IR-nonlinear errors: 2017 experience & implications for HL-LHC

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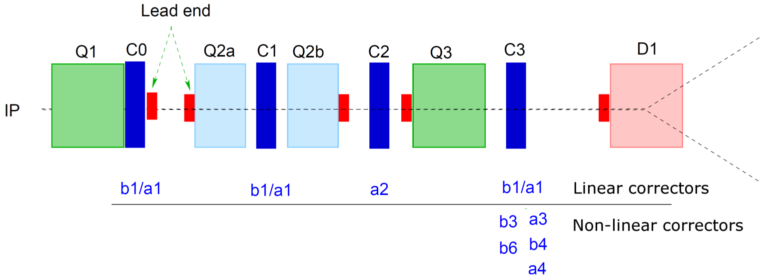
First commissioning for NL-errors in IR1 & IR5 performed in 2017

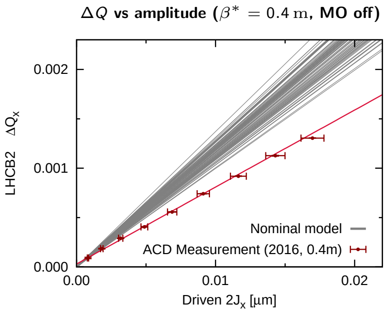
- Various studies in 2016 demonstrated that reduction of β^* to $\leq 0.4\,\mathrm{m}$ meant nonlinearities in ATLAS/CMS IRs started to be relevant to operation

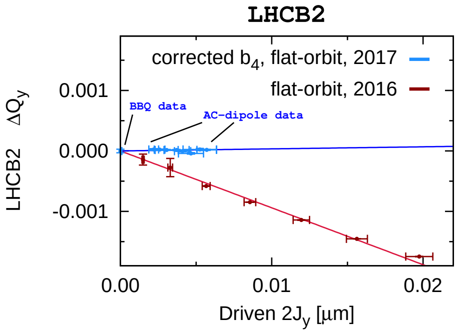


Corrections operational for:

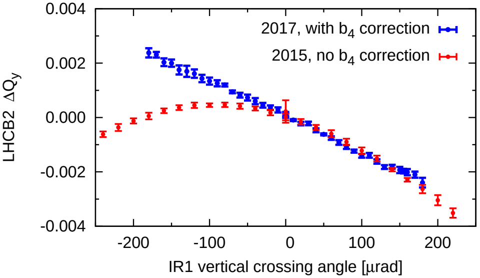
- b_4 in IR1/IR5
- b_3 in IR1/IR5
- a_3 in IR1
- a_4 in IR1 (KCOSX3.R1 only: L1 is dead)

- **Beam-based corrs mandatory in LHC**
  → e.g. see ∼ 30 % discrepancy with model amplitude detuning

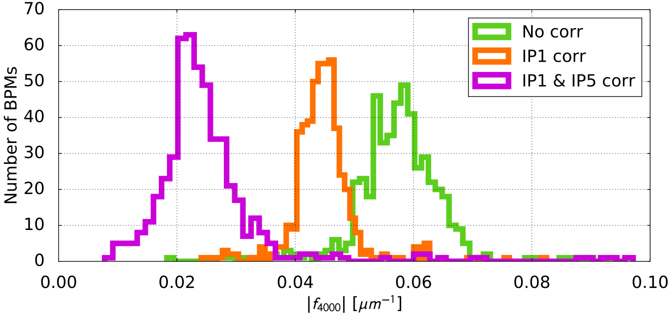




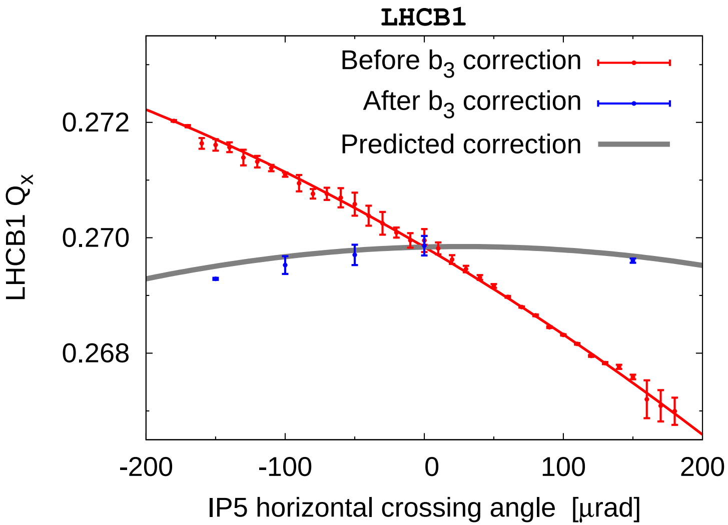
- **Beam-based correction compensated the amplitude detuning generated by b_4 in IR1/IR5**



