Impact of orbit perturbations on luminosity calibrations

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- **Orbit drifts: why doesn't this beam stay still !?**
  - impact on van der Meer (vdM) scans
  - impact on length-scale calibrations (LSC)

- **Hysteresis effects during LSC & vdM scans**

- **Summary**
Impact of orbit drifts on vdm calibration: 2 (+1) effects

- **In-plane drift:** \(x\) [\(y\)] during \(x\) [\(y\)] scan \(\rightarrow \Sigma_{x\{y\}}\)
  - Equivalent to a change in calibration of closed-orbit bump (i.e. in length scale)
  - +ve/-ve drift in \(x\) [\(y\)] \(\rightarrow\) increase {decrease} of \(\Sigma_{x\{y\}}\)
  - \(\mathcal{L}_{\text{peak}}, x/y\) unaffected

- **Peak-to-peak drift:** \([x \&/or \ y]\) \(\rightarrow \mu_{\text{peak, } x \& y}\)
  - \(\rightarrow\) beams poorly centered in \(y\) during \(x\) scan (and/or v-v) \(\rightarrow \mathcal{L}\)
  - \(\Sigma_{x/y}\) unaffected

- **Out-of-plane drift:** \(y\) [\(x\)] during \(x\) [\(y\)] scan \(\rightarrow \Sigma_{x\{y\}}\) \(\rightarrow\) in practice, negligible
Orbit drifts during vdM scans: the *real* world

**Hor. (x) scan**
- Beam-beam deflection
- + ??

**Vert. (y) scan**
- Vertical drift often smaller, consistent between DOROS & Arc BPMs
- Apparent $x \to y$ coupling?

**Drift consistent between DOROS & Arc BPMs**
- (this time – but not always!)
- DOROS: "head-on" (!)
- DOROS: scanning
- Arc BPMs extrapolation to IP

**Time on 28 Jul 2017**

**30 µm total span**

IP1
vdM scan 1
28 Jul 2017
Orbit drifts during vdM scans: correction procedure

- Parameterize drift in x & y beam separation
  - DOROS: include only quiescent periods, exclude scanning periods
    - avoid b-b deflections, apparent x-y coupling, in-scan hysteresis, DOROS length scale
  - Arc BPMS: include all data
    - only if knob leakage negligible (not true for all optics!); otherwise as for DOROS
    - average extrapolations from Left & Right of the IP → eliminate x-y coupling signature

- Correct $\sigma_{vis}$ for each x-y scan pair separately (all 3 effects)
  - final vdM calibration is scan-averaged $\sigma_{vis}$ value from all head-on scans
  - OD-related syst. uncertainty: typically Arc-DOROS difference on $<\sigma_{vis}>$
Impact of orbit drifts on absolute $L$ calibration: in numbers

- Rule of thumb $[\pm 6 \sigma_{vdM \, scan}, \varepsilon \sim 3 \mu m, \beta^* \sim 19 \, m, \sqrt{s} = 13 \, TeV \rightarrow \Sigma \sim 130 \, \mu m]$

  - **Bias** on $\sigma_{vis}$ (for **one** x-y scan pair), if left uncorrected:
  - In-plane drift: 10 $\mu m$ total $\rightarrow \sim 1 \%$ on $\Sigma$ (per plane, $\pm$)
  - Peak-to-peak drift: 10 $\mu m$ $\rightarrow \sim 0.15 \%$ on $\sigma_{vis}$ (x or y, always -ve)
  - Out-of-plane drift: 10 $\mu m$ total $\rightarrow \sim 0.004 \%$ on $\sigma_{vis}$ (per plane, always +ve)
    - NB: apparent x-y coupling seen by DOROS $\sim 6$-7 $\mu m$ total $\rightarrow$ negligible impact

- Orbit-related systematic uncertainties on absolute $L$ (2015-18, 13 TeV)
  - Main issue: scan-to-scan consistency of bunch-averaged $\sigma_{vis}$ values
    - Orbit-drift correction critical to reducing these inconsistencies:
      - 1.2 / 0.6 % (2.0 / 1.0 %) S-to-S inconsistency in 2017/2018 w/ (w/o) orbit-drift correction
  - Uncertainties on orbit-drift correction
    - vdM scans: 0.1 - 0.2 % on scan-averaged $\sigma_{vis}$ value ($\leftrightarrow$ $\Sigma_{x/y}$, $\mu_{peak, x/y}$)
    - LSC scans: $\sim 0.3 \%$ on $x*y$ length-scale product (reflected in $\sigma_{vis} \sim 1/ \Sigma_x \Sigma_y$)
  - Beam-position jitter: from rapid position jumps within a scan step
    - evaluated using sample-to-sample IP-position jitter (Arc BPMS): $\Delta \sigma_{vis} / \sigma_{vis} \sim 0.2$ - 0.3 %
Impact of orbit drifts on length-scale calibration

Principle

- Beams are scanned transversely // to each other over approximately ±3 σ, while remaining in head-on collision (except for mini-scans of the "other" beam).
  
