BPMs in turn-by-turn mode: LHC experience and HL-LHC requirements

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Outline

- Measurement conditions
- LHC experience
  - BPM gain (calibration)
  - Positional noise
  - Faulty BPMs
- HL-LHC
  - Plans for optics measurements
  - ➢ Required BPM performance

LHC Measurement conditions

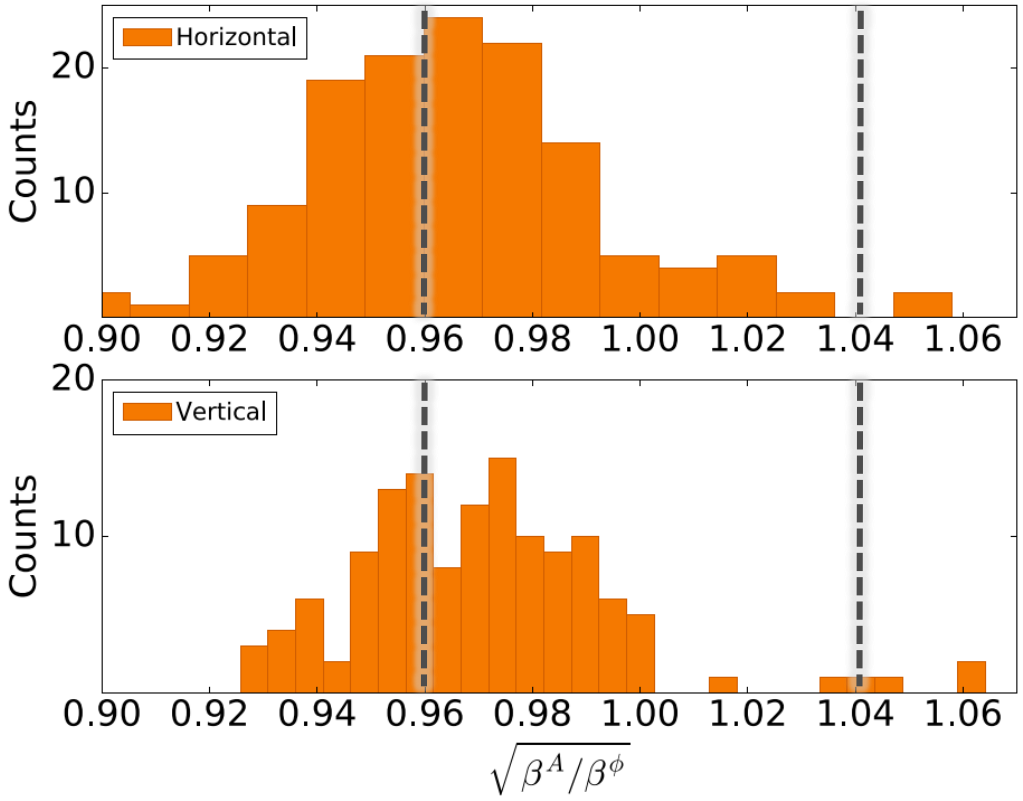
- Beam?
  - 1 pilot bunch (maybe 3 in Run3)
    - Pilot bunches have $5 \cdot 10^9$ to $1 \cdot 1^{10}$ protons
- Acquire Turn-by-turn (bunch-by-bunch) BPM data
  - After excitation (AC-dipoles, kickers, RF-modulation)
  - Limited to about 40000 turns · bunches per BPM

