LHC beam orbit and collision position determination & control – performance and issues, prospects for Run 3

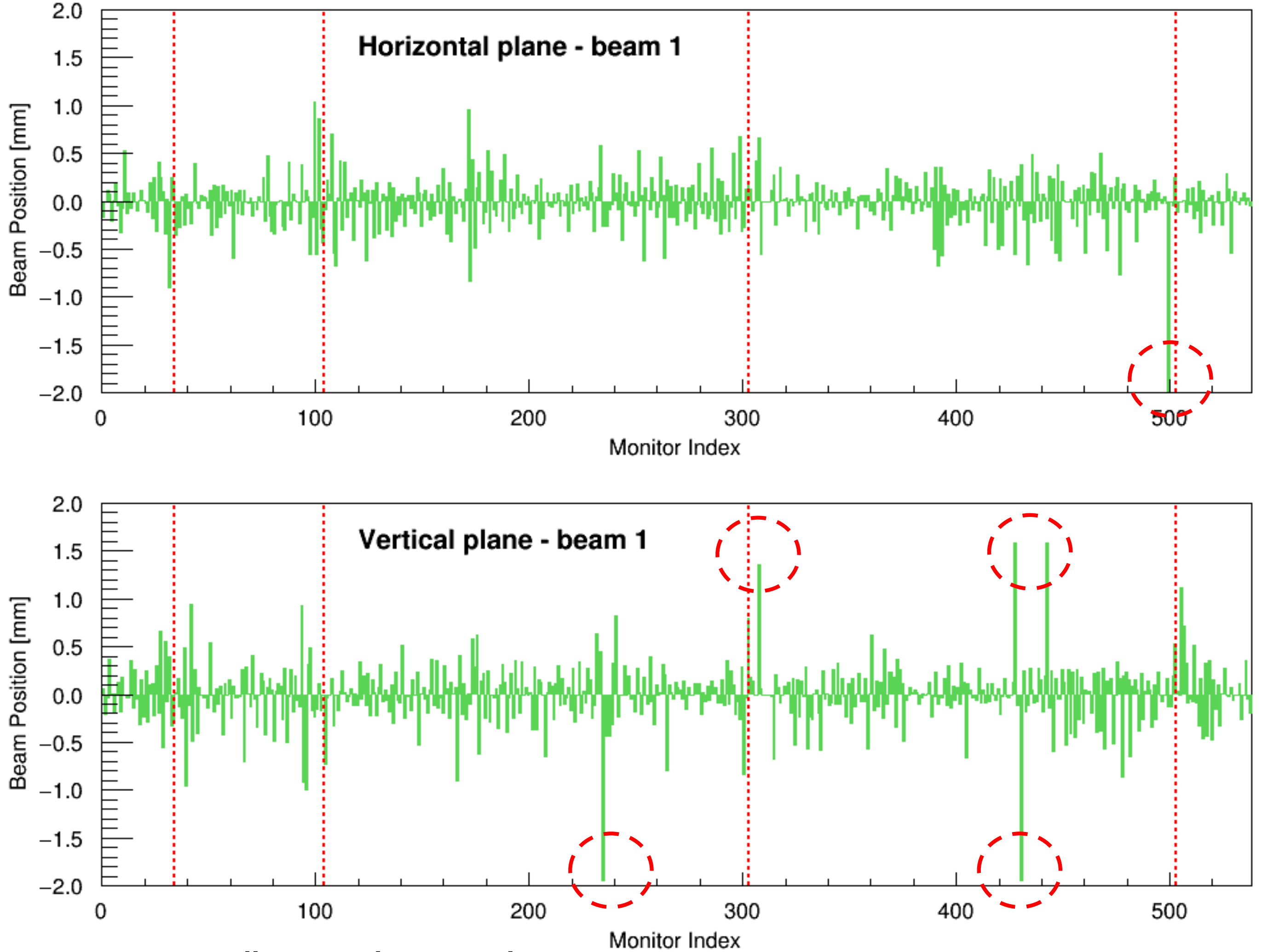
J. Wenninger / BE-OP-LHC

LHC orbit – step 1 @ injection

- Every year during early commissioning a 'flat' orbit at injection is cleaned before applying any bumps for crossing angles etc.
  - Establish the best plausible correction.
  - Identify fake outliers due to BPM reading offsets (common sense & strange corrector settings).
  - Includes offsets measurements (BPM-quadrupole) from k-modulation for triplet BPMs.
  - Initial LHC specs accounted for peak orbit errors of ±3 mm, in 2018 we had ~ ±1 mm.
- The reference orbit at injection is used as baseline flat orbit for the entire cycle and generally even for all configurations.
  - Various bumps (and associated shape & amplitude changes) are added.