- Compare nominal beam displacement (= IP-knob setting) to transverse displacement of the luminous centroid (with the beams perfectly centered).
  
- Done separately for the 4 closed-orbit bumps B1X, B2X, B1Y, B2Y.
  
- The requirement that beams be perfectly centered is achieved by miniscans of the "other" beam (say B2) around the setting of the bump being calibrated (say B1) with ±10 µm.
Impact of orbit drifts on length-scale calibration (2)

Typical impact: rule of thumb

$$\epsilon \sim 3 \, \mu m, \beta^* = 19.2 \, m, \sqrt{s} = 13 \, TeV$$
$$\sigma_b \sim 91 \, \mu m, \text{LSC scan over } \pm 2.5 \, \sigma_b :$$

10 \mu m drift (1 beam, 1 plane) / $\Delta = 450 \, \mu m \ast \frac{1}{2}$

[bec. vdM scans antisymmetric: length-scale = (B1+B2)/2]

= 1.1% bias on $\mathcal{L}$ scale (if uncorrected)
Observation of hysteresis effects in length-scale scans

**Principle**

- Compare nominal beam displacement (= IP-knob setting) to the single-beam displacements recorded by DOROS BPM
  - linear? reproducible? sensitive to scan direction?

**The tricky parts – in order of increasing pain**

- beam-beam deflection
  - 0 (or negligible) if consider only mini-scan steps with nominalSeparation == 0
- orbit drifts/jumps, real or instrumental: the curse!
- exacting requirements on the relative calibration of the DOROS wrt IP knobs
  - LSC scans typically over ± 220 μ → 1% error on DOROS-knob intercalibration mimics a ~ 4 μ (total) non-linearity
Residual displacement: \( B1,2X_{\text{res}} = s \times B1,2X_{\text{DOROS}} - B1,2X_{\text{nom}} \)

DOROS B1X calibration: \( s = 0.971 \)

DOROS B2X calibration: \( s = 0.973 \)

DOROS B1X calibration: \( s = 0.966 \)

DOROS B2X calibration: \( s = 0.976 \)

Out-of-plane scans masked

After DOROS-knob intercalibration

Nov’17 LSC
Out-of-plane scans masked

Hysteresis effects in LSC: sign sensitivity

The $B_2$ miniscans affect the reproducibility of the $B_2$ displacement

The sign of the orbit distortion flips with the scanning direction
Residual (= measured-nominal) beam displacement in vdm scans

Nov'15 vdm (scans 1-3)

Beam-beam deflection (corrected for) & hysteresis (not corrected for) add up in $\Delta_{x,y} = B1_{x,y} - B2_{x,y} \rightarrow$ bias on $\Sigma_{x,y}$?
Summary

❖ Orbit drifts (OD)
  ◦ Drifts as large as 20 µm/beam were observed during both vdm & LSC scans
  ◦ Consistency between Arc & DOROS BPMs varies scan-to-scan: ➔ multiple sources?
  ◦ Main impact is scan-to-scan reproducibility of vdm calibrations [~ O (1-1.5%)]
  ◦ vdm (LSC) uncertainty on OD correction ~ 0.2% (0.3%) (partial cancellations!)

❖ Hysteresis effects
  ◦ Unambiguous evidence for small magnetic non-linearity of IP knobs
    ◦ Independently from DOROS BPMs (LSC & vdm) & luminous-region data (LSC)
  ◦ The sign of the non-linearity is correlated, and flips, with the scan direction (ascending or descending), for both beams/both planes
    ◦ The characterization of the shape of the non-linearity (best attempted in LSC scans (b-b deflections!)) is limited by the quality of the data (limited # points, orbit drifts)

❖ Implications
  ◦ Essential to apply consistent + reproducible scan protocols in vdm & LSC scans
  ◦ Reproducibility of magnetic non-linearity in consecutive vdm scans to be analyzed
  ◦ Associated systematics on LSC & vdm calibrations to be quantified for final Run-2 L

❖ Orphan topics: beam-position jitter & apparent x-y coupling

Help needed from our LHC colleagues to identify the sources!

Systematic characterization during Run 3 needed (easy!)
Supplementary material
Residual displacement during LSC scan: B1X, B2X, collision point

Out-of-plane scans masked

After DOROS-knob intercalibration

DOROS B1X calibration: $s = 0.971$

DOROS B2X calibration: $s = 0.973$

Collision point $\sim \frac{(B1X_{\text{res}} + B2X_{\text{res}})}{2}$

Only antisymmetric component can impact LS
x-y coupling in vdM-scanning knobs: apparent or real?

