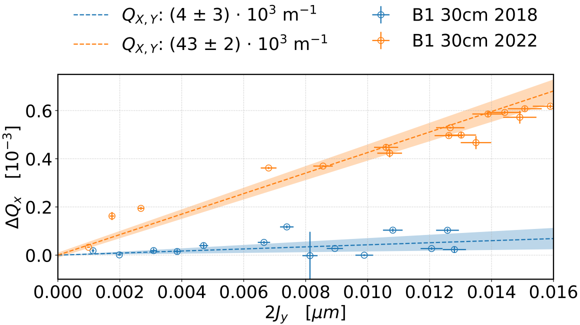
→ **Essential demonstration for HL-LHC where b_6 correction mandatory**



Significant progress at $450\,\mathrm{GeV}$ on decapole studies (first chromatic-detuning measurement) and first measurements of Q''''' (decatetrapole!!)

- **Several big puzzles for NL-optics appeared in 2022**
- **Tune hysteresis vs crossing-angle**
- **Significant deterioration of b_4**
- **Not understood!**



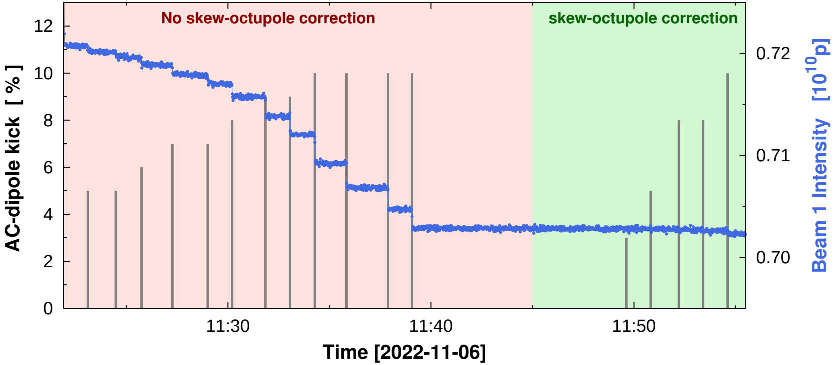


- **NLoptics analysis and measurement still quite manual/time-consuming**

→ **clear candidate for automation to be ready for HL-LHC!**

Ran out of time in 2022 to attempt any skew-octupole correction

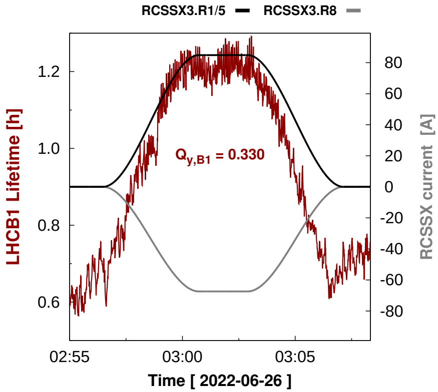
→ **followed up in MD2 and plan for correction in 2023**



- **Normally want to make final optics check at OP working point**
  → **In 2022 couldn't kick with AC-dipole at OP-WP due to beam-losses!**
- a_4 **correction improves DA of driven oscillation at nominal WP**

Could consider mitigation of $3Q_y$ resonance for 2023 (or beyond)

- **Loss maps with strong MO and Q' show very high losses at TDIS.B1**
  $\rightarrow$ **potentially associated with $3Q_y$**
- **several studies suggest $3Q_y$ could contribute to ϵ-growth in ramp (WP dependent)**
- **One option is to reduce vertical tune (showed improvement for TDI loss maps)**



To recover flexibility in WP could correct 3Qy resonance with MCSSX

$\rightarrow$ **demonstrated for single-beams in 2022**

$\rightarrow$ **if find dual-beam correction can be interesting option for commissioning: would need $\sim$ 2 shifts to implement**

