Experience with IR-nonlinear correctors

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Many thanks to the Optics Measurement and Corrections team and M. Giovannozzi
1 Summary of beam-based measurements in Run1 & 2

2 What we know

3 What we don’t know

4 Limitations

5 New techniques

6 Conclusions
Experience with beam of the nonlinear errors in experimental insertions:

- 2011: Initial parasitic studies
- 2012: 2 hour
- 2015: 1 hour, IRscans. PC fault.
- 2015 MD3: \( \sim 0 \) hour. Trip of RS
- 2016 commissioning: 3 hour IR scans. Trip of RB. RCX trim exception.
- 2016 EoF: 15 mins (IR-corrs with nominal)
- 2016 MD1: beam unavailable
- 2016 MD2: 3.5 hours, IR scans, dump by BCM
- 2016 MD2: 2.5 hours, IR scans, dump by MS trip

High priority, but unfortunate with circumstance

Availability:
2012 MD: 100 %; 2015 MD: 8 %; 2016 commissioning: 50 %; 2016 MD: 30 %
What we know
Run 1: initial studies of IR-nonlinear errors via feed-down (FD)


- Closed orbit bumps through IR varied
- BBQ measurements compared to MAD predictions
- If WISE model validated by beam-based measurements can determine corrections

<table>
<thead>
<tr>
<th>Multipole</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; order</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; order</th>
<th>3&lt;sup&gt;rd&lt;/sup&gt; order</th>
<th>4&lt;sup&gt;th&lt;/sup&gt; order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal displacement</td>
<td>( \Delta Q )</td>
<td>( \Delta C )</td>
<td>( \Delta Q )</td>
<td>( \Delta C )</td>
</tr>
<tr>
<td>Vertical displacement</td>
<td>( \Delta C )</td>
<td>( \Delta Q )</td>
<td>( \Delta Q )</td>
<td>( \Delta C )</td>
</tr>
</tbody>
</table>

- FD to \( Q_x, y \) used previously in RHIC
Parasitic study in 2011 demonstrated use of FD to $|C^-|$, e.g. FD in IR2

Validated magnetic model of $b_3$ in IR2 separation dipoles

- must account for initial state of $f_{1001}$ when using FD to $|C^-|$ 
- Different evolution of $|C^-|$ vs Xing for two beams due to initial $f_{1001}$

Best measurements need:
- AC-dipole measurement for baseline model
- Start with $|C^-| \approx 0.000$

Issue generally for NL-dynamics studies vs Xing angle
Validated for higher-order multipole FD to $|C^-|$
**Shift to dedicated measurements in 2012:**

- $|C^-|$ used to validate $b_3$ and $a_4$ errors in IR1 (40 cm, 2012, LHCB2)
- At 40 cm FD measurements can resolve uncertainty on wise seeds

![Graph showing measurement and model comparison](image)

**Vertical crossing angle in IR1 [μrad]**

<table>
<thead>
<tr>
<th>Corrector</th>
<th>KCSX3.L1</th>
<th>KCSX3.R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta K$</td>
<td>$-5.05 \times 10^{-4}$ m$^{-3}$</td>
<td>$+2.27 \times 10^{-4}$ m$^{-3}$</td>
</tr>
</tbody>
</table>

- $a_4$ corrector left of IP1 is dead
- Determine correction via DA simulation

<table>
<thead>
<tr>
<th>Corrector</th>
<th>KCOSX3.L1 ideal</th>
<th>KCOSX3.R1 ideal</th>
<th>KCOSX3.L1</th>
<th>KCOSX3.R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta K$</td>
<td>$-0.823$ m$^{-4}$</td>
<td>$-0.066$ m$^{-4}$</td>
<td>N/A</td>
<td>$-0.236$ m$^{-4}$</td>
</tr>
</tbody>
</table>
Large FD from $b_4$ in IR1 agrees well with magnetic model

FD to $Q_{x,y}$ of LHCb2 @ 40 cm in 2012:

- LHCB2 only @ 40 cm, B1 dumped earlier
- Discrepancy in $a_3$ between model/meas'
- Good agreement of big quadratic FD to $Q_y (b_4)$
FD to $Q_{x,y}$ of LHCB1 & LHCB2 @ 40 cm in 2015:
(Brown = effective model for $a_3$ discrepancy)

- FD from normal octupole in IR1 consistent between 2012, 2015 & 2016
- FD from normal octupole in IR1 agrees with WISE prediction
Amplitude detuning at 40 cm is dominated by $b_4$ errors in IR1&5

- Conventional measurement (single kicks) not possible at top energy  
  → Destructive & insufficient strength of kickers

- AC-dipole based measurement  
  → Measure variation of natural tunes with action of driven oscillation  
  → Direct detuning terms enhanced by factor 2 wrt free oscillation

- Theory and method demonstrated during Run 1  
  PRSTAB 16 071002 (2013), S.White, R.Tomás, E.H.Maclean