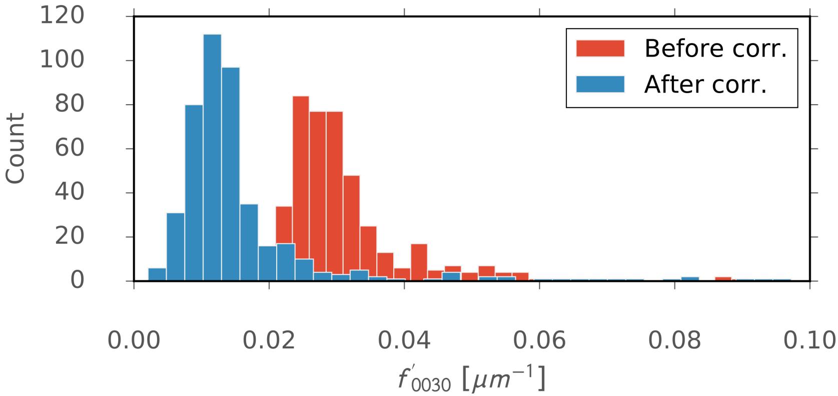
- **Feed-down demonstrates achieve reasonably local correction of b_4**
- **Obtain reduced strength of $4Q_x$ resonance**



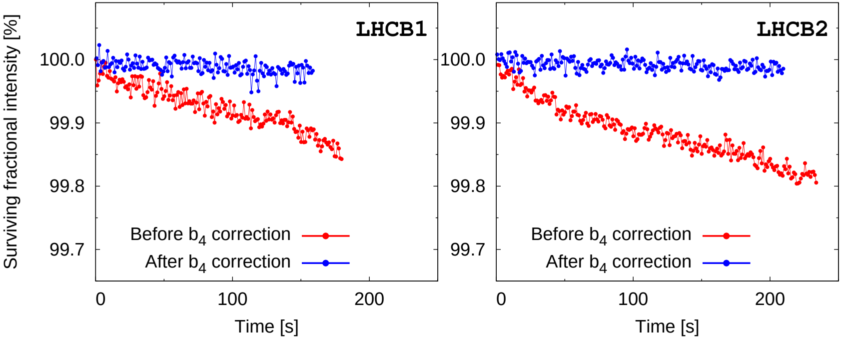
- **After b_4 compensation, corrections applied for feed-down to tune in IR1/5 and coupling in IR1**



- a_3 **correction in IR1 demonstrated to reduce strength of** $3Q_y$



- **Clear improvement to lifetime at $0.14\,\mathrm{m}$ when IR-b_4 correction was applied during ATS MD**



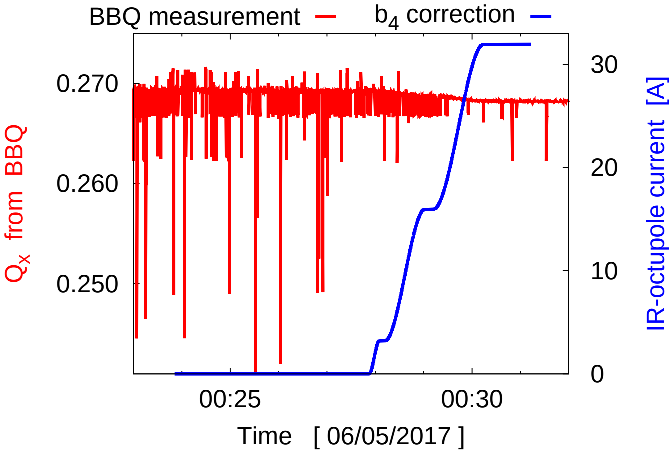
Recent studies with beam have demonstrated we can achieve several baseline aims for IRNL correction in HL-LHC

- **Beam-based corrections**
- **Local correction of sextupole and octupole errors**
- **Compensation of resonance driving terms**
- **Improvements to lifetime at low-β^***

Unfortunately additional challenges have also been revealed...