2018 flat reference orbit

Some outlying BPMs (flat orbit) are OK, just static offsets

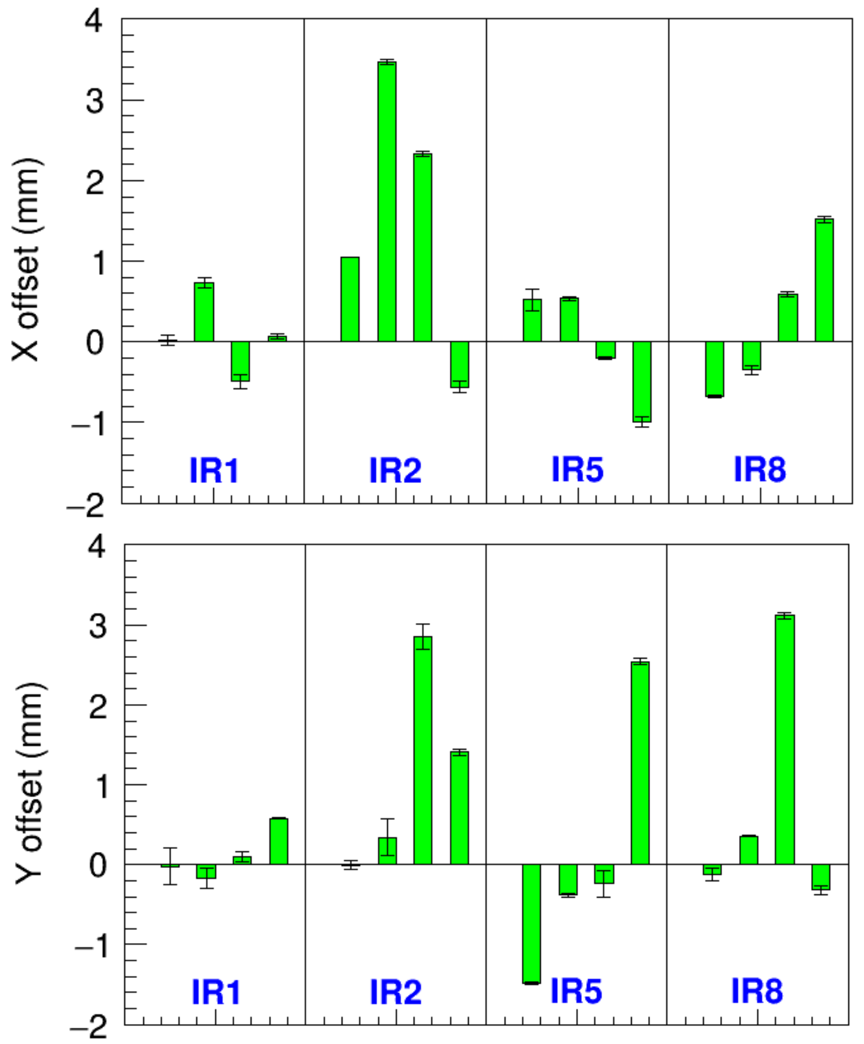


~540 readings per beam & plane

BPM offsets – example of triplets

- For **individually powered quadrupoles** it is possible to determine the offset between BPM and quadrupole centre.
  - The strength of the quadrupole is modulated while the beam is scanned in the quadrupole (‘**K-modulation**’).
    - The modulation on the beam orbit is proportional to the offset wrt quadrupole center, vanished for a centred beam.
  - Unfortunately a lengthy measurement…
- K-modulation measurements were performed for the triplets (Q1 and Q2 BPMs).
  - Offsets are large – up to 3.5 mm !
  - Offsets are correlated between B1 and B2 despite independent processing electronics → mechanical offset.
  - Since 2017 the offsets are directly subtracted from the orbit by the orbit feedback (OFB, acts as data concentrator).

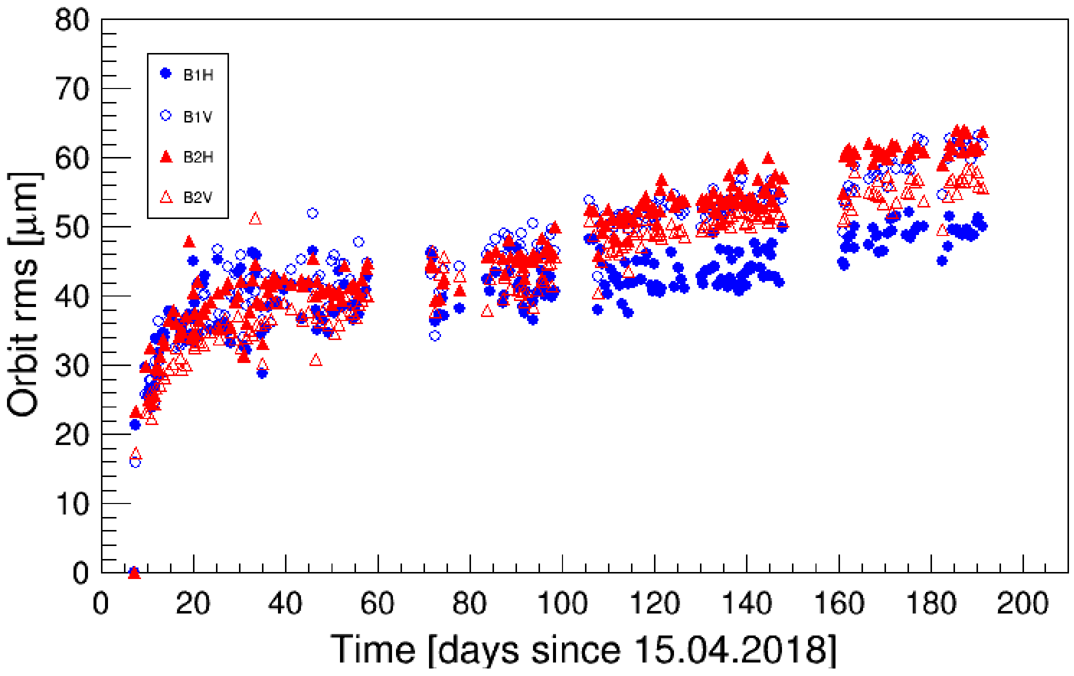
BPM offsets in triplets (Q2.L → Q2.R)



Orbit in the cycle – step 2

- The target orbits along the cycle are constructed by adding the theoretical shape of all the bumps (crossing angles, separation, lumi scan etc) to the flay orbit obtained at injection.
  - The target is calculated automatically from the bump settings.
- The reference orbits are used by the orbit feedback as targets for the corrections.
  - For injection, ramp and squeeze the targets generally do not change during the year.
  - Lumi scan correction drifts are updated periodically (only affects collisions).
- The long term reproducibility of the global orbit rms (for a given beam type) is at the level of ~50 µm.
  - Residual after correction by OFB.
  - Long term BPM stability? Residual from ground motion? Some investigations planned during LS2.

