Beam-based studies of nonlinear optics in the LHC

The LHC Optics Measurement and Correction Team

The Large Hadron Collider (LHC)

→ 8 arcs, 4 low-$\beta$ IRs

→ $b_3, b_4, b_5$ spool piece correctors

→ Landau octupoles strongly powered in OP
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Large Hadron Collider (LHC)

→ strongly squeezed optics means even small NL-errors in IR can significantly perturb optics

→ dedicated correctors installed in low-$\beta$ IRs (common to LHCB1/2)

→ Normal/Skew up to dodecapole order
For optics studies $\sim 500$ dual plane BPMs + kicker and AC-dipole


Various observables used for LHC studies

- Nonlinear chromaticity
- 1st/2nd order amplitude detuning
- Chromatic detuning
- Feed-down to $Q,C^-$, detuning
- RDT
- Dynamic aperture
Overview:

- Dynamic aperture studies
- comparing to magnetic model and beam-based corrections at injection
- studies of NL-errors in low-$\beta$ insertions
Dynamic aperture
DA from beam-loss 30s after single-kick vs prediction of SIXTRACK

→ small $Q'$, moderate MO $K_3 = 3 \text{ m}^{-4}$ (2023 $K_{MO} = 18 \text{ m}^{-3}$)

→ best-knowledge LHC model (all known errors/alignments)
MO turned off, and beam-based minimization of $Q''$ and $Q'''$ applied with octupole and decapole spool-piece correctors

$Q_x$ vs $dp/p \times 10^{-3}$

$Q_y$ vs $2J_x [\mu m]$ with Lattice octupoles

Before correction

After correction

$4\sigma$, $6\sigma$, $8\sigma$, $10\sigma$
Minimizing nonlinear chroma and detuning increased DA

Surviving Intensity [%]

MO on, no correction

MO off, with correction

\[ \sigma_x [\sigma_{\text{nominal}}] \]
DA measurement with residual nonlinearities after corrections

- Good agreement of measured DA to LHC models with errors/alignments provided detuning well reproduced
- For LHC/FCC MD with enhanced $b_3$ necessary to match detuning from sextupoles to replicate measured DA

M.Hofer et.al, CERN-ACC-NOTE-2020-0049, MD 3603: Dynamic Aperture with uncorrected dipole $b_3$
Complementary measurements of long-term DA by heating beams with transverse damper

- example of blow-up with ADT →
- also good agreement vs applied $b_4$ at 450 GeV
- particular use at top energy (single-kicks banned)

beam-loss at 6.5 TeV ($\epsilon \sim 20 \mu m$) increasing IR-$b_6$ to replicate HL-LHC at 15 cm
Effect of applied dodecapole agrees well with SIXTRACK up to $10^6$ turn (1.5 minutes) → DA still not fully saturated well beyond typical simulation
Good control of linear coupling absolutely vital!

- Extreme example below: effect of MO on lifetime with $|C^-| \approx 0$ or $|C^-| \approx 2/3\Delta Q$

![Graph showing beam intensity and MO current over time with values of $|C^-| < 0.001$ and $|C^-| = 0.020$.]

- All LHC measurement/correction of DA/NL-optics predicated on excellent control of global and local linear coupling.
Injection

- Benchmark LHC magnetic model
- Find improved corrections for NL-optics vs nominal corrs based on magnetic measurements
\( Q'' \) and \( \partial Q / \partial \epsilon \) \textbf{order of magnitude} worse at injection than predicted by measured errors and alignments

- Majority explained by observed linear variation with decapole (MCD) powering
  → systematic 0.25mm MCD offset (inconsistent with measured alignment: MB sagitta?)
  → or cross-talk between MCD and MCO circuits

- \( Q'' \) with MCDO off agree very well with magnetic model
  (effective model of \( b_4 \) error introduced by MCD included for DA studies)
Minimization of residual $Q''$ generated by MCD, via global MCO trim, also improved detuning, decoherence, beam-losses kicking with ACD
Appear to have factor 40% discrepancy in the $b_5$ of virgin machine (MCDO off) → expected to be dominated by $b_5$ of main dipoles