Impact of nonlinear errors on linear optics commissioning

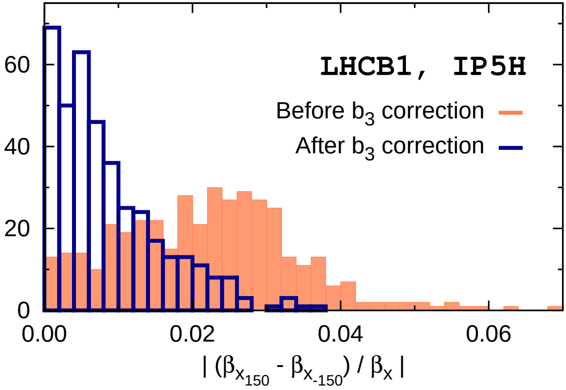
Clear improvement to BBQ upon IR-octupole correction



K-mod to correct β^* requires high-quality tune measurement

$\rightarrow$ **Reduced BBQ performance due to IR-octupoles may impede ability to correct linear optics**

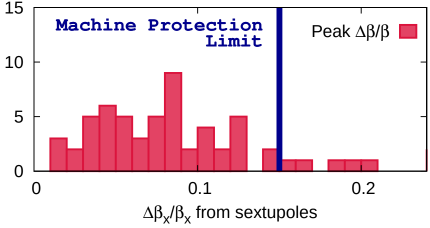
NL-errors contribute directly to linear optics quality via feed-down

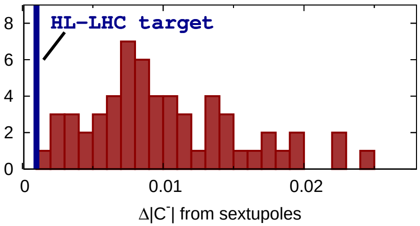


- Already observe non-negligible impact of sextupoles on β^*-imbalance ($\sim 2\,\%$)

Impact on linear optics can become considerably more serious for smaller β^*

e.g. simulation studies of HL-LHC (15cm, 295μrad)





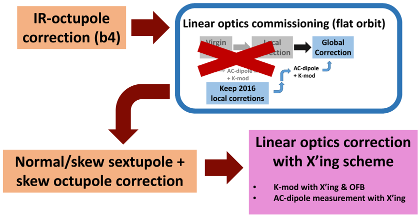
Also need to consider effect on linear coupling

- Direct impact due to feed-down
- Ability to measure

- **At low-β linear and nonlinear optics commissioning cannot be considered independent**
  - **$\longrightarrow$ Nonlinear optics correction requires good linear optics**
  - **$\longrightarrow$ Can't measure or correct linear optics to desired quality without also compensating nonlinearities**

Combined linear & nonlinear optics commissioning

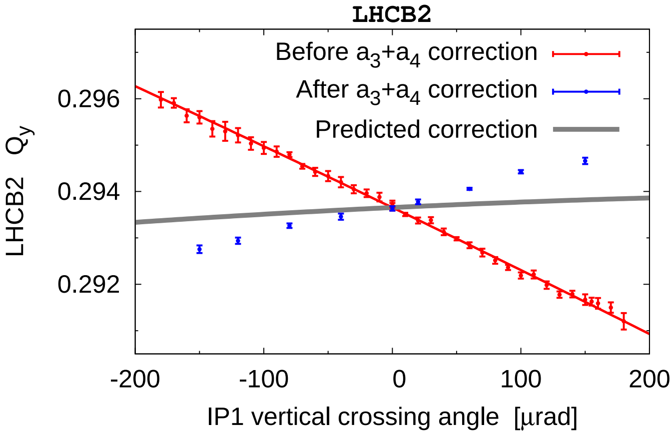
Being pushed towards iterative commissioning strategy, e.g. 2017



Effect of higher-order NL-corrections on lower-orders

In Run1 saw issues with alignment/orbit in b_4 correctors introducing additional sextupole errors