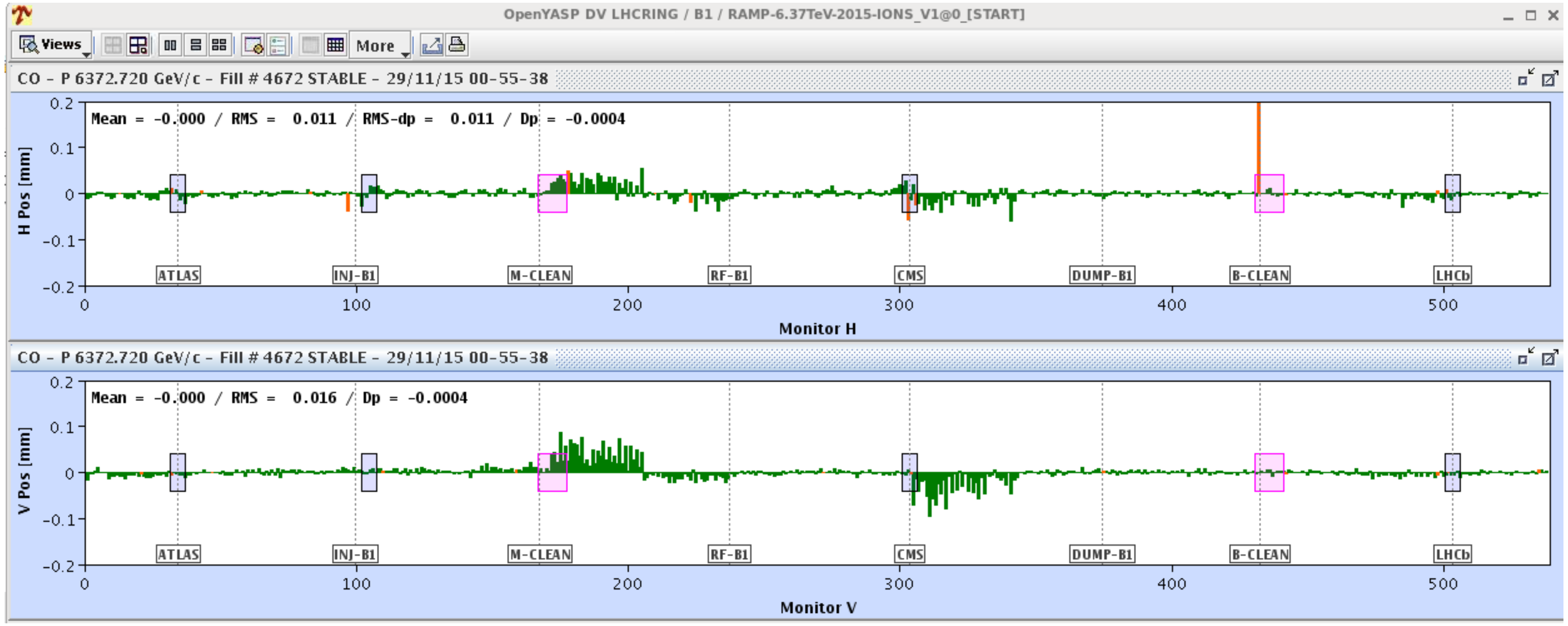
Global orbit rms evolution (change wrt start of physics)



BPM systematic errors

- Crate temperature induced systematic offsets were a plague of the BPM readings during Run 1, with offsets of up to 100's μm building up in certain fills !
  - Impact on reproducibility, steering in stable beams with OFB ~ impossible.
- During LS1 all crates were renovated and stabilised in temperature, giving a large improvement of the data quality and reproducibility.
  - Despite this improvement, some 10's μm systematic effects can be observed in some fills for certain crates.
  - Signature: ~ same shift in H & V.

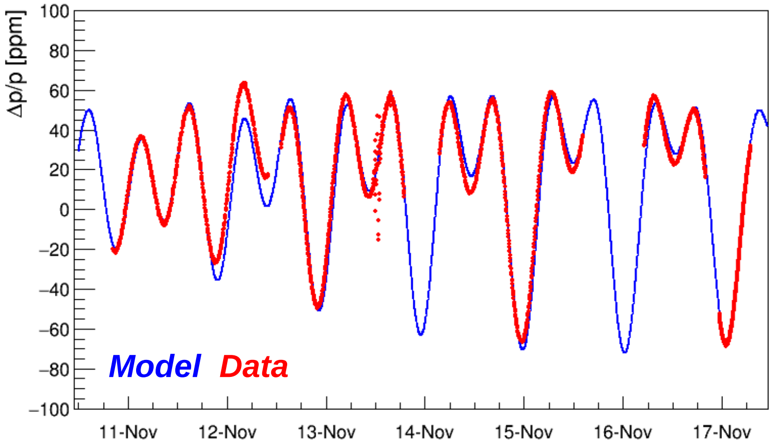
Example of temperature driven BPM reading errors



