Optics correction in HL-LHC: Experience and implications from the LHC

Ewen H. Maclean
(University of Malta)

With particular thanks to
M. Giovannozzi, X. Buffat, N. Karastathis, R. Tomas and the LHC Optics Measurement and Correction Team
LHC commissioning has traditionally focused on linear optics

Reduction in $\beta^*$ means nonlinear errors in experimental IRs can also significantly perturb the beam

Dedicated nonlinear correctors left and right of the experimental IRs (similar to HL-LHC)
Before 2017 these nonlinear correctors were never used

- Since 2017 we have incorporated beam-based correction of nonlinear optics into the LHC commissioning strategy

- Measure a variety of beam-based observables for nonlinear optics

- Determine normal/skew sextupole and normal/skew octupole corrections in low-$\beta^*$ IR

- Led to operational improvements in the LHC

Important experience for HL-LHC: we will squeeze to even lower $\beta^*$ and similar correction scheme is planned

What did we learn relevant to HL-LHC?
Concern over reduction of lifetime & dynamic aperture from nonlinear errors in low-\(\beta\) IRs should be taken seriously.
Observed pronounced effect of IR-nonlinear corrections on lifetime of non-colliding pilot during tests of $\beta^* = 0.14\,\text{m}$ optics
Multiple studies demonstrate good agreement between simulated and measured dynamic aperture

- observe agreement at level of $\approx 10\%$ using different techniques & over different machine configurations, e.g. injection in 2012:
Multiple simulation studies indicate non-correction of nonlinear errors in low-\(\beta\) IRs is a problem for dynamic aperture

- LHC experience motivates a target DA \(\geq 6\sigma\) in HL-LHC

Even dodecapole errors must be corrected if HL-LHC is to reach its desired performance
Strong nonlinear errors in the IRs are detrimental to much more than just dynamic aperture

- Also detrimental to instabilities
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze

LHC squeeze: $\beta^* = 1.6 \, [m]$
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze

**LHC squeeze:** \[ \beta^* = 1.2 \, [\text{m}] \]

Footprint needed for Landau damping

Footprint obtained with octupole errors
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze.

**LHC squeeze:** $\beta^* = 0.9 \, [m]$
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze

LHC squeeze: $\beta^* = 0.7$ [m]

Footprint needed for Landau damping

Footprint obtained with octupole errors
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze

LHC squeeze: $\beta^* = 0.4 \text{ [m]}$

Footprint needed for Landau damping

Footprint obtained with octupole errors
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze.

LHC squeeze: $\beta^* = 0.33 \; [\text{m}]$

Footprint needed for Landau damping

Footprint obtained with octupole errors
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze

LHC squeeze: $\beta^* = 0.27 \, [m]$

Footprint needed for Landau damping

Footprint obtained with octupole errors
Tune footprint distortion can be detrimental to Landau damping

→ Not just normal octupole errors! Landau damping is also critically dependent on transverse coupling

→ Skew octupole & normal/skew sextupole can distort footprint too!

We have demonstrated in LHC that we can measure and correct nonlinear errors up to octupole order with beam
Significant reduction in Landau octupole strength required to maintain Landau damping since 2017

(Courtesy Xavier Buffat)
Significant reduction in Landau octupole strength required to maintain Landau damping since 2017

Expected strength from impedance model

Strength used in LHC

Improvement associated with correction of nonlinear optics and coupling

(Courtesy Xavier Buffat)
Any non-correction of the nonlinear optics will eat into the margins available for Landau damping in HL-LHC

- implications for non-colliding bunches at end-of-squeeze
- implications for required tele-index during squeeze
Strong nonlinear errors in the IRs are detrimental to much more than just dynamic aperture

- Detrimental to linear optics
- Detrimental to our ability to measure linear optics
Before 2017 all optics commissioning of LHC was performed at flat-orbit → nonlinear errors generate $\beta$-beating when crossing-scheme applied

2.5% luminosity imbalance from uncorrected nonlinear errors in LHC at $\beta^* = 0.4$ m

- Sextupole correction improved optics stability vs crossing-scheme
- Additional iteration of linear optics to correct residual $\beta$-beating

Nonlinear optics correction + linear iterations corrected $\beta$-beating to same level obtained at flat-orbit
Potential for much larger $\beta$-beating at end-of-squeeze in HL-LHC

- in worst case $\beta$-beating from nonlinear errors gives substantial luminosity imbalance and impinges significantly on machine protection limits

- expect similar commissioning procedure to LHC will be mandatory

![Graph showing peak $\beta$-beat with and without nonlinear optics corrections](image-url)
Key instrumentation & tools we use to measure linear optics are deteriorated by strong nonlinear errors.
At low-$\beta^*$ the success of linear optics commissioning is contingent on the correction of nonlinear errors in the IRs

- Commissioning of the linear and nonlinear optics cannot be considered independently
- A combined approach is necessary

A first iteration of the nonlinear corrections needs to be available from **DAY 1 of low-$\beta$ commissioning**
Beam-based corrections determined in LHC were not consistent with the magnetic measurements
Observe significant discrepancies for several beam-based observables between predictions of magnetic model and LHC measurements.
Corrections determined from magnetic model did not agree with those needed to optimize LHC observables → reason is under investigation.