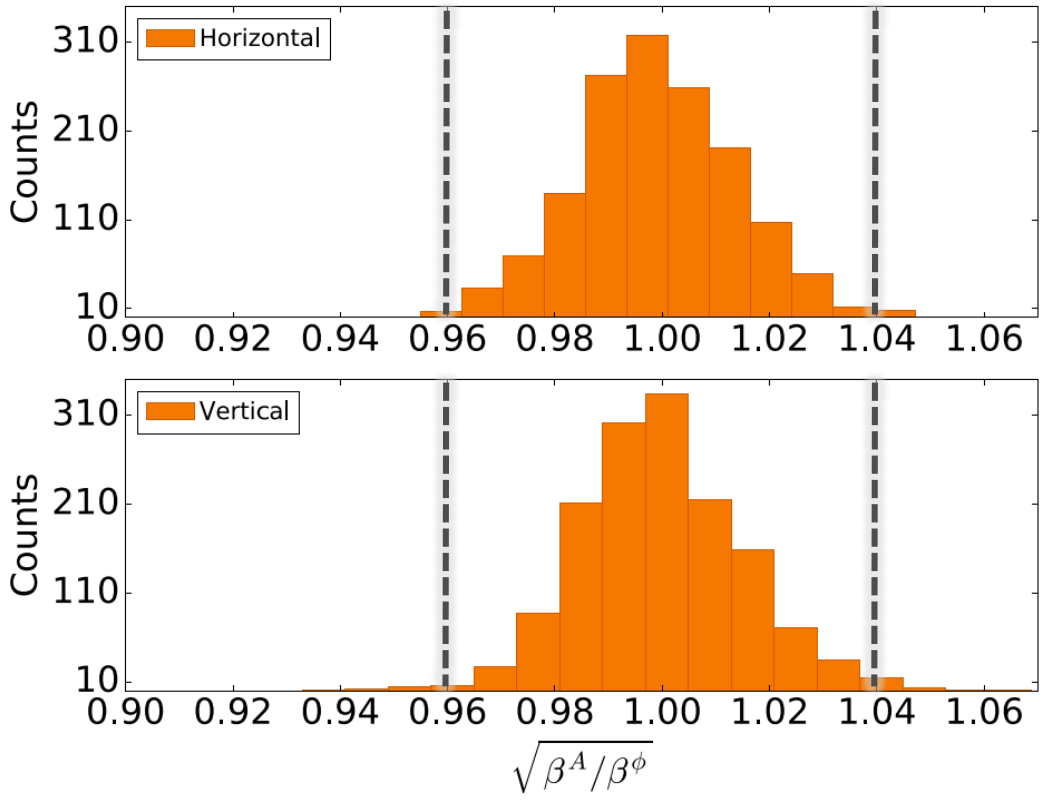
LHC BPM calibration factors

- Calculated from measured $\sqrt{\frac{\beta_{amp}}{\beta_{phase}}}$
  - β_{amp} depends on BPM calibration while β_{phase} does not
  - With respect to average gain in the arcs
- Between Q1-Q4 fit from ballistic optics measurement
  - can decrease the uncertainty by about factor of 2 [1]
- Specified performance: maximal gain error of 4% [2]