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**
  - → **AC-dipole issues didn't limit 2022 commissioning efforts**
  - → mostly solved remotely/quickly $\approx$ [hour])
  - → 2 cases required access to repair
  - → 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**
  - → 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**
  → more rapid kicks and longer ACD-flattop have potential to significantly speed up OMC in commissioning

Key messages from 2022:

- **Successful 2022 commissioning: condensed 3 years of iterative improvements into single commissioning!**
- **Very long/challenging commissioning (considerably longer than expected)**
  → Main time-sinks in 2022 were the surprises!
- **For 2022 requested** $\sim 120\,\mathrm{h} \approx 15\,\mathrm{shifts}$
  15 shifts
  + 3 shifts → availability
  + 6 shifts → reproducibility studies plus 1 for local iteration
  + 2 shifts → ATS local errors in arcs (failed global / arc-bump corrs)
  + 1 shifts → Extra-detuning measurements for IR-b4 degradation
  $= \mathbf{27}\,\mathrm{shifts}$
- **2022 commissioning is in no way a blueprint for 2023**
  → good optics corrs in place from 60cm, verified in MD
  → blueprint for 2023 commissioning is 2017/2018
  → re-use as much as possible!

what will we be aiming for in 2023?

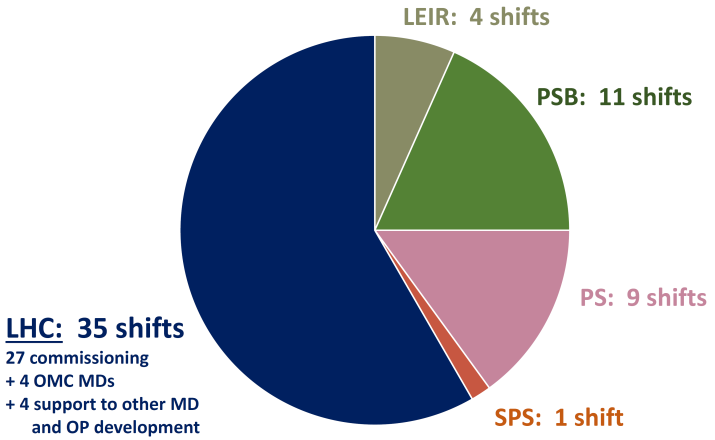
- **Start with all corrections from 2022 and '23 configuration MDs already applied**
- **Begin OMC commissioning with CO and crossing-scheme already established**
- $1\,\mathrm{shift}$: **injection corrs + spool piece setup (coupling-decay,MCDO)**
  saw degradation of inj corr from 2021-22. Might require iteration in '23
- $1\,\mathrm{shift}$: **Ramp optics/coupling**
- $1-2\,\mathrm{shifts}$: **Iteration of arc-bump / global corrs at 2m**
  B1H peak-$\Delta\beta/\beta = 24\%$ in 2023 MDs: plan new correction at 2m
- $1\,\mathrm{shift}$: **Incorporation of new corrs / validation to 30cm. Implementation of a4**
- $1\,\mathrm{shift}$: **iteration of normal/skew sextupoles at 30cm**
- $1\,\mathrm{shift}$: **Validation of full-cycle with 3 bunches. Final k-modulation for β^* and IP4**
- $2-3\,\mathrm{shifts}$: **Commissioning of High-Beta optics (90m & 3/6km)**
- $0-2\,\mathrm{shifts}$: 3Qy compensation/incorporation if opportunity arises

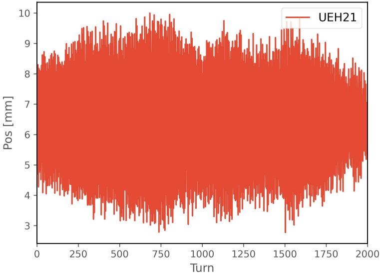
Could potentially aim at between 8-12 shifts for commissioning of nominal optics + 2× high-beta optics

Realistic scenario based on 2022 experience and MDs, approaching 2018 level of efficiency. Doesn't include any margin for availability or surprises!