Measurements at $\beta^* = 40$ cm performed in 2015 and 2016 (flat orbit)
2015: LHCB2 amplitude detuning @ 6.5 TeV, 40 cm (flat orbit)

- Comparison to MAD-X tracking simulation, including AC-dipole

Measured detuning $\sim \frac{1}{2}$ expected from magnetic measurements of $b_4$
2016: LHCB2 amplitude detuning @ 6.5 TeV, 40 cm (flat orbit)

- Comparison to PTC 60 seeds (adjusted for AC-dipole detuning)

- Measured detuning $\sim 2/3$ nominal

- Comparable results obtained for LHCB1 vertical detuning
  (No LHCB1 horizontal measurement due to broken AC-dipole)
Nominal $b_4$ corrections for IR1+5 over-correct amplitude detuning
LHCB2 cross term detuning in 2016:

- As expected cross term detuning very small
- Similar results to 2015
- \( \frac{\partial Q_{y,x}}{\partial \epsilon_{x,y}} \leq 3000 \, m^{-1} \)
### Table: Measured vs. Model Values

<table>
<thead>
<tr>
<th></th>
<th>LHCb1 $\frac{\partial Q_x}{\partial J_x}$ [$10^3$ m$^{-1}$]</th>
<th>LHCb1 $\frac{\partial Q_y}{\partial J_y}$ [$10^3$ m$^{-1}$]</th>
<th>LHCb2 $\frac{\partial Q_x}{\partial J_x}$ [$10^3$ m$^{-1}$]</th>
<th>LHCb2 $\frac{\partial Q_y}{\partial J_y}$ [$10^3$ m$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured 2016</td>
<td>N/A</td>
<td>40 ± 1</td>
<td>40 ± 1</td>
<td>40 ± 1</td>
</tr>
<tr>
<td>Model (WISE 60seed mean)</td>
<td>63 ± 9</td>
<td>−64 ± 9</td>
<td>58 ± 4</td>
<td>−70 ± 4</td>
</tr>
<tr>
<td>Model (bare lattice + $K_{MO} = 13.38$ m$^{-4}$)</td>
<td>114</td>
<td>113</td>
<td>112</td>
<td>120</td>
</tr>
</tbody>
</table>

- Amplitude detuning coefficients $\frac{\partial Q_x}{\partial J_x}$ & $\frac{\partial Q_y}{\partial J_y}$ relate directly to normal octupole Hamiltonian terms we wish to compensate.

- Direct detuning at 40 cm is completely dominated by IR1 & 5.

- IR1 FD indicates nominal $b_4$ → infer contribution of IR5 to detuning.

- Correct IR5 via minimization of residual detuning after nominal correction of IR1.

- As phase advance over IR L/R is small, minimizing direct detuning contribution locally for each IR should compensate RDTs generally.

- Only possible as one IR constrained by FD → Can always compensate $b_4$ at small $\beta^*$ unambiguously via single-IP squeeze.
At 40 cm IR $b_4$ contribution to direct detuning is comparable with nominal MO

- PTC tracking simulation: LHCB2 @ 6.5 TeV 40 cm
- Effective model for measured detuning without Xing, $K_{MO} = 13.38 \text{ m}^{-4}$

![Graph showing measured detuning and nominal MO contribution](image-url)

- Measured detuning $\sim 1/3$ nominal MO contribution
- Nominal $b_4 \rightarrow \sim 1/2$
- Enhances detuning in one plane, compensates other
- Changing tune spread through the squeeze
What we don’t know
Skew sextupoles in IR1

- Large discrepancy between modelled and measured $a_3$ in IR1

![Graphs showing discrepancy between modelled and measured $a_3$ in IR1]

- Consider effective model for linear FD using MCSSX

<table>
<thead>
<tr>
<th>Corrector</th>
<th>$K_{3,skew} L [m^{-2}]$</th>
<th>matched KL RDT correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_3$ left of IP1</td>
<td>$0.832 \times 10^{-3}$</td>
<td>67 %</td>
</tr>
<tr>
<td>$a_3$ right of IP1</td>
<td>$0.3792 \times 10^{-3}$</td>
<td>38 %</td>
</tr>
</tbody>
</table>
- Linear part of IR1 FD to tune changed between 2015 and 2016
- Orbit change between 2015 & 2016? $\beta^*_{\text{waist}}$?

