The 8th Evian Workshop:
New optics correction approaches in 2017

Ewen H. Maclean
and the Optics Measurement and Correction (OMC) Team
Commissioning was tough this year...
Major revisions to OMC strategy in 2017

→ Optics commissioning in 2016 was exclusively linear, performed with flat-orbit

Linear optics commissioning (flat orbit)

Virgin Optics → Local Correction → Global Correction

AC-dipole + K-mod

AC-dipole + K-mod
Major revisions to OMC strategy in 2017

→ 2017 strategy omitted virgin measurement, use local corrs from ATS MD in 2016

Linear optics commissioning (flat orbit)

Virgin $\rightarrow$ Local Correction $\rightarrow$ Global Correction

Keep 2016 local corretions

AC-dipole + K-mod

AC-dipole + K-mod
- Local correction degraded between 07/2016 → 04/2017

- Global corr’s compensated for local residual in 2017

- May be unsustainable if more degradation & $\beta^*$ reduction
Major revisions to OMC strategy in 2017

→ Core of optics commissioning remains linear correction, but now integrated into a combined linear/nonlinear commissioning.

Combined linear & nonlinear optics commissioning

- IR-octupole correction (b4)
- Normal/skew sextupole + skew octupole correction
- Linear optics correction with X’ing scheme
  - K-modal with X’ing & OFB
  - AC-dipole measurement with X’ing
Combined linear & nonlinear optics commissioning

IR-octupole correction (b4)

Normal/skew sextupole + skew octupole correction

Linear optics commissioning (flat orbit)

- Virgin
- Local correction
- Global Correction
- AC-dipole + K-mod
- Keep 2016 local corrections

Linear optics correction with X’ing scheme
- K-mod with X’ing & OFB
- AC-dipole measurement with X’ing
IR-octupole errors distort tune footprint during $\beta^*$-squeeze

Desired MO footprint, Obtained footprint

- Reduced stability for given MO
- ≡ 150 A MO trim between 0.4/0.3m
- Dramatic influence on 0.14m lifetime → observed to loose 1% of beam in 15 minutes (non-colliding)
Local correction with MCOX eliminated contribution to tune footprint from normal octupole errors in IR1 & IR5

![Graph showing LHCB2 data]

- Corrected $b_4$, flat-orbit, 2017
- Flat-orbit, 2016

Data sources:
- BBQ data
- AC-dipole data
Clear improvement to BBQ upon IR-octupole correction

→ big reduction to noise in tune measurement
→ Mandatory to obtain good K-mod at 30cm!
Combined linear & nonlinear optics commissioning

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Linear optics correction with X’ing scheme
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Normal/skew sextupole + skew octupole correction
Corrected feed-down to linear coupling in IR1

LHCB2  $\text{Im}[f_{1001}]$

Before correction

Big skew octupole FD! (quadratic)

$\text{Im}[C^-]$ [10^{-3}]

IP1 vertical Xing [\mu rad]

-200  -100  0  100  200

$\Delta |C^-|_{0\rightarrow150 \mu \text{rad}} = 5 \times 10^{-3}$

$\Delta |C^-|_{0\rightarrow150 \mu \text{rad}} = 1.5 \times 10^{-3}$

Before correction: $\Delta |C^-|_{0\rightarrow150 \mu \text{rad}} = 5 \times 10^{-3}$

After correction: $\Delta |C^-|_{0\rightarrow150 \mu \text{rad}} = 1.5 \times 10^{-3}$

Important for instabilities and crossing-angle leveling

No IR5 correction as smaller than IR1 (relevant at smaller $\beta^*$)
Corrected feed-down to tune in IR1 and IR5

LHCB1

Before $b_3$ correction

After $b_3$ correction

Predicted correction

IP5 horizontal crossing angle [µrad]
Corrected feed-down to tune in IR1 and IR5

→ reduced strength of $3Q_y$ resonance
Corrected feed-down to tune in IR1 and IR5
→ reduced strength of $3Q_y$ resonance
Corrected feed-down to tune in IR1 and IR5

→ Improved stability of linear optics vs X’ing scheme

contribution of nonlinear errors to linear optics quality never previously considered in LHC commissioning
Combined linear & nonlinear optics commissioning

IR-octupole correction (b4)

Linear optics commissioning (flat orbit)

- Virgin
- Local correction
- Global Correction

Keep 2016 local corrections

Normal/skew sextupole + skew octupole correction

Linear optics correction with X’ing scheme

- K-mod with X’ing & OFB
- AC-dipole measurement with X’ing
Global correction for nonlinear sources at operation crossing scheme restores comparable optics quality to flat-orbit.

![Graph showing beam 1 data with two sets of data: nominal (flat-orbit) in yellow and operational (ATS) in blue. The graphs display the variation of $\Delta\beta/\beta$ with longitudinal location in [km].]
Operational configuration now compensated to level previous achieved only for flat-orbit

<table>
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<th>2017 ATS (w Xing)</th>
<th>2016 Nominal (flat)</th>
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<tr>
<td></td>
<td>Beam 1</td>
<td>Beam 2</td>
</tr>
<tr>
<td>$\beta^*_x</td>
<td>_{IP1}$</td>
<td>39.8 ± 0.1</td>
</tr>
<tr>
<td>$\beta^*_y</td>
<td>_{IP1}$</td>
<td>40.8 ± 0.4</td>
</tr>
<tr>
<td>$\beta^*_x</td>
<td>_{IP5}$</td>
<td>40.3 ± 0.2</td>
</tr>
<tr>
<td>$\beta^*_y</td>
<td>_{IP5}$</td>
<td>40.2 ± 0.2</td>
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$$\frac{L_{IP5}}{L_{IP1}} = 1.003 \pm 0.004$$

Similar quality obtained for $\beta^* = 0.3 \text{ m}$
Expansion of OMC activities only possible thanks to rapid and continual development of optics tools

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- Integration of new observables & correction techniques
- Explore machine learning to improve measurement & correction
- A big push towards increased automation of OMC tools
  → automation of basic tasks: logging, SVD-cleaning & FFT
  → allows basic global coupling correction to be calculated online
An operational tool for coupling correction

Jorg’s parameter safari (Evian 2016):

- Parameter safari: the big five
  - Tune
  - Chromaticity
  - Coupling
  - Orbit
  - IP offsets

Linear coupling: one of the big 5!