LHC BPM calibration errors

A. García Tabarés





Stripline (IRs): $(-3 \pm 5)\%$

Button (arcs): spread 1.7%

LHC: Positional Noise

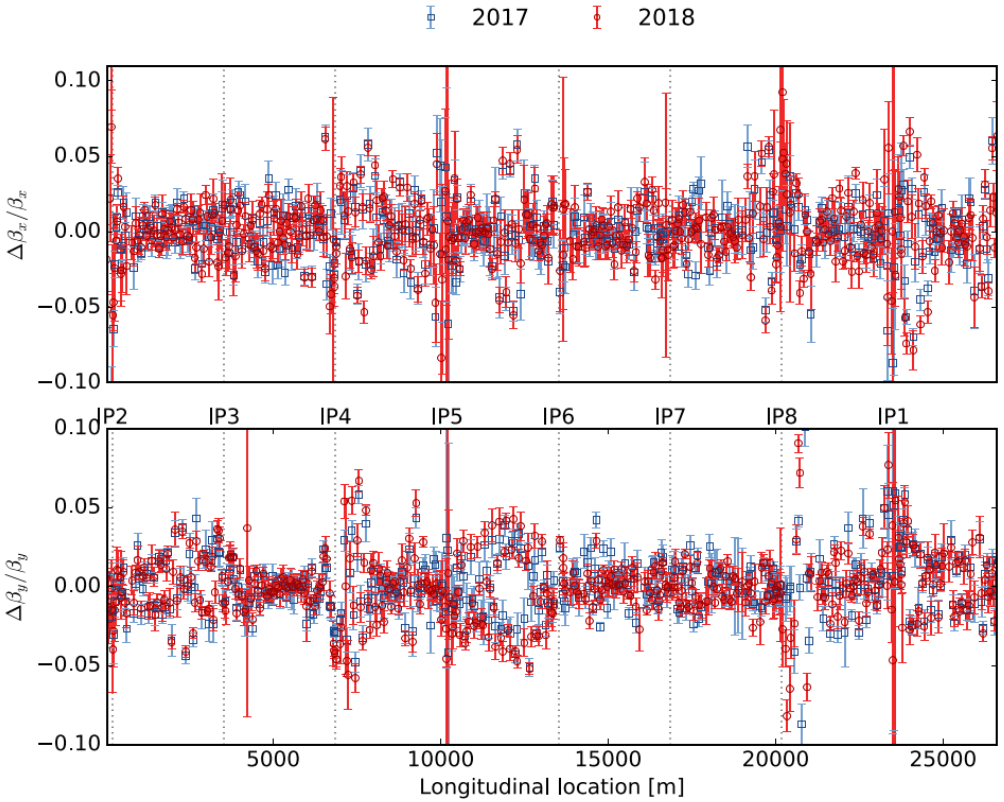
- Estimated by SVD from turn-by-turn data
  - Can be optics dependent (e.g. ATS)
  - Based on difference between raw and cleaned TbT data
  - Trade off between noise and small signals
- **100 µm** in arcs, **200 µm** in IRs and **15 µm** with DOROS* [3]
  - 30 % relative error
  - Specified performance of **200 µm** [2]

*estimated from spectral noise at normalised frequencies around 0.3

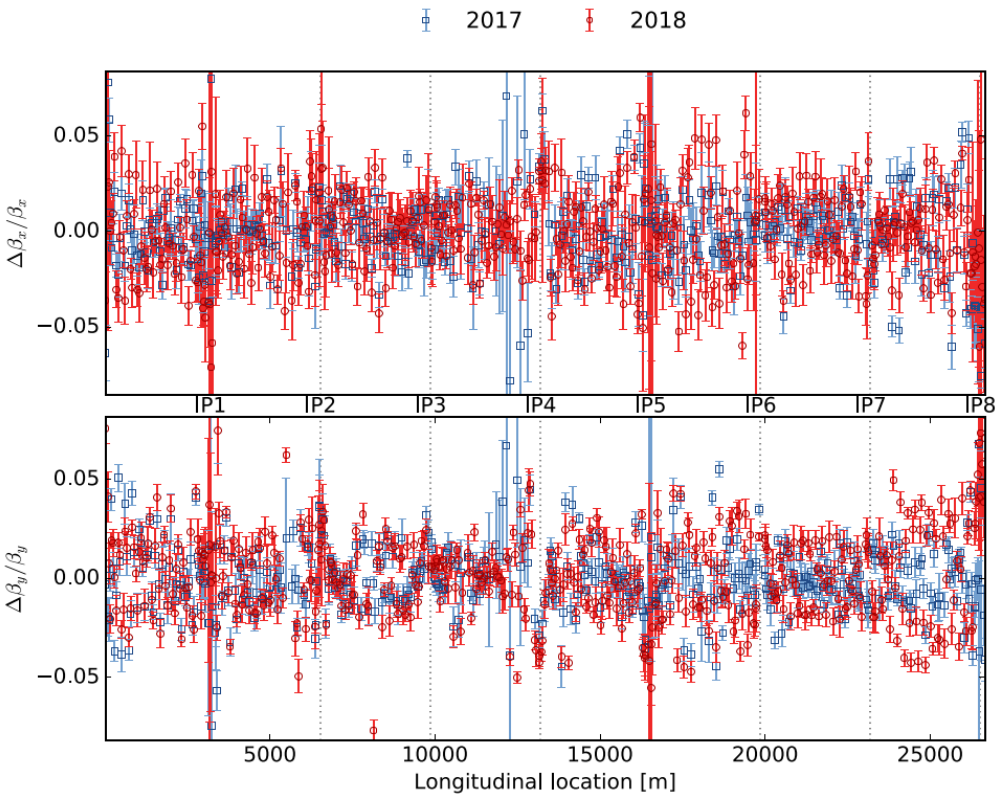
Bad LHC BPMs in optics measurements

- Identified based on cuts
  - Amplitude, tune, correlation (SVD)
- 20 out of 500 BPMs were faulty in 2018 (E. Fol)
  - Average per beam and plane based on 2200 excitations
- In total: 4 % of BPMs are found malfunctioning
- Critical **BPMSW.1R5.B2 (vertical)** missing in whole Run 2