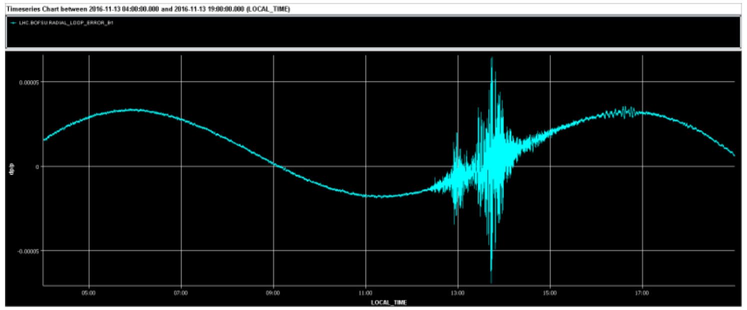
Orbit drifts and orbit correction

- In stable conditions (i.e. injection, stable beams) the LHC orbit drifts slowly due to:
  - Ground motion, rms movement of elements over 1 year ~0.1-0.2 mm,
  - Tides and geological circumference changes (including earthquakes),
    - Mainly visible as radial (circumference) changes.
  - Triplet movements (sources other than ground motion).
    - Thermal shield temperature, cryostat pressure (quenches).
  - Uncorrected drifts can add up to ~ 0.1-0.2 mm (arcs) in a fill.
- Orbit correction in stable beams:
  - Run 1: the orbit in SB was corrected manually.
    - Limited by BPM systematics due to crate temperature.
    - Was 'rocky' since the correction steps are discrete and separated by large time intervals. Not good for offset levelled experiments.
  - Run 2: the orbit in SB was corrected with the OFB since ~2016.
    - Gentle correction (very low gain, only global structures) to minimize interference with levelling by offset and lumi scans.
      - The target orbit of the FB did not track lumi offsets changes. Tracking all changes (also during luminosity, emittance and vdm scans) is technically possible but adds ~15-30 seconds to each step, therefore not used.

Tides in November 2016 (4 TeV p-Pb)



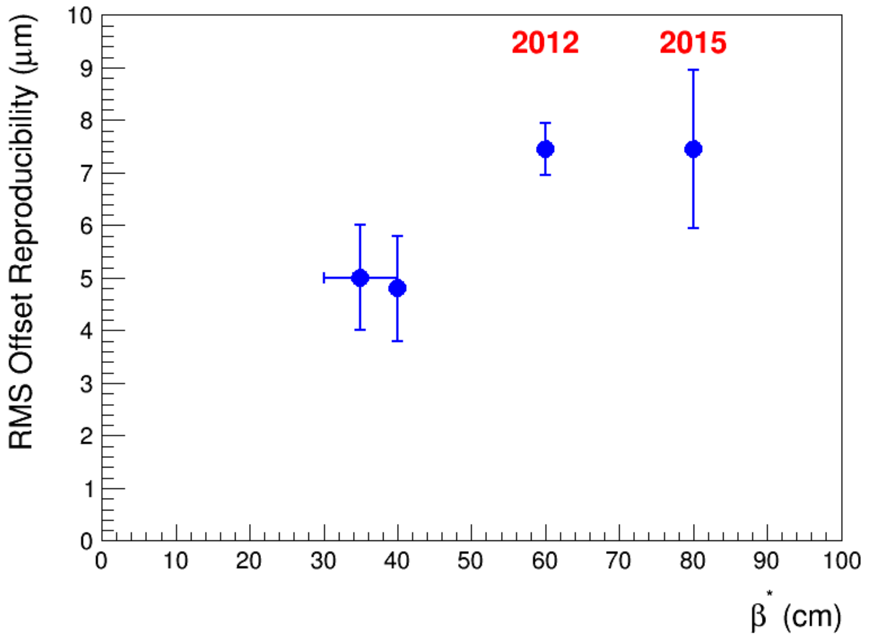
New Zealand earthquake (13th Nov 2016)



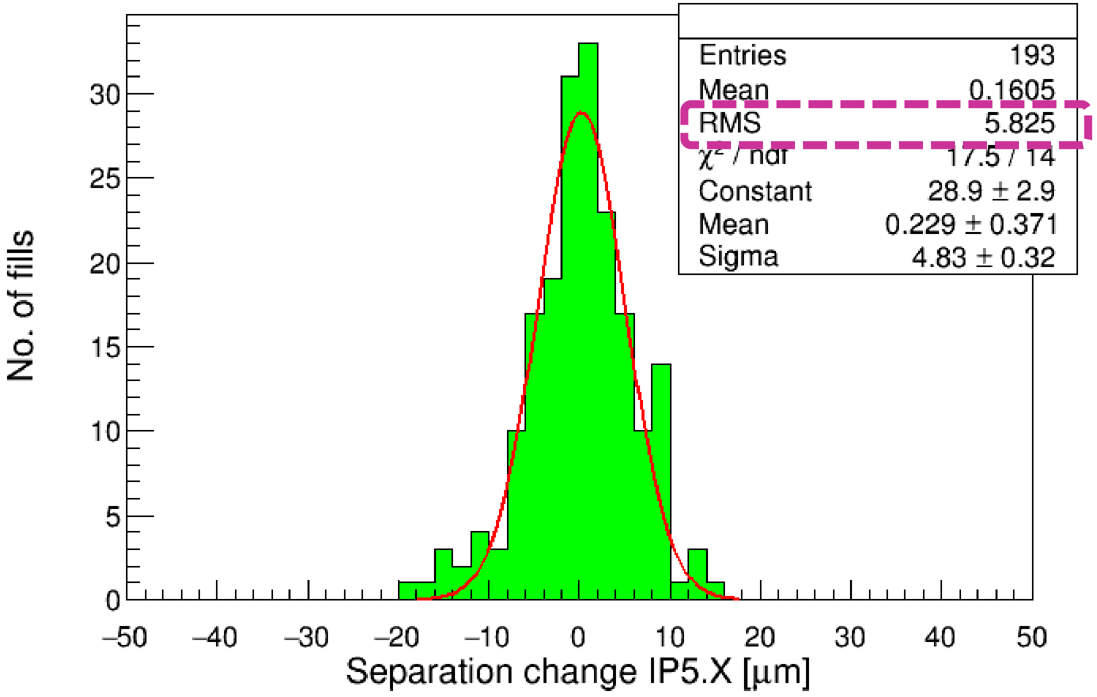
Beam offset reproducibility at start of fills

- The reproducibility of the beam separation (B1-B2) at IP1 and IP5 from one fill to the next is at the level of 5-8 μm rms.
  - Excluding violent events like triplet quench events and long periods between fills like TSs, MDs…