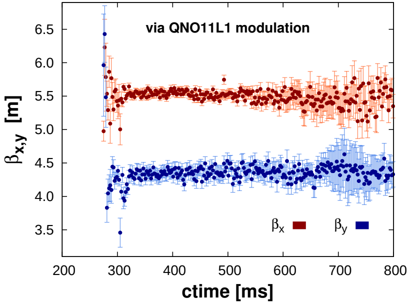
Majority of OMC team focus in 2022 has been LHC

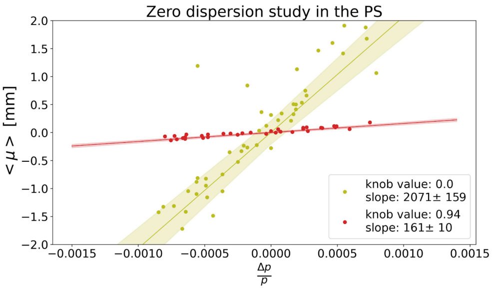
→ increasing focus on injector chain compared to previous Runs



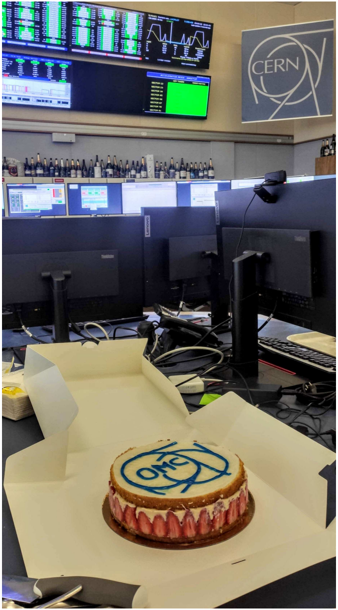


- **Lots of interesting activities in injectors!**
- significant progress on LEIR TbT data
- optics studies during PSB ramp
- testing alternative PSB measurement methods
- testing natural RDT measurement in PSB+PS
- alternative optics for PS emittance measurement
- detailed benchmarking of PS MU magnetic model
- contributing to CC studies in SPS



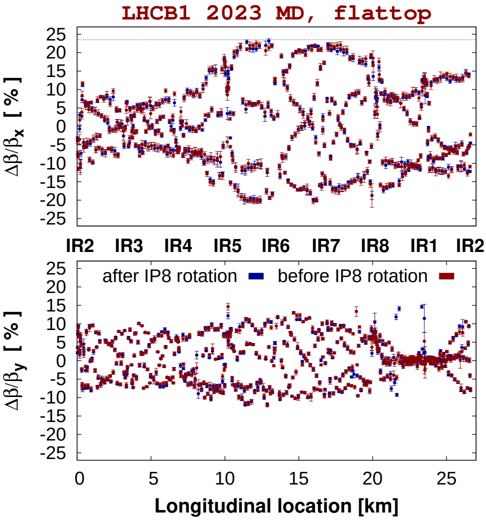


Lots of potential from improved OMC knowledge transfer between injectors/LHC!



Big thanks to everyone who contributed to OMC studies in 2022!!

Reserve



LHCB1 2023 MD, flattop
Δβ/βx [%]
IR2 IR3 IR4 IR5 IR6 IR7 IR8 IR1 IR2
Δβ/βy [%]
after IP8 rotation
before IP8 rotation
Longitudinal location [km]

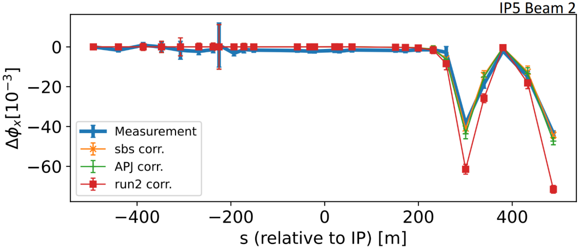
Many global factors affecting all aspects of OMC commissioning