LHC Optics corrected: 2% rms (β*=0.3 m)



Beam 1



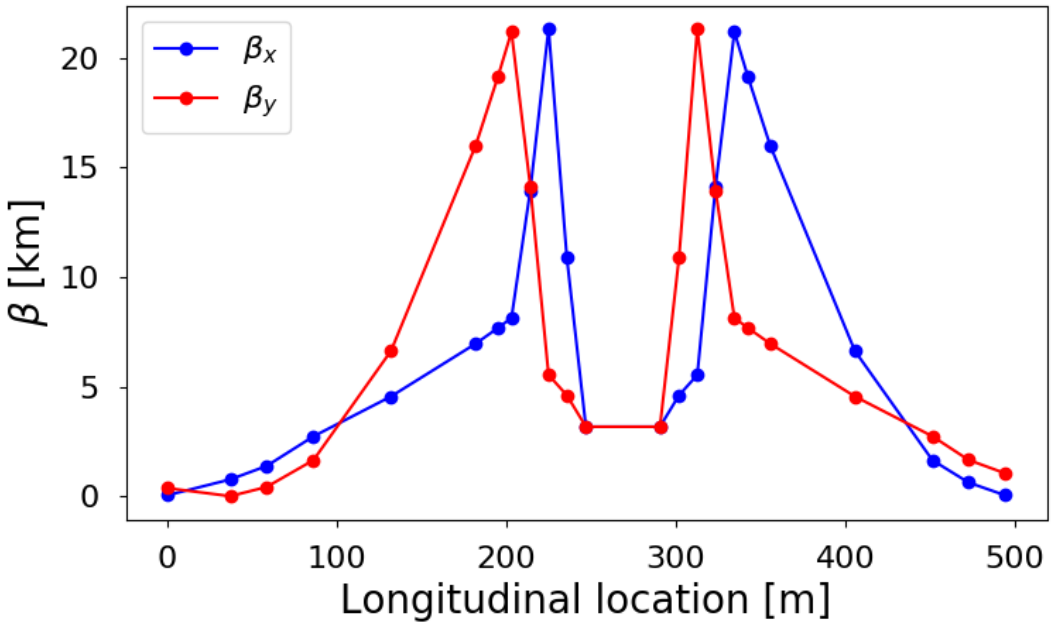
Beam 2

HL-LHC β^* and β_{waist} measurements

- Require less than 5% luminosity imbalance between IP1 / 5
  - β^* error should be below 2.3 %
- K-modulation: slow (β^* error ≈ 8% for β^*= 15cm) [4]
  - Can be improved to 4% with main bend power supplies
- Luminosity scan: (very slow, needs collisions) [5]
- BPM turn-by-turn data of excited beam: (faster)
  - relies on **BPMs (calibration and noise)**

HL-LHC IR BPMs: 1 and 5

- β-function up to 22 km
  - Oscillation amplitude during optics measurements up to 10 mm
- Phase advances between BPMs of few mrads
  - As low as 0.4 mrad
  - Needs low noise



BPMs for measurement with $\beta^* = 15$cm

- Positional noise < 15 μm
  - Calculate β from phase advance of 0.4 mrad (Q3-Q4)
    - Get error of about 10% from a single BPM combination
  - Phase advance error of 0.2 mrad over IP for β_{waist} [5]
  - Can be relaxed with longer AC-dipole plateau
- Calibration error < 1.6% (Assuming beam-based calibration)
  - Get β_{waist} error < 2.3 %

HL-LHC Requirements (**turn-by-turn**)