*Fill-2-fill reproducibility of the B1-B2 separation for different years and β**



Fill-2-fill reproducibility of the B1-B2 separation

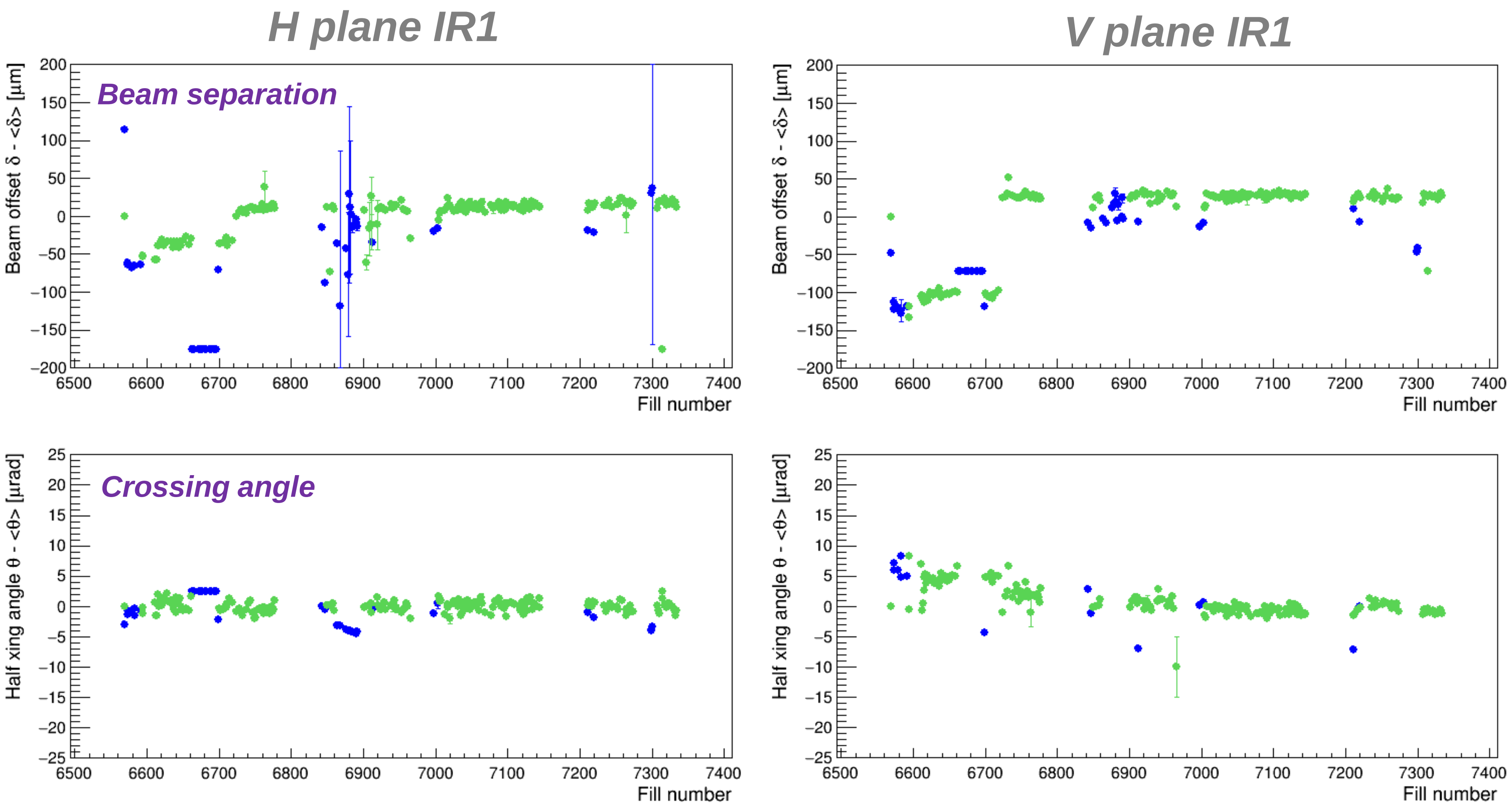


- Separation change is defined as the optimal setting for fill *j* wrt optimal setting for fill *j-1*.

DOROS electronics (Q1)

- During Run 2 the DOROS electronics connected to the Q1 BPMs around the IPs was continuously improved by M. Gasior et al, with a positive impact on accuracy and stability.
  - Short terms stability ~ 1 μm or less.
- The DOROS channels were not used in the OFB during Run 2 (different data stream). They were only used operationally to steer beams into collision during machine setup, in particular once a pervious reference had been established.
  - Replaced lengthy scans of the beams around each other at the IPs.
  - Used for high beta, vdm, ion setups, MDs…
- To estimate the long term reproducibility of the Q1 DOROS data, the readings at the start of SB (first ½ hour) were analysed for all 2018 fills.
  - Assuming that the beams were correctly steered head-on in IP1 and IP5, and to a reproducible target in IP8, it is possible to evaluate the stability of the beam. offset values predicted with DOROS.
  - For the crossing angle the data is not corrected a possible levelling steps (→small).

- Evolution of the beam offsets and crossing angles in 2018 for IP1.
  - Evolution wrt mean values.
- There are stable periods, but also a significant number of outliers.