- **For 2022 collimation team provided dedicated 'Non-linear optics' sequences**
  → **fundamental to all NL-optics studies in 2022**
  → **in practice also vital to the linear optics commissioning / stability studies**
  → **huge thanks to the collimation team!**
- **Optics measurements with 3 pilots substantially improve OMC efficiency**
  → **want to utilize as early as allowed in future commissioning**
- **Significant diversification of OMC commissioning tasks over Run2**
  → **core omc functionality well implemented in user-friendly tools**
  → **newer tasks need integration into general OMC toolset**
- **Good integration with OP!**
  → **highly productive OMC-OP workshop held in 2019**
  → **made extensive use of new OP tools:
  e.g. improved multiturn for Run3 and OFB trim orchestration**
  → **first time doing commissioning with OMC expert as EIC!!**

Variety of techniques exist to identify local errors or determine corrections:

- **Segment-by-segment (R.Tomas et. al. used for all Run1/2 LHC commissioning)**
- **Action-Phase Jump (J.Cardonna et al, Universidad Nacional De Colombia)**
- **Machine-learning based technique (E.Fol et al)**
- **LOBSTER (A.Wegscheider et al)**
- **LOCO-based technique (simulation only, S.Fartoukh)**

SbS,APJ,ML were tested during 2022 commissioning

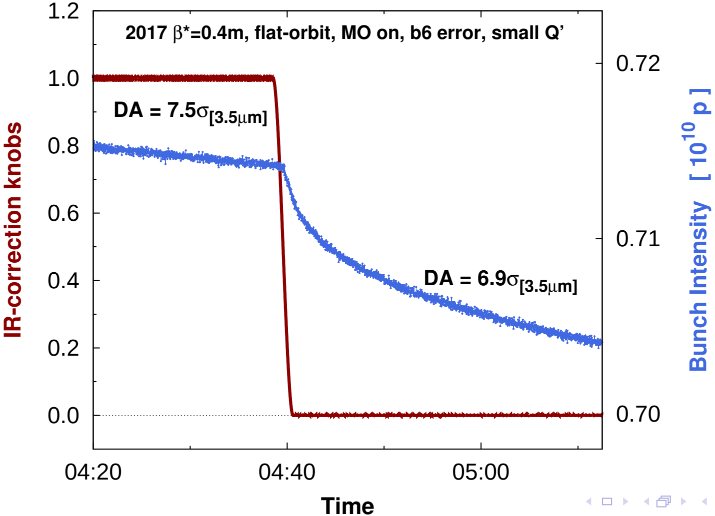


- **APJ correction deployed in IR1, traditional SbS method used in IR2,IR5,IR8**
- **First time using alternative local correction techniques for operation!**
  → methods all quite equivalent in outcome and time

Traditionally main concern w.r.t. NL-errors is DA

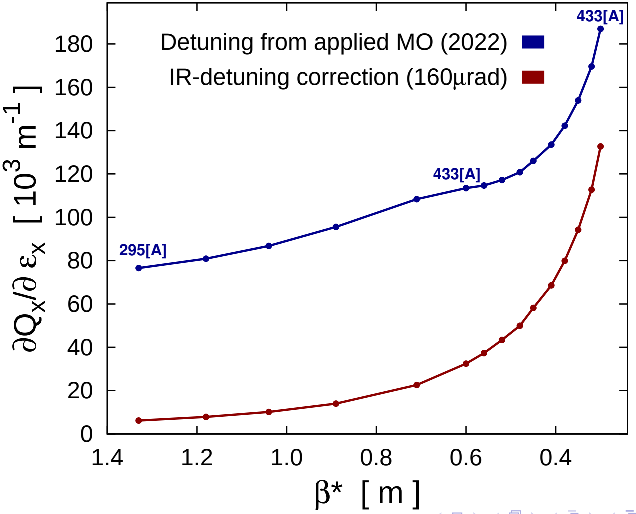
→ not studied with beam for OP configuration