- $Q''' \sim 40\%$ of best models
- Chromatic detuning ($\frac{\partial^2 Q}{\partial \epsilon \partial \delta}$) 
  $\sim 40\%$ of best models
- still not understood
- Nominal MCD corrs based on magentic measurements over correct
AC-dipole allows 6000 turn large-amplitude excitation with no decoherence

→ Example of measured TbT data from LHC injection, 2023-04-08

![Measured TbT from ACD-kick (BPM.28L1.B2 H-kick=2% V-kick=38%)](image-url)
Example of Q-spectra from AC-dipole kick at LHC injection, 2023-04-08
Online correction of decapole Resonance Driving Term $f_{1004} (Q_x - 4Q_y)$

- RDTs measured with AC-dipole kicks
- MCD set via RDT response-matrix pre-generated by MAD-X
- M.Le Garre ‘b5 correction at LHC injection’, https://indico.cern.ch/event/1298166/

2 − 3% impact on pilot lifetime in OP-configuration
First LHC measurements of 5th-order chromaticity performed in 2023

- From model expect $Q^{''''}$ to be dominated by $b_7$ of MB
- See consistent 5th-order term over several measurements with different lower-order chroma

consistent factor $\approx 1.8$ between meas & model across beams and planes

M. Le Garrec, IPAC'23 MOPL027, First measurement of fourth and fifth order chromaticity in the LHC
Also able to very clearly measure skew-sextupole $3Q_y$ RDT ($f_{0030}$) with AC-dipole kicks

![Graph showing vertical amplitude vs frequency for $Q_{y, AC}$, $Q_{y, natural}$, and $-2Q_{y, AC}$]
Measurements of LHCB1 in 2022 show good agreement for RDT magnitude compared to models with all known errors/alignments

LHC designed without correctors for 3Qy compensation at injection
In practice now shown we can use common LHCB1/2 IR-\(a_3\) correctors to compensate both beams

With strong MO and Q’ see clear improvement to lifetime from RDT correction. Both close to \(3Q_y\) and further away (\(Q_y = 0.31\))
NL-errors in low-\(\beta\) IRs

- For HL-LHC ultimately aim to locally correct all normal/skew multipoles up to dodecapole order
At low-$\beta$ observe discrepancies for several beam-based observables between model predictions and beam-measurements

→ measured detuning with amplitude $\sim 2/3$ of expectation
Even small $b_4$ errors in ATLAS/CMS can significantly distort footprint → e.g. impact on 2016 squeeze with operational MO, non-colliding (last time IR-b4 was uncompensated)
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LHC squeeze: $\beta^* = 1.2 [\text{m}]$

Footprint needed for Landau damping

Footprint obtained with octupole errors
Even small $b_4$ errors in ATLAS/CMS can significantly distort footprint
→ e.g. impact on 2016 squeeze with operational MO, non-colliding
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\[
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IR-$b_4$ errors corrected by minimizing amplitude detuning and quadratic feed-down to $Q_{x,y}$ in IR1 and IR5
Minimize all terms LHCB1 and LHCB2, also reduced $4Q_x$ RDT

<table>
<thead>
<tr>
<th>Detuning coefficients $10^3$ m$^{-1}$</th>
<th>$\beta^* = 0.4$ m (no correction)</th>
<th>$\beta^* = 0.3$ m (with correction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCB2</td>
<td>$\frac{\partial Q_x}{\partial \epsilon_x}$</td>
<td>$38 \pm 1$</td>
</tr>
<tr>
<td></td>
<td>$\frac{\partial Q_x}{\partial \epsilon_y}$</td>
<td>$1 \pm 1$</td>
</tr>
<tr>
<td></td>
<td>$\frac{\partial Q_y}{\partial \epsilon_x}$</td>
<td>$-44 \pm 1$</td>
</tr>
<tr>
<td></td>
<td>$\frac{\partial Q_y}{\partial \epsilon_y}$</td>
<td>$2 \pm 1$</td>
</tr>
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![Graph showing data comparison](image-url)
- IR $a_4$ corrected directly on RDT via MAD-X response matrix to correct $f_{1012}/f_{1210}$ driving ($Q_x - Q_y$)