→ **Observed again in 2017 with a_4 correction spoiling a_3 compensation**

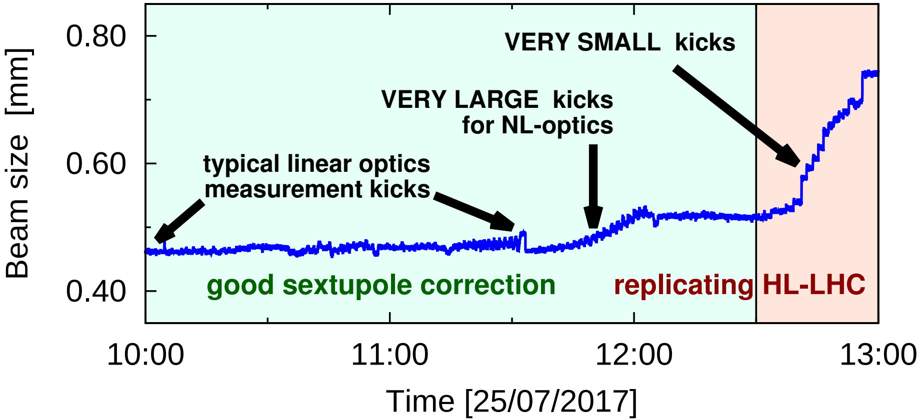


a_3 correction in 2017 had to be re-iterated after application of a_4

→ *expect HL-LHC needs iterative corrections as more orders are added!*

Impact of nonlinear errors on AC-dipole performance

Tried kicking AC-dipole after artificially increasing skew sextupoles using KCSSX3.R1



Appear to loose AC-dipole adiabaticity with strong a_3 errors

Potentially a massive problem for low-β commissioning

- After 8 **VERY** low-amplitude kicks beam was basically unusable
- Performed $\sim 460\,\mathrm{kicks/beam}$ at $\beta^* \leq 0.6\,\mathrm{m}$ during 2017 commissioning
- Forget AC-dipole amplitude detuning & RDTs...

Only explored this on a single occasion,
with single configuration for large a_3

→ **Want to understand how reproducible this is**

→ **How much worse does this become with all multipole orders**

→ **Have MD proposal for 2018 to look at free/driven DA, scaling all multipole correctors to replicate HL-LHC - like conditions**

If DA of driven oscillations / AC-dipole adiabaticity is a problem:

- **Can ADT-AC dipole measure optics? Longer excitation?**
- **Felix demonstrated use of AC-dipole WP to enhance/diminish RDTs**

  → To follow up in MD

  → Depending on natural WP, may be limited by existing ACD hardware
- **Start with model-based corrections applied**

  → Require very accurate magnetic and alignment data
- **Iterative commissioning strategy for decreasing β^***

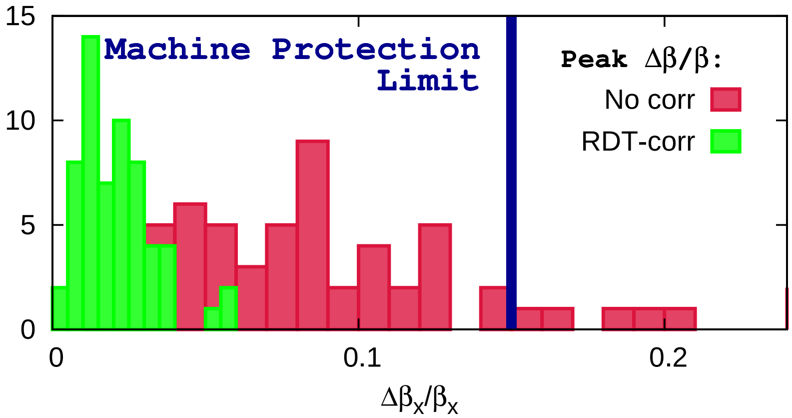
  → ≥ 2 complete linear+nonlinear commissionings at decreasing β^* would significantly increase time required

What should we correct???

- IRNL-errors influence many aspects of operation, directly & via feed-down
- How do we decide what to correct?
- What is the effect of optimizing on different observables?

e.g. linear optics:

→ In simulation ideal sextupole RDT correction leaves up to 7 % residual beta-beat from sextupole errors



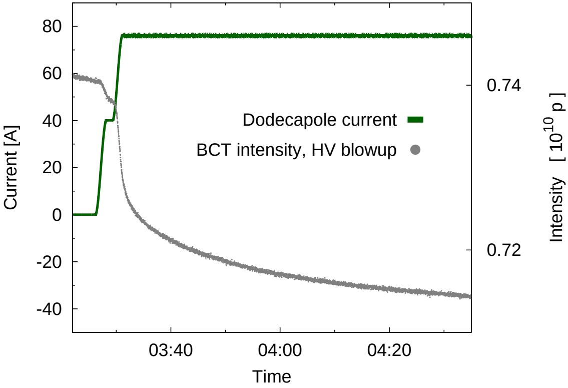
- Can we do better by optimizing for beta-beat / β^* rather than RDTs ?
- If so how much is the DA deteriorated?