→ pronounced effect on lifetime at very low-β^*, smaller effect at e.g. 40cm



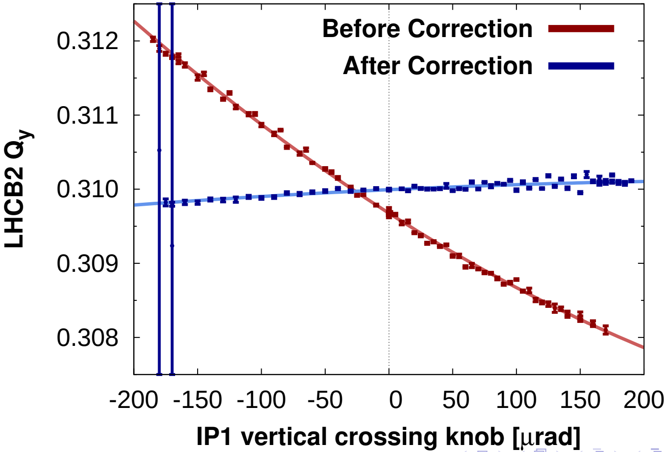
IR1 and IR5 generate significant detuning by end-of-squeeze

$\equiv$ 310[A] of MO at 30cm with 160 μrad crossing-scheme (worst case)



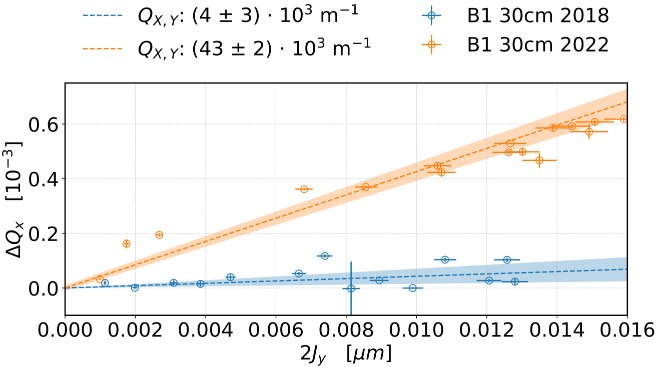
Normal/skew sextupole corrections determined by minimizing feed-down vs crossing-angle

- **sextupole feed-down generates $\Delta\beta/\beta \leq 5\,\%$ at $30\,\mathrm{cm}$**
  $\rightarrow$ majority of β-beat compensated by MCSX/MCSSX, rest with global-corrs
- **particularly relevant to maintaining stable $|C^{-}|/\Delta Q$ if crossing-scheme varied in operation**



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

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



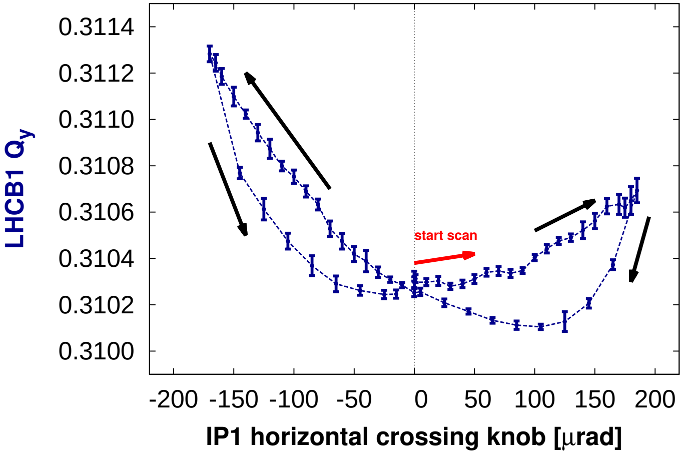
Effectively loose 20 % **of available LHCB1 MO strength at** 30 cm **due to residual b_4**

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

→ **at level where detrimental impact on BBQ/k-mod expected**

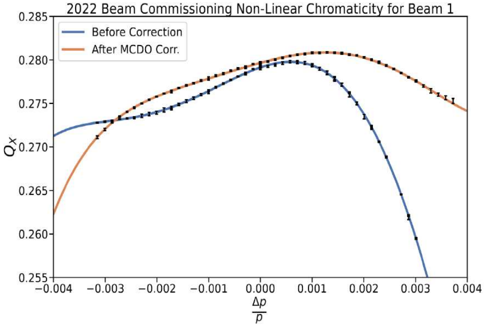
Observed tune hysteresis during crossing-angle scans (not seen/noticed in Run2)