- $a_3, b_3$ IR-errors corrected via feed-down to tune and coupling
  - poor agreement with corrections expected from measured $a_3$ and $b_3$
  - heavily influence by settings of higher-order correctors
  - infer typical alignment errors of $\sim 1$ mm for higher-order correctors
For $\beta^* \leq 30\,\text{cm}$ 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

\begin{align*}
Q_x, x: (-14 \pm 4)^* \cdot 10^3 \text{ m}^{-1} & \quad \text{B2 30cm flat} \\
Q_x, x: (36 \pm 3)^* \cdot 10^3 \text{ m}^{-1} & \quad \text{B2 30cm xing w/o b6} \\
Q_x, x: (-20 \pm 2)^* \cdot 10^3 \text{ m}^{-1} & \quad \text{B2 30cm xing w/ b6}
\end{align*}

*corrected for AC-Dipole.
- Beam-based corrections of $b_6$ agree consistent with the measured $b_6$ errors!
At typical LHC $\beta^* \geq 0.3\, \text{m}$ don’t expect IRNL to have large effect on lifetime

Observed pronounced effect of IR-nonlinear corrections on lifetime of non-colliding pilot during tests of $\beta^* = 0.14\, \text{m}$ optics
Efficiency of optics commissioning is key for LHC: heavily rely on AC-dipole
→ 2023 nominal cycle commissioning needed correction/validation of 17 different optics
→ + ion optics + VdM optics + high-beta optics

- DA of AC-dipole kick generally << than free-oscillations
  F.Carlier et al, PRAB 22 031002, First experimental demonstration of forced DA measurements with LHC ac-dipoles

- Reduction of AC-dipole DA by IR-errors causes issue for low-β optics commissioning
  e.g. 2022 uncompensated IR-a₄ prevented linear optics measurements at nominal WP
Compensation of detuning generated in IRs seen to significantly improve tune measurement at low-$\beta$ → key for using K-modulation to correct $\beta^*$

- at low-$\beta^*$ can end up in peculiar situation where efficient commissioning of linear optics requires some decent corrections of the nonlinear optics to already be in place
- since 2017 first optics correction implemented at low-$\beta$ is for detuning
Conclusions:

Dynamic aperture:
- For configs studied see good agreement between measured and predicted DA for models including measured errors and alignments when detuning is well reproduced
- Where long-term DA measurements performed, see that DA saturation persists considerably beyond length of typical LHC DA simulation
- Good control of local and global linear coupling is essential for DA (and all nonlinear optics) studies in LHC

Injection:
- Initially saw order-of-magnitude $b_4$ error discrepancy with best-knowledge model → now understood as influence of higher-order corrector generating extra $b_4$ component
- Appear to have factor 2 discrepancies in $b_5$ and $b_7$ related observables which are still not understood
- Initial studies of 3Qy resonance show good agreement to best-knowledge models with all known sources
- Inspite of discrepancies to magnetic model, where correctors are available can perform beam-based corrections. Compensation of $a_3$ and $b_5$ RDTs demonstrated with beneficial impact on lifetime

IRs:
- Beam-based corrections implemented for $a_3, b_3, a_4, b_4$ and $b_6$ errors in ATLAS and CMS insertions
- Agreement to expected corrections from magnetic measurements mixed
- See strong impact on lifetime at very low-$\beta^*$ (below LHC operational range)
- Correction of IR-nonlinear errors can become significant to achieve efficient linear optics commissioning
Reserve
Change to injection optics for 2023 altered many resonances
Detuning at top energy measured with AC-dipole: change of natural tune with action of driven oscillation
Measure second-order detuning ($\propto J^2$) and feed-down to first-order detuning ($\propto J$) to study decapole/dodecapole errors

CERN-ACC-NOTE-2018-0021

- Dodecapole errors too small to measure in LHC
- Measurements from deliberately introduced $b_6$ agree with model
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
After initial validation with pilots, MCSSX corrections passed to e-cloud team (Kostas Paraschou) for tests crossing $3Q_y$ resonance with nominals:

→ Very clear improvements to beam-losses!!