Model-based corr (ATLAS=IR1)  
Beam-based corr (ATLAS=IR1)  

Model-based corr (CMS=IR5)  
Beam-based corr (CMS=IR5)  

(K_{4,\text{right}})^{-4}  [ m^{-4} ]

(K_{4,\text{left}})^{-4}  [ m^{-4} ]
All our experience in LHC suggests high-order corrections can be critical to successful commissioning and operation of HL-LHC

- Any rapid ramp up in performance will be contingent on having good nonlinear corrections in place early

Baseline strategy for HL-LHC optics commissioning is all IR-nonlinear correctors powered according to magnetic measurements on **DAY 1**

- We will be using and relying on the magnetic measurements from the start of commissioning
- It is critical we have good measurements of even the very high-order errors and good understanding of the associated uncertainties
- Quality assurance of the measurements and database will be essential
We also care about alignment errors of nonlinear correctors in the experimental insertions
Misalignments of nonlinear correctors in low-$\beta^*$ IRs can significantly complicate optics commissioning

- During dedicated tests in LHC observed normal octupole correction introducing extra skew sextupole error $\approx 2 \times$ larger than the bare $a_3$

- During 2017/18 LHC commissioning observed that skew octupole corrector powering changed required skew sextupole correction by 30%

- Both cases compatible with 1 mm level corrector misalignments

Even high-order corrector alignment is a non-negligible concern for HL-LHC

→ need good measurement of corrector alignments to plan commissioning strategy
Conclusions
- Correction of nonlinear optics errors at low-$$\beta^*$$ will be essential for successful operation of the HL-LHC
  → clear indications the nonlinear errors are relevant for lifetime (as expected)
  → nonlinear errors are relevant to Landau damping and linear optics

- Demonstrated ability to measure & correct IR-errors to octupole order

- Success of the linear commissioning is contingent on the quality of nonlinear corrections
  → can’t consider linear and nonlinear optics commissioning independently

- Rapid progression of HL-LHC performance will rely on nonlinear corrections calculated from the magnetic measurements
  → Need accurate measurements of even very high-order errors
  → Quality assurance of the measurements & database will be key

- High-order corrector alignment in the IRs can’t be neglected
  → rely on good measurements to plan commissioning strategy
A detailed review of the changes to LHC optics commissioning strategy since 2017 is available in PRAB:

**New approach to LHC optics commissioning for the nonlinear era**

E. H. Maclean

*CERN, Geneva CH-1211, Switzerland and University of Malta, Msida MSD 2080, Malta*


*CERN, Geneva CH-1211, Switzerland*

(Received 16 October 2018; published 21 June 2019)

In 2017, optics commissioning strategy for low-$\beta^*$ 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.

DOI: 10.1103/PhysRevAccelBeams.22.061004

**I. INTRODUCTION**

Control of linear optics is a key operational concern at the CERN Large Hadron Collider (LHC). In the High-Luminosity LHC (HL-LHC) collider [11,12], In the High-Luminosity LHC (HL-LHC) [13] compensation of nonlinear errors in experimental IRs is expected to be an operational necessity [14–16], with
Reserve
Although not directly used to determine corrections clearly saw reduction in strength of $4Q_x$, $3Q_y$ and $Q_x - Q_y$ resonances
Correction of $\beta$-beating from nonlinear errors in ATLAS/CMS IRs is now an intrinsic part of LHC commissioning strategy

→ nonlinear corrections improve optics stability vs crossing-scheme
→ additional round of optics commissioning to correct any residual $\beta$-beating in operational configuration

\[
\frac{L_{CMS}}{L_{ATLAS}} = 1.003 \pm 0.004
\]
Linear optics commissioning is dependent on the AC-dipole

→ but strong nonlinear errors deteriorate its performance!

A first iteration of the nonlinear corrections needs to be available from

DAY 1 of low-β commissioning
Observed discrepancies with predicted sextupole correction:

- Magnetic model correction
- Beam-based correction

<table>
<thead>
<tr>
<th>Normal sextupole (right) $[10^{-3} m^3]$</th>
<th>Skew sextupole (right) $[10^{-3} m^3]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal sextupole (left) $[10^{-3} m^3]$</td>
<td>Skew sextupole (left) $[10^{-3} m^3]$</td>
</tr>
</tbody>
</table>

- Optimal sextupole correction depended on skew octupole powering
- Indicates 1-mm level misalignment of octupole corrector introducing additional sextupole errors
Surviving Intensity 30s after kick [%]

Horizontal Kick $[\sigma_{\text{nominal}}]$

- Measured loss
- Predicted loss

Simulations: $|C^-|=2\times10^{-3}$ $|C^-|=4\times10^{-3}$

DA inferred from measured loss data