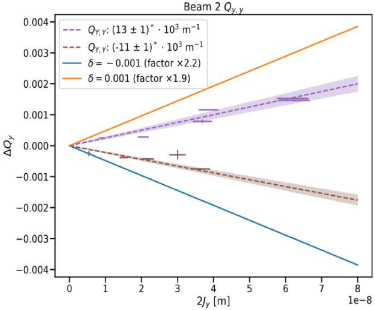
→ **One possibility is NL-errors generated by orbit correctors, will aim to follow up in MD**



- **Analysis+measurement of orbit scans for IRNL feed-down still very manual and time consuming in CCC**

  → **clear candidates for automation to improve OMC efficiency ready for HL-LHC**

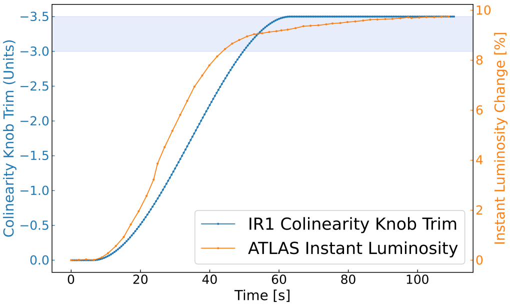




- **First measurements of fourth and fifth order chromaticity**
  → allows initial studies of dodecapole and decatetrapole errors at 450GeV
- **First measurement of chromatic amplitude detuning**
  → long-standing issue of factor 2 error in MCD correction at injection
  → combined Q''' and chromatic detuning results allow refinement in 2023

Rigid waist / coupling colinearity used in commissioning for first time

- **In 2018 local coupling temporarily reduced ALICE lumi by $\approx 50\,\%$**
- **For Run3 new method of local coupling correction in the IRs was tested for first time, using 'colinearity knob' to redistribute correction between left/right sides**
- **Equivalent settings were determined by two different methods**
  $\rightarrow$ by OMC team using new rigid waist technique
  $\rightarrow$ by OP using luminosity scans
- **Comfortable situation for future: can study LHCB1/LHCB2 independently with rigid-waist before luminosity available, or via lumi-scans if short on commissioning time.**



IR	Luminosity gain [%] $\beta^* = 0.3\,\mathrm{m}$	$\beta^* = 0.42\,\mathrm{m}$
ATLAS	9.7	5.2
CMS	3.5	1.5

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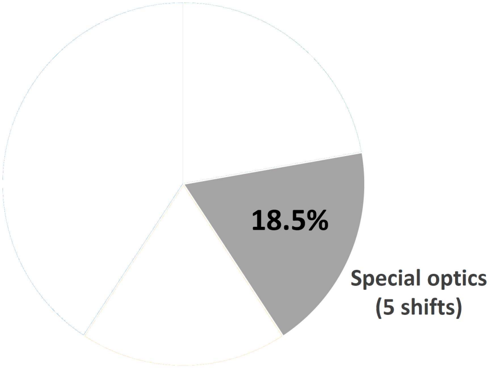

- **"Special optics" =**
  Niche HEP optics (VDM) and calibration optics (Ballistic, 60-degree)
  $\rightarrow$ motivation discussed extensively at last Evian *'OMC perspective on commissioning'*
- **Typical year expect ≤ 1 special optic... $\rightarrow$ In 2022 commissioned 3**
- **Expect $\approx 1\text{shift}$ per special-optics**
  $\rightarrow$ **unlucky with availability $\rightarrow$ 5 shifts total**

First ever use of 60-degree optics in LHC!

- **Threading → optics correction of LHCB1 in 1 shift!**

  → big thanks to Matteo + Jorg!