- **DOROS: scanning**
- **DOROS: head-on**

Candidates:
- BPM rotation?
- coupling in optics?
- tilted X/YCORs?
- elx cross-talk??

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**Is it real?**
Compare to luminous-centroid displacement in LSC

**If real:**
impact on $\sigma_{vis}$ from out-of-plane drift
$\sim 0.002 \%$

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**B1X during Y scan**

2.5 $\mu$ / 1160 $\mu$ = + 2 mrad

**B1Y during X scan**

~ + 4 mrad

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**B2X during Y scan**

~ + 2 mrad

**B2Y during X scan**

~ - 1.8 mrad

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Same sign & magnitude $\rightarrow$ cancel in $\Delta x = B1X - B2X$

Opposite sign $\rightarrow$ enhanced in $\Delta y = B1Y - B2Y$

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IP1
vdM scan 5
28 Jul 2017

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Slide 15
2019 L Days, CERN, 4-5 Jun 2019
A few examples of orbit-drift symptoms during vdM scans

- **Global orbit: 1 h before S2**

![Graphs of orbit-drift symptoms](image)

vdM Fill 6868
30 Jun-1 Jul 2018
A few examples of orbit-drift symptoms during vdM scans

- Global orbit: during S4X

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Examples of orbit-drift symptoms during vdM scans (2)

- Beam position @ IP1: reoptimization following a long drift after S6

vdM Fill 6868
30 Jun-1 Jul 2018

S6X
S6Y
Examples of orbit-drift symptoms during vdM scans (3)

- Beam position @ IP1: manual recentering between S4X & S4Y

![Graph showing beam position changes during vdM Fill 6868, 30 Jun-1 Jul 2018]
A few examples of orbit-drift symptoms during vdM scans (4)

- IP1-orbit & $L$ glitches during S2X

vdM Fill 6868
30 Jun-1 Jul 2018
A few examples of orbit-drift symptoms during vdM scans (5)

- Inconsistency in peak $L$ between S3Y & S5Y (off-axis $\rightarrow$ more sensitive)

vdM Fill 6868
30 Jun-1 Jul 2018
Impact of orbit drifts on vdM calibration: 2 (+1) effects

- **In-plane drift:** $x$ [$y$] during $x$ [$y$] scan $\rightarrow \Sigma x$ [$y$]
  - $L_{\text{peak, } x/y}$ unaffected

- **Peak-to-peak drift** $[x \&/or y] \rightarrow \mu_{\text{peak, } x \& y}$
  - $\Sigma x/y$ unaffected

- **Out-of-plane drift:** $y$ [$x$] during $x$ [$y$] scan $\rightarrow \Sigma x$ [$y$]: *typically negligible*
Observation of hysteresis effects in length-scale & vdM scans

Principle

- beams are scanned transversely // to each other over approximately ± 3 σₜ, while remaining in head-on collision (exc. for mini-scans of the "other" beam)
  
- compare nominal beam displacement (= IP-knob setting) to displacement recorded by (i) DOROS BPM (single beams) & (ii) luminous centroid
  
  - linear? reproducible? sensitive to scan direction?

The tricky parts – in order of increasing pain

- beam-beam deflection
  
  - 0 (or negligible) if consider only mini-scan steps with nominalSeparation == 0

- orbit drifts/jumps, real or instrumental: the curse!

- exacting requirements on the relative calibration of the DOROS wrt IP knobs
  
  - LSC scans typically over ± 220 μ → 1% error on DOROS calibration mimics a ~ 4 μ (total) non-linearity

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Out-of-plane scans not shown

**DOROS calibration by the consistency method: B1X**

- **Set or measured displacement [microns]**
  - PLB number: 0 to 250

- **Residual displacement [microns]**
  - PLB number: 0 to 250

**Equations:**

- \( B1X_{\text{res}} = 0.991 \times B1X_{\text{meas}} - B1DXSet \)
- \( B1X_{\text{res}} = 0.971 \times B1X_{\text{meas}} - B1DXSet \)

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Nov 2015
LSC

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Comparison of nominal & measured displacements: X (Nov 2015 LSC)

Out-of-plane scans not shown

After DOROS-knob intercalibration
Comparison of nominal & measured displacements: Y (Nov 2015 LSC)

Out-of-plane scans not shown

After DOROS-knob intercalibration

B1Y_res

B2Y_res

Y_BPM_res

Residual displacement [microns]

PLB number

Residual displacement [microns]

PLB number

Residual displacement [microns]

PLB number

Data - Fit [µm]

Beam 2 Y bump amplitude [µm]

ATLAS Preliminary

χ²/ndf = 38.3294/3

p0 = -562.6202 ± 0.0043

p1 = 0.0974 ± 0.0004

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Sensitivity to relative DOROS-knob calibrations?

- Nominal calibration
- Nominal - 0.4%
- Nominal +0.4%
- Beams in head-on collision

A hard way to make a living…