- Observed to reduce dynamic aperture
- Huge influence on nonlinear optics
- Distorts footprint from MO causing loss of Landau damping
Linear coupling: a real operational challenge!
Coupling measurement from BBQ of limited use:

![Graph showing coupling measurement from BBQ](image)

- No info on $\Re e$ and $\Im m$ corrs
- Gives nonsense measurement with strong octupoles
- Doesn’t actually measure $|C^-|$
- Best measurement is AC-dipole
  → Only used with single pilot

Previously there has been no reliable way to monitor & correct linear coupling during regular operation
ADT can now drive forced oscillations of individual bunches

→ ADT-AC dipole!

- Used in regular operation → overcome limit of regular AC-dipole
- Obtain spectral data all around ring → overcome limit of BBQ
- Automated OMC methods used to provide online correction for $\Re e$ and $\Im m$ parts of coupling
Substantial effort by many groups!

Non-expert tool deployed in CCC to provide measurement & correction of linear coupling during regular operation
Well on the way to taming linear coupling!
Still not the end of the story for coupling

- Local coupling (requires dedicated measurement with AC-dipole)

- Linear coupling from beam-beam
Changes to strategy for 2018

- **Remove/revisit MCO @ 450 GeV**
  - correction deteriorated from 2015
  - Possible gain in spool piece ramp

- **Measurement-based incorporation of optics corr’s in RAMP**
  - 2.5 TeV commissioning showed excellent $\Delta \beta/\beta$ without correction
  - Injection correction to be trimmed out by 2.5 TeV

- **Start low-\(\beta\) commissioning with existing local corr’s in place:**
  - iterate if necessary

- **Start low-\(\beta\) commissioning with 2017 NL-corrections in place**
  - online re-validation + coupling feed-down in IR5
Changes to strategy for 2018

Big OMC priority for 2018 is skew octupole compensation in IR1/5

\[ \text{skew octupole } (a_4) \rightarrow \text{rotated normal octupole } \left( \frac{\pi}{8} \right) \]

- Skew octupoles distort Q-footprint
  \[ \rightarrow |C^-| + a_4 \text{ gives amplitude detuning like normal octupole} \]
  \[ \rightarrow a_4 + b_4 \text{ create amplitude dependent } \Delta Q_{\text{min}} \]

- Potential for large impact on instabilities at small \( \Delta Q \)
Changes to strategy for 2018

- 1 shift, Injection & Ramp
- 0.5 shift, linear optics through squeeze
- 1 shift, linear+nonlinear optics 27cm
- 3 shift, linear+nonlinear optics 25cm
- 0.5 shift, IR4 K-mod

Total: 6 shifts

Aperture becomes more critical for linear/nonlinear commissioning at small $\beta^*$

Received a lot of support from various groups this year:
→ support from BI to allow BSRT for pilots at 6.5 TeV
→ support from collimation

We will rely on this more & more as $\beta^*$ decreases
Conclusions

- At low-\(\beta\) linear and nonlinear optics are intrinsically linked
  
  → Can’t measure or correct linear optics to desired quality without also compensating nonlinearities

  → Nonlinear optics correction requires good linear optics

- Nonlinear optics is an operational concern, particularly for instabilities

- Changes to OMC strategy & new tools deployed in the control room are delivering meaningful improvements, particularly to:
  
  linear optics, linear coupling, performance of instrumentation, & control of footprint for Landau damping of instabilities
as always, many interesting things to look at in 2018...
Reserve Slides
- 3 new optics commissioned
- 11 shifts (3-days, 8-nights)
- 76 hours of measurements
Clear improvement to BBQ upon IR-octupole correction

→ remove fake coupling signal from BBQ
Chromatic coupling correction (flat orbit) \( \rightarrow \) change of \( |C^-| \) with \( \frac{\partial p}{p} \)

- corrected by skew sextupoles in arc

![Graph showing before and after correction with \( \frac{\partial p}{p} = 1 \times 10^{-4} \) and \( \Delta|C^-| = 0.001 \)]

- Corrections operational for first time in 2017
- Improved control of \( |C^-| \) w.r.t radial errors in arcs
  \( \rightarrow \) particularly relevant for \( Q', Q'' \) measurements
Linear re-optimization: Various updates to procedures & software tools required:

- First K-modulation with crossing angles and Orbit-Feed-Back
- First time correcting beta-beat & dispersion with crossing-scheme

ATS dispersion-beat (with Xing) comparable to 2016 Nominal (flat)
Achieve comparable $\beta$-beat for ATS (with Xing) as for 2016 Nominal (flat-orbit)
Achieve comparable $\beta$-beat for ATS (with Xing) as for 2016 Nominal (flat-orbit)
Big steps towards automation of the optics measurements
- Logging, analysis and coupling measurement of AC-dipole kicks
- Human intervention only needed for more complex analysis allowing distinction between operational and expert tools

Constant code performance and quality improvements

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- Replacement of legacy codes → easy improvements and better maintainability
- Full optics analysis stack implemented in Python loosening the dependency on Java GUIs also allowing further automation
- Exploring machine learning techniques