Dodecapole errors have many potential effects

- During DA MD started seeing significant losses at 40 cm for max MCTX powering (80 A) at **flat-orbit**

- WISE b_6 corr $\sim 10\,\mathrm{A}$

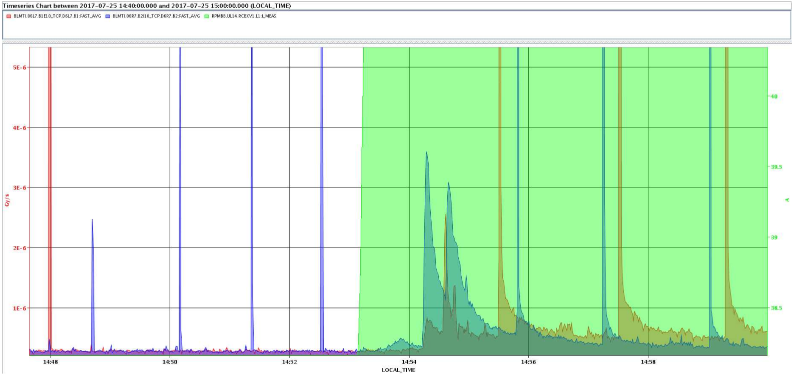
- b_6 not relevant at 40 cm
  $\rightarrow$ but scales with $(\beta^*)^{-3}$



- **80A @ 40cm $\equiv$ 1-2A @ 10cm**

- **Should expect direct impact b_6 to become relevant for very low β^***

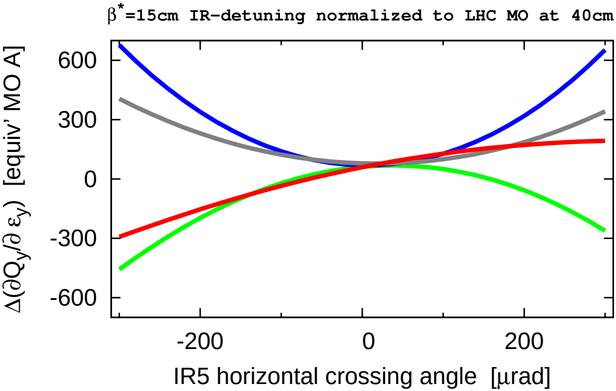
Performed AC-dipole kicks with max MCTX powering in separate MD



- Observe typical AC-dipole losses at flat orbit (white)
- With X-ing angle (green) see slow persistent losses following AC-dipole kicks (signature of free-DA)

  $\longrightarrow$ b_6 **feed-down possibly more relevant for DA than direct** b_6

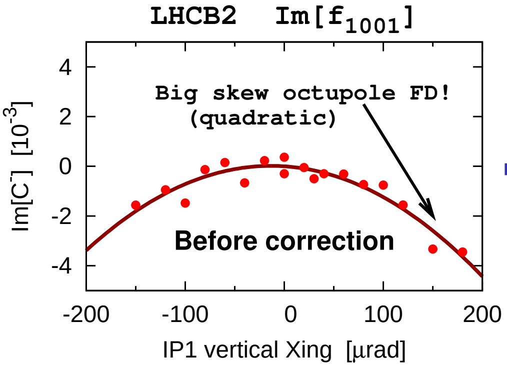
Feed-down from decapole/dodecapoles to normal octupole likely to be a particular challenge for instabilities in HL-LHC



- Correction of b_6: $\propto \beta^3$
- Correction of b_6 feed-down to b_4: $\propto \beta^2 \Delta_{orbit}$