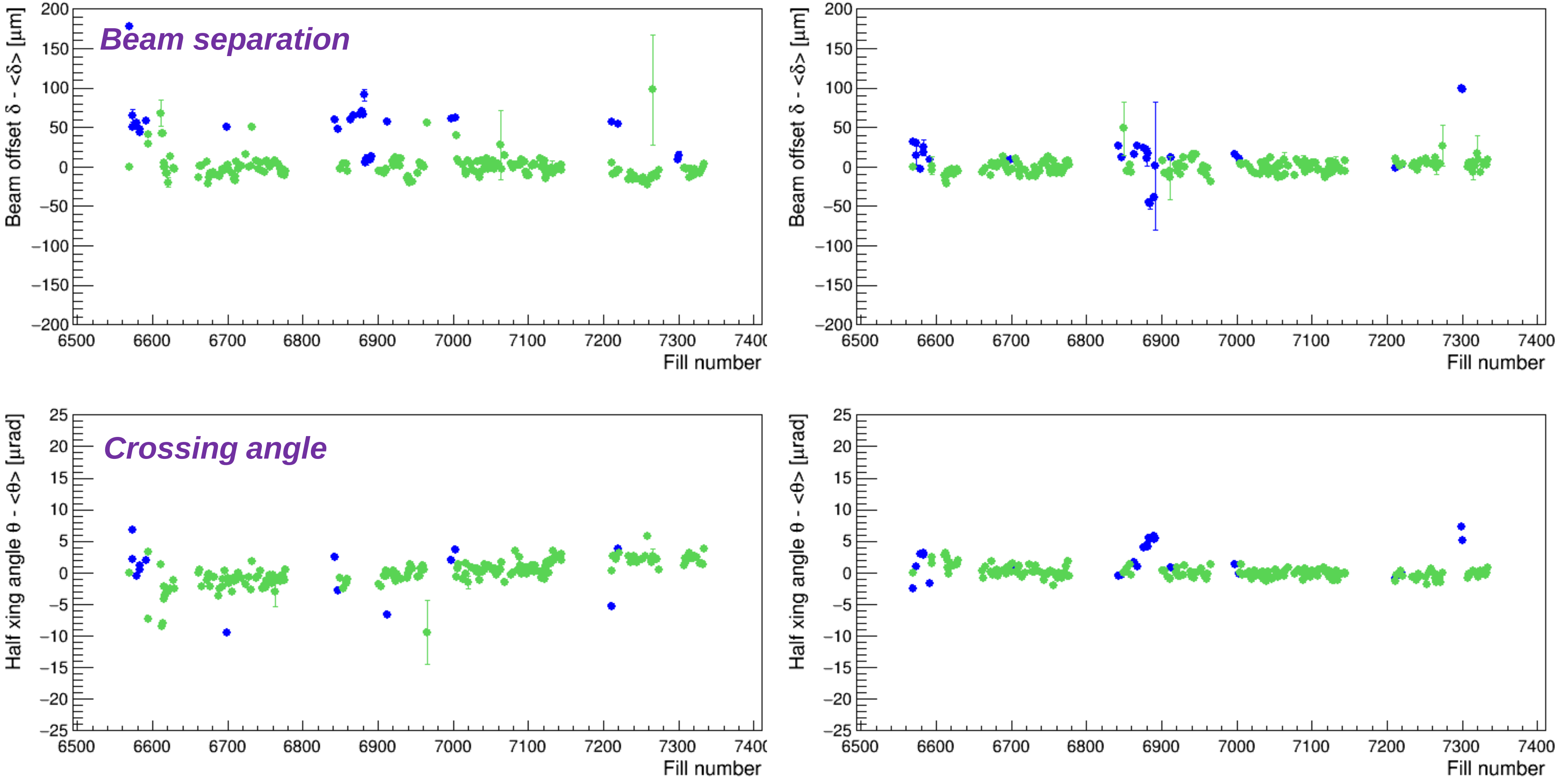


Green: high intensity fills with > 2000b, Blue: other fills

DOROS @ IP5

- Evolution of the beam offsets and crossing angles in 2018 for IP5.
  - Evolution wrt mean values.