→ Very clear improvement to vertical emittance growth!!

→ Good candidate to improve modelling of incoherent e-cloud effects!!

(*plots courtesy K.Paraschou*)

Exciting results!!

→ various dedicated tests in works

→ tests planned in scrubbing

→ strong motivation to find operational correction!
$Q_{y,LHCB2} = 0.31$

![Graph showing LHCB2 lifetime and RCSSX currents](image)

- $|f_{0030}| \approx 3.5 \text{ m}^{-1/2}$
- $|f_{0030}| \approx 10 \text{ m}^{-1/2}$
$Q_{y,B1} = 0.330$

$Q_{y,B2} = 0.331$
- Very nice improvement to LHCB2
- Small improvement to LHCB1 from single knob corr, more limited capability than LHCB2
- (back of envelop corrs - didn’t take time to carefully scan knobs)
$\Sigma K_{\text{MCO}} = -50.3 \text{ m}^{-4}$

$\Sigma K_{\text{MCO}} = -95.9 \text{ m}^{-4}$

$\Sigma K_{\text{MCO}} = +204.8 \text{ m}^{-4}$
Vertical amplitude $[\sigma_{3.75\mu rad}]$

Horizontal amplitude $[\sigma_{3.75\mu rad}]$

No artificial $b_6$

Survived $> 10^6$ turns
Survived $< 10^6$ turns

with enhanced $b_6$

Survived $> 10^6$ turns
Survived $< 10^6$ turns
Surviving intensity [%]

Turns since reaching max $b_6 \times 10^6$

H-blow up
V-blow up
Closed orbit and beta-beat have small impact on predicted DA at injection for 2012 config.
By far the biggest use of RDTs in LHC is linear coupling control

- local arc-by-arc and global coupling corrections performed via minimization of $f_{1001}$
- Simulated change of $\text{Re}(f_{1001})$ and $\text{Im}(f_{1001})$ used to construct response matrix of all BPMs to skew quads circuits and knobs
- Inverted response matrix acting on measured $f_{1001}$ around the ring determines corrs

\[
|\Delta Q_{\text{min}}| = |C^-| \approx 4 \times |\Delta Q| f_{1001} |
\]
MO current [A]

Intensity $[\text{charges} \times 10^{10}]$

MOF current

Beam intensity

Time [23/08/2016]

Coupling corr applied
For Run1 / early-Run2 detuning shifts from typical OP-range of $|C^−|$ significantly larger than WISE seeds

![Graph showing magnetic errors with LHC operational configuration at injection, June 2012.](image)

- Magnetic errors, $0.000 \leq |C^−| \leq 0.005$
- Magnetic errors, $|C^−| = 0.000$
<table>
<thead>
<tr>
<th>IR3</th>
<th>IR4</th>
<th>IR5</th>
<th>IR6</th>
<th>IR7</th>
<th>IR8</th>
<th>IR1</th>
<th>IR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.05</td>
<td>0.00</td>
<td>0.05</td>
<td>0.00</td>
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</tr>
</tbody>
</table>

**Longitudinal location [km]**
DA as function of turns

- Apply scaling law to measured/simulated DA:

\[ D(N) = D_\infty + \frac{b}{(\log N)\kappa} \]

M. Giovannozzi, Phys. Rev. ST Accel. Beams 15, 024001
Various DA studies performed in LHC to test model predictions

Measurements with single kicks performed in 2012


Operational config’  Beam–based corrections

Two configurations examined at injection:

- **∼ 2012 operation configuration:**
  → small $Q'$, but MO powered to $K_3 = 3 \, \text{m}^{-4}$ ($dq/d\epsilon \approx 30 \times 10^3 \, \text{m}^{-1}$)

- **corrected configuration:**
  → MO off, beam-based correction of $b_{4,5}$. Measuring residual nonlinearities.