Skew octupoles also have multiple observables which could be optimized

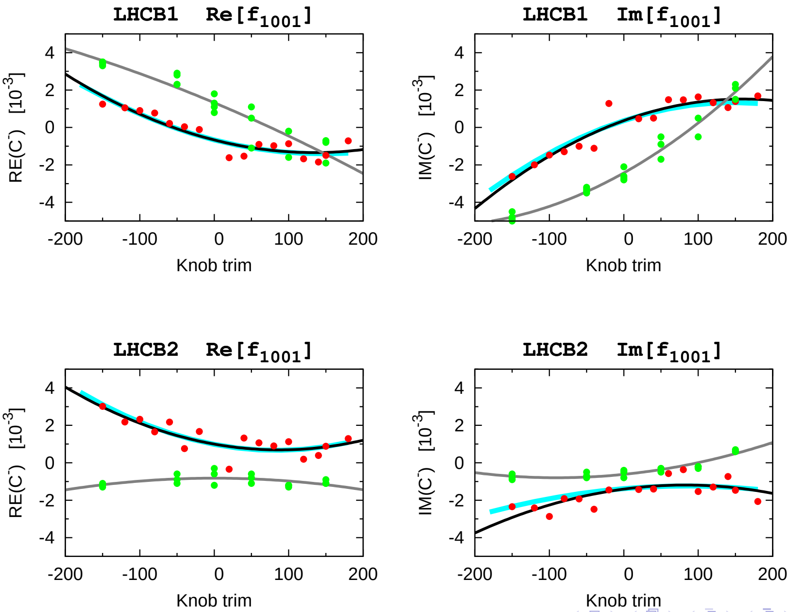
→ potential for large feed-down to linear coupling



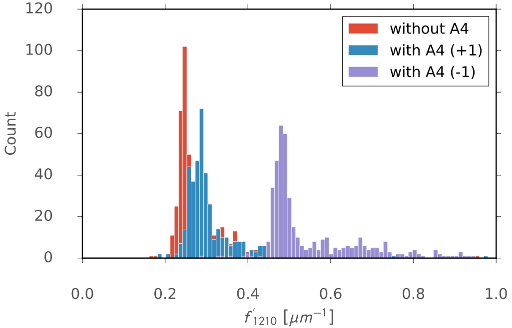
- **Important for instabilities and crossing-angle leveling**

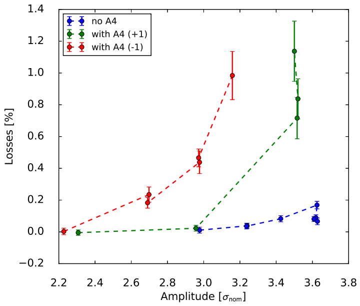
- **Before correction:** $\Delta|C^-|_{0\to150\mu\mathrm{rad}} = 5 \quad \times 10^{-3}$
- **After correction:** $\Delta|C^-|_{0\to150\mu\mathrm{rad}} = 1.5 \times 10^{-3}$

IR5 a_4 correction based on FD gives over-correction



Over-correction also observed in RDTs at 30cm



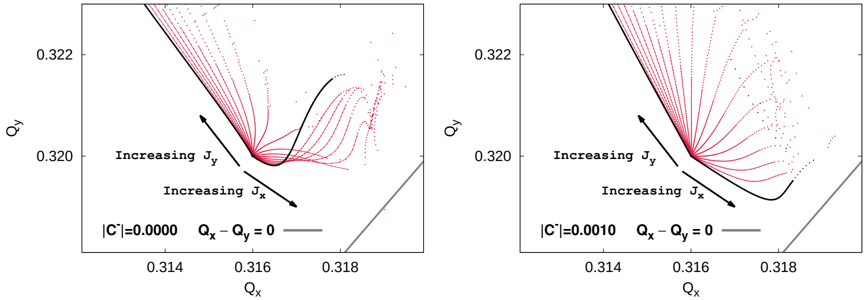


Increasing a_4 RDT is clearly associated with increased losses when kicking with AC-dipole

a_4 errors also directly influence the tune footprint

→ tentative confirmation at injection (offline analysis needed)

→ potential for large influence on Landau damping



- a_4 has at least 3 behaviours with potential relevance to operation:
  → footprint, DA (free/driven), feed-down
- Want to understand the extent to which these are consistent with each other & identify priorities for correction in HL-LHC

Conclusions

- **Have already achieved some initial objectives of IRNL-correction in HL-LHC, during 2017 LHC commissioning**

  $\longrightarrow$ Local correction of sextupoles/octupoles to improve RDTs and lifetime

- **Starting to get an idea of what nonlinear optics commissioning of HL-LHC may involve**

  $\longrightarrow$ Iterative corrections between linear/nonlinear optics

  $\longrightarrow$ Iterative corrections between multipole orders

  $\longrightarrow$ some nonlinear corrections in place before progressing to smallest β^*

- **Some clear challenges identified**

  $\longrightarrow$ Performance of AC-dipole with strong nonlinearities

  $\longrightarrow$ Need to decide priorities for correction with given multipole order