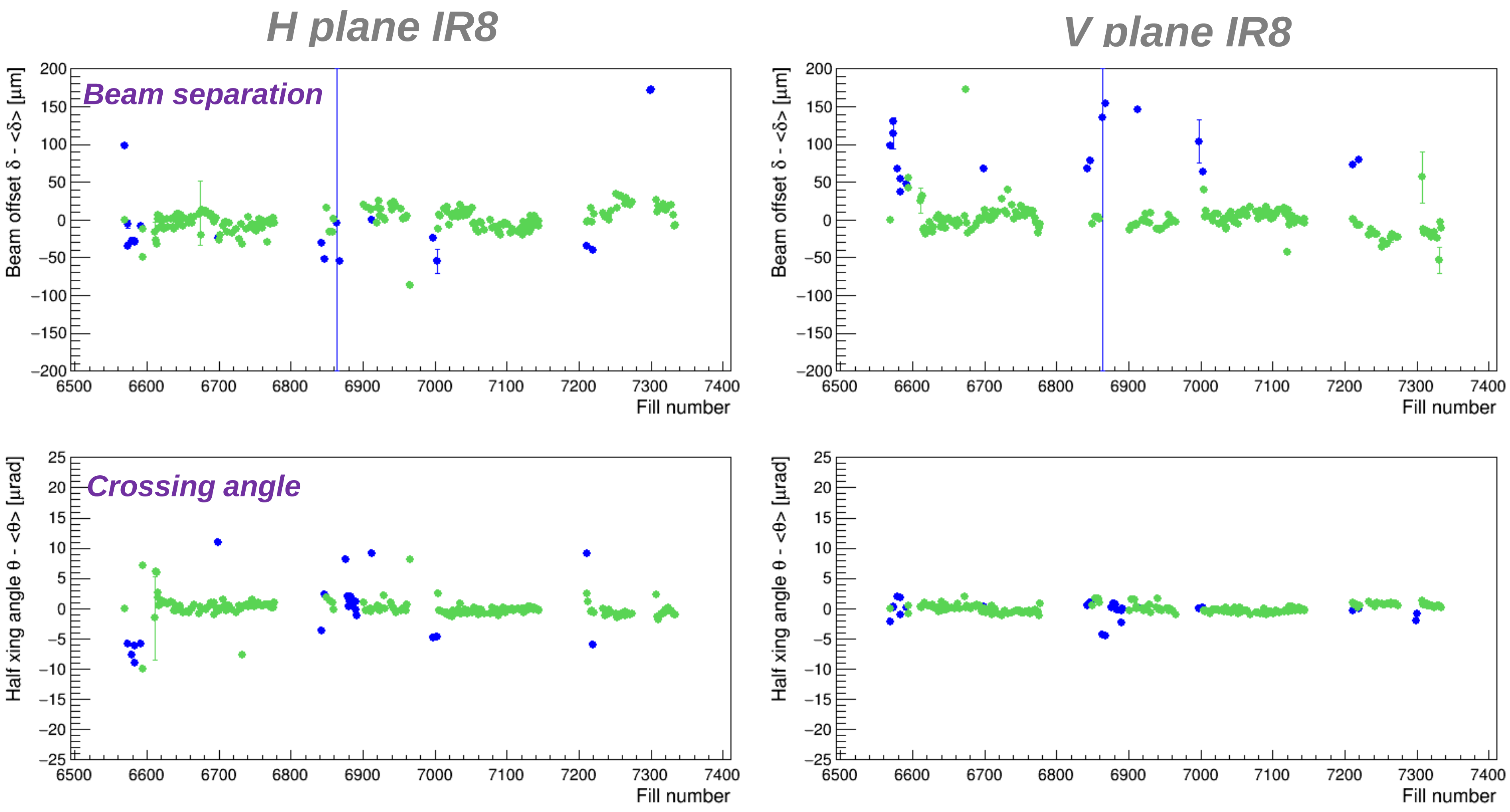
H plane IR5 *V plane IR5*



Green: high intensity fills with > 2000b, Blue: other fills

DOROS @ IP8

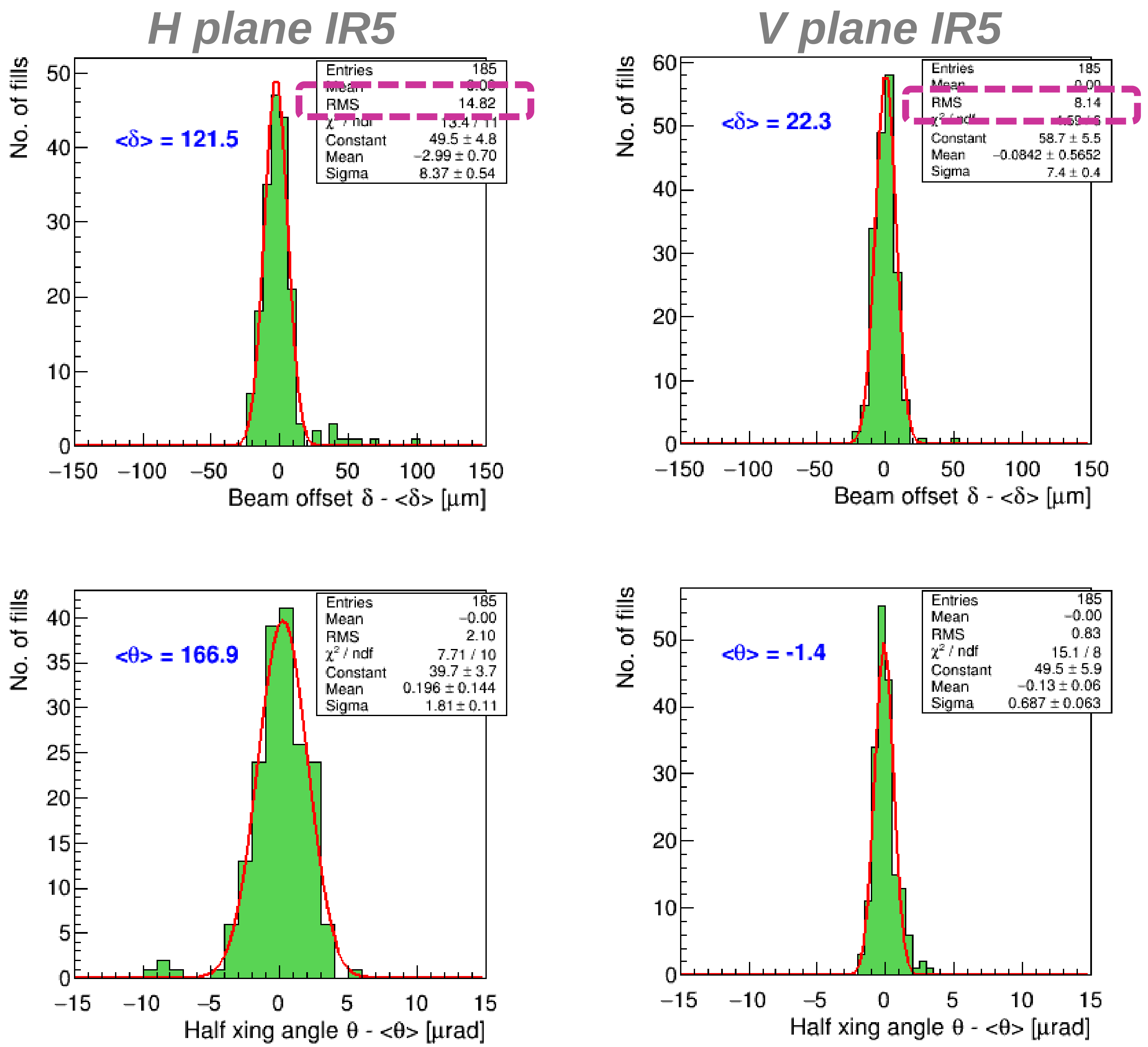
- Evolution of the beam offsets and crossing angles in 2018 for IP8.
  - Evolution wrt mean values.
  - Vertical plane is of course affected by the levelling !