Changes to errors with changing settings is a particular challenge
- Re-validation of corrections will have to be included in commissioning
Consistently see large difference between model and measured FD in IR5

- Significant differences in normal sextupole
- Smaller octupole FD than model consistent with detuning measurements
- Observed quadratic FD not consistent with common sources. Not correctable by MCOX.
Limitations
Various reasons to mistrust the closed orbit in the IRs
(Changing sextupole errors, FD inconsistent with common sources, MCBX currents)
→ measure offset of beam in MCSX via FD
Infer orbit at the MCSX (assuming no alignment errors of MCSX and nominal $\beta$).
- Significant discrepancies of measured orbit with applied setting (up to 50%)
- Decent agreement of FD with BPMs (doesn’t include any BPM offset)
- Asymmetric orbit between the two beams and two sides of the IP
Twofold difficulty relating to orbit deviations:

- Reproduction in simulation
- Feed-down from corrections themselves

e.g. Correction of $b_4$ in IR1 generating large $a_3$ error:

- Affects beams differently
- Can’t correct locally with common correctors
- Can re-balance generated errors between beams
- Best solution is to fix the orbit
Non-closure of the applied orbit bumps may also influence FD studies

- Non-closure in the arcs was studied in Run1, had a negligible impact
- During 2016 commissioning observed Xing scan in one IR was generating a sizable orbit in the other

![Graph showing changes in orbit and current](image_url)

- Seriously limits all methods based on FD
- Cannot distinguish contribution from the two IRs
EIC performed manual OFB throughout scan

- Some significant changes (sign change of quadratic FD to $Q_x$ of LHCB2)
- Doesn’t explain all differences with model
- Manual OFB is impractical over long term
- Need implementation of true OFB for these studies
Several challenges associated with FD to $|C^-|$ measurement

- Reliability issues with the $|C^-|$ measurement

- BBQ $|C^-|$ measurement can’t be trusted with strong octupoles
Measure FD to linear coupling RDT \( (f_{1001}) \) directly with AC-dipole

- Tested in 2016
- Kicked with AC-dipole every 40 \( \mu \text{rad} \) up to maximum Xing trim
- Reliable measure of FD to coupling
  
e.g. \( f_{1001} \) variation in LHCB2 during IR5 crossing angle scan

![Graph showing variation in location [m] vs. absorbance]
New Methods
Use dedicated orbit bumps to understand source of sextupole discrepancies

- Asymmetric bumps L/R of IP to distinguish sources either side
Close bumps further out from IR to exclude large errors in D2 and Q4

Some initial tests performed on right side of IR5 in MD
- Outer bump R5 suffered from bad non-closure
- With manual OFB achieved large bump at D2 with $1 - 2\,\text{mm}$ in central IR
- Limited by aperture (beam blown up earlier in MD)

- After O.C. for non-closure see negligible FD to $Q_{x,y}$
- Eliminates D2.R5 as source of $b_3$ discrepancy
No time available to scan inner R5 bump

Performed quick test applying knob for first time

Inner bump R5 appeared to suffer less from non-closure

Achieved $\sim 5 - 6 \text{ mm}$ bump, limited by MCBX strength

Clear FD to $Q_x, y$ observed

Definite application to understanding sextupole discrepancies
Struggle to measure FD to $Q_{x,y}$ & $|C^-|$ with multipole order $>\text{octupole}$

- Measure FD from high-order multipoles to amplitude detuning

![Graphs showing detuning terms](image)

- Uncertainties on detuning measurement typically $\sim 1 - 2 \times 10^3 \text{ m}^{-1}$
- FD to detuning of higher-order multipoles potentially measurable
- Physical and dynamic aperture may prove limitations
- To be tested in MD...
Can measured Resonance Driving Terms directly with AC-dipole

- Spectral lines corresponding to $b_3$, $a_4$ & $b_4$ observed in 2016 data
- Application of IR1+5 nominal correction for $b_4$ (over-correction) reduced $f_{4000}$

- Exploring possibility to improve measurement of selected RDTs by choice of working point

- F.Carlier is performing RDT studies of LHC as part of his Ph.D
Direct measurement of dynamic aperture

- Ultimately DA/lifetime are properties of interest
- Conventional DA measurement (single kicks) impractical at 6.5 TeV
- Method based upon blow-up with the ADT demonstrated in Run1 at injection:

![Graph showing D(N) vs N for different values of ΣK_{MCO}]

- Easily measure changes to DA of 0.5 \( \sigma_{\text{nom}} \)
- Of particular interest for \( b_6 \) which may not be measurable by other means
- Plan to test in MD
Conclusions

- Several multipoles are believed to be well understood:
  \[ b_3 \text{ in IR2, } b_3 + a_4 \text{ in IR1, } b_4 \text{ in IR1, } b_4 \text{ in IR5} \]

- Clear discrepancies in \[ a_3 \text{ of IR1 & } b_3 \text{ of IR5} \]

- Several key challenges associated with these studies
  \[ \rightarrow \text{knowledge of the real orbit} \]
  \[ \rightarrow \text{non-closure of the IR bumps} \]
  \[ \rightarrow \text{changes of IR-errors with machine settings} \]

- None of these challenges are insurmountable, and there are clear strategies to follow
Conclusions

- **Several developments of the methodology been tested this year**
  - Measure feed-down to $f_{10001}$ rather than BBQ $|C^-|$
  - Dedicated orbit bumps

- **Hope to test several new methods later this year**
  - Direct RDT measurement
  - Feed-down to amplitude detuning
  - Direct measurement of DA at top energy

- **Commissioning of these corrections is not a quick job, but we are optimistic!**