Green: high intensity fills with > 2000b, Blue: other fills

Example : DOROS distributions @ IP5

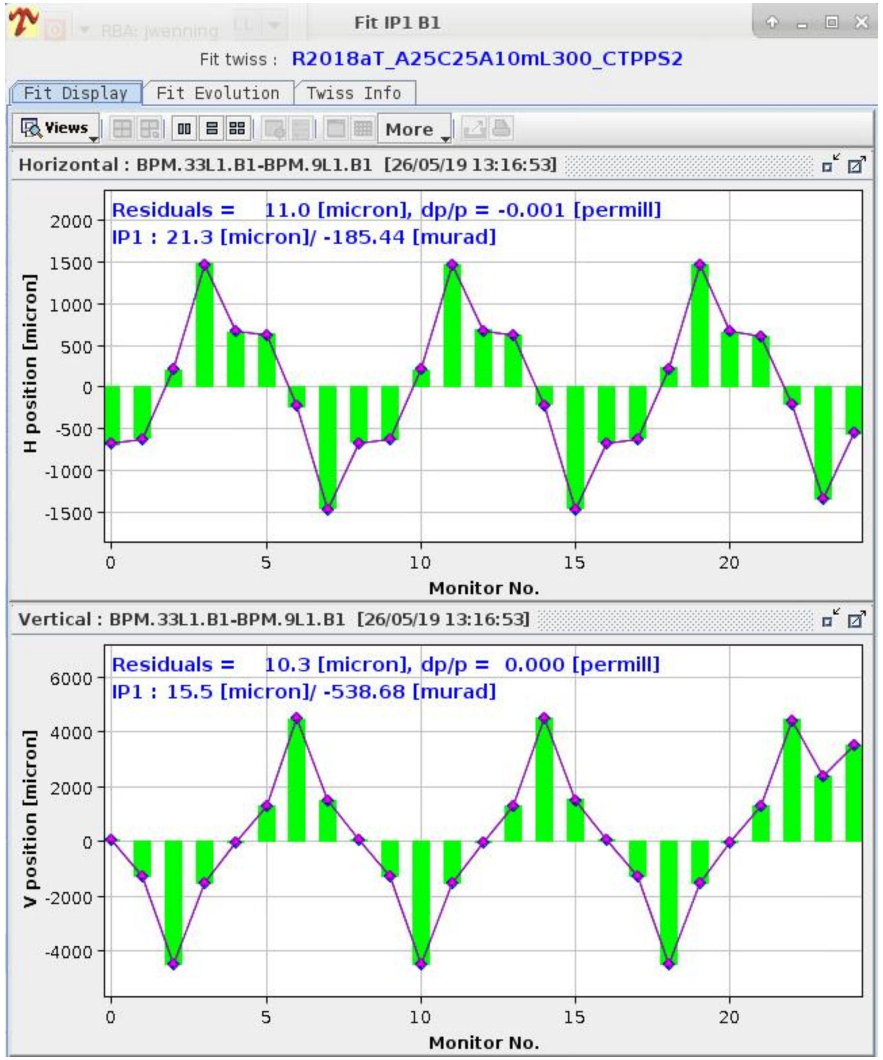
- Distribution of the beam offsets and crossing angles in 2018 for IP5 for high intensity fills (> 2000 b).
  - wrt mean values.
- IR5 fill-2-fill spread of the offsets **14 μm (H) and 8 μm (V)**.
  - Those number approach the fill-2-fill reproducibility.
  - Figures for IR8 are similar, IR1 and IR2 suffer from large jumps (see previous slides).
- Spread of crossing angle values at the level of 1-2 urad.
  - Absolute precision ~5-10 μrad.
- >> very encouraging results – but the outliers must be understood before we can rely on DOROS operationally.



Orbit interpolations

- During vdm scans, the OFB is generally not switched on to avoid interferences with the scans.
  - Any orbit drift therefore affects the scan results.
- A generic orbit/trajectory fitting tool of the steering application is currently used to estimate possible IP position shifts during scans.
  - Fit to the orbit data recorded in the arcs around scanned IP, result interpolated to the IP.
  - Left & right predictions maybe be used to judge the quality of the predictions.
    - Inconsistent result point towards the scanned IP as source of the orbit drift.
- For Run 3, one could consider building a dedicated fit tool for the vdm analysis instead of the current manual extraction and fitting.
  - Option 1: re-use the code (JAVA) with a light UI on top (time & optics selection, result file, lightweight display) → JW (if time permits…).
  - Option 2: rebuild the fit with Python using the existing Python data extraction tools → volunteer ?
    - Fit part is totally straightforward !

B1: Fit example for IP1.L (BPM.33L1 to BPM.9L1)



Summary

- With the improved BPM measurement stability after LS1 and the maturity of orbit related controls tools as of 2016, the LHC orbit became reproducible and reliable (2016-2018).
  - No major change expected for Run 3, except for a complete re-design of the LHC OFB.
    - With the same / improved functionality, but it's the BPM data quality that is the key to success.
- Continuous improvements of the DOROS electronics during Run 2 led to excellent results in 2018, with beam offset predictions close to the reproducibility of the machine.
  - The DOROS at Q1 are now the standard tool to establish collisions for new machine configurations.
  - Understanding outliers in the data would be a good objective for Run 3, in view of establishing DOROS firmly as tool (besides relative tracking inside a fill).
- Some time could be invested into a dedicated orbit interpolation tool for vdm scans.
  - Depending on the performance of the re-designed OFB, one might consider running vdm scans with OFB active, the target orbit being updated at each scan step. To be discussed when the option become available.