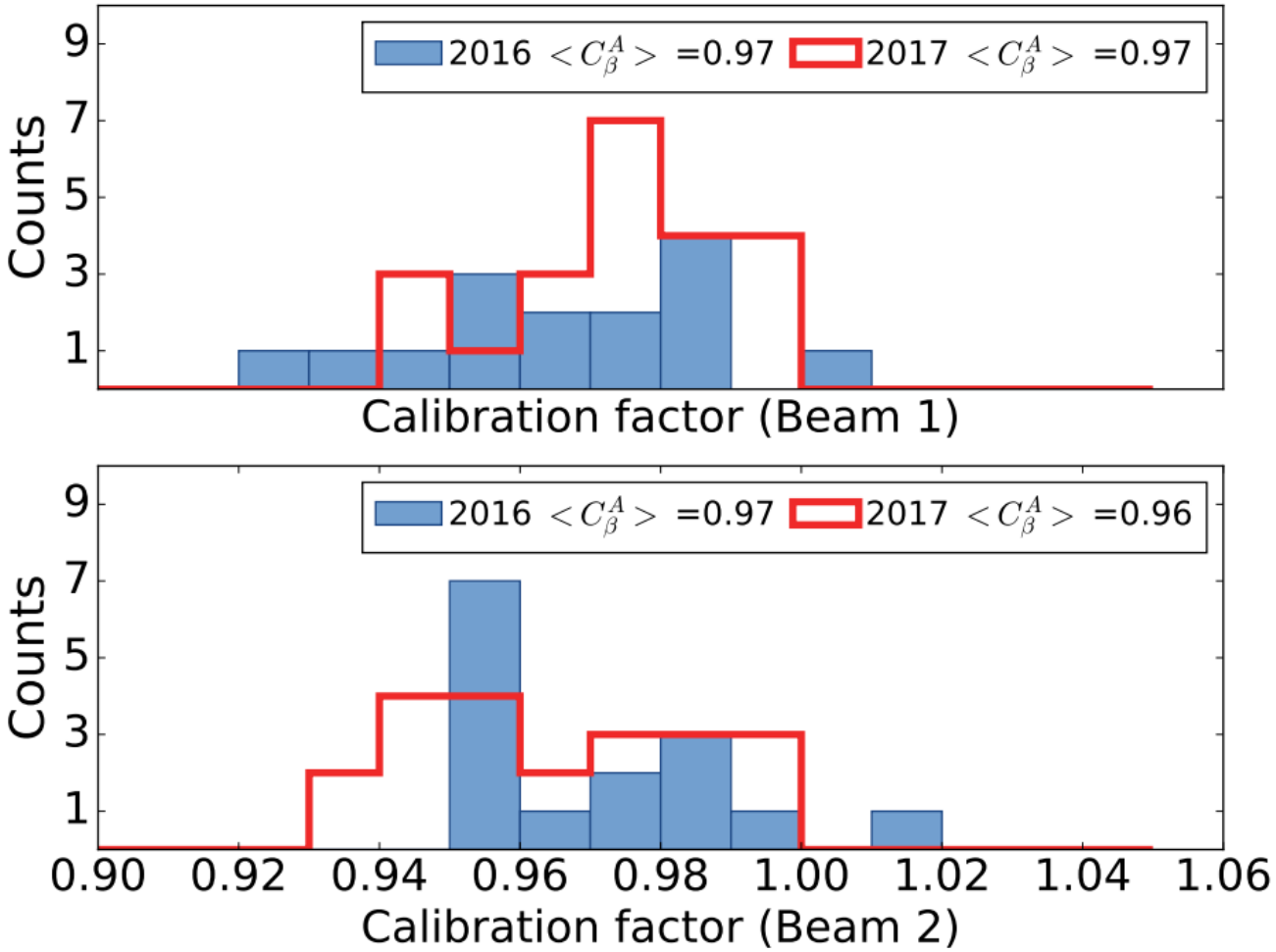
- Bunch-by-bunch acquisition (all BPMs)
  - At least 20000 turns for 3 bunches
- IR BPMs for a **pilot** bunch in ± 20 mm around the centre:
  - Position noise below 15 µm
  - Calibration errors below 1.6 %
- Any improvements of arc BPMs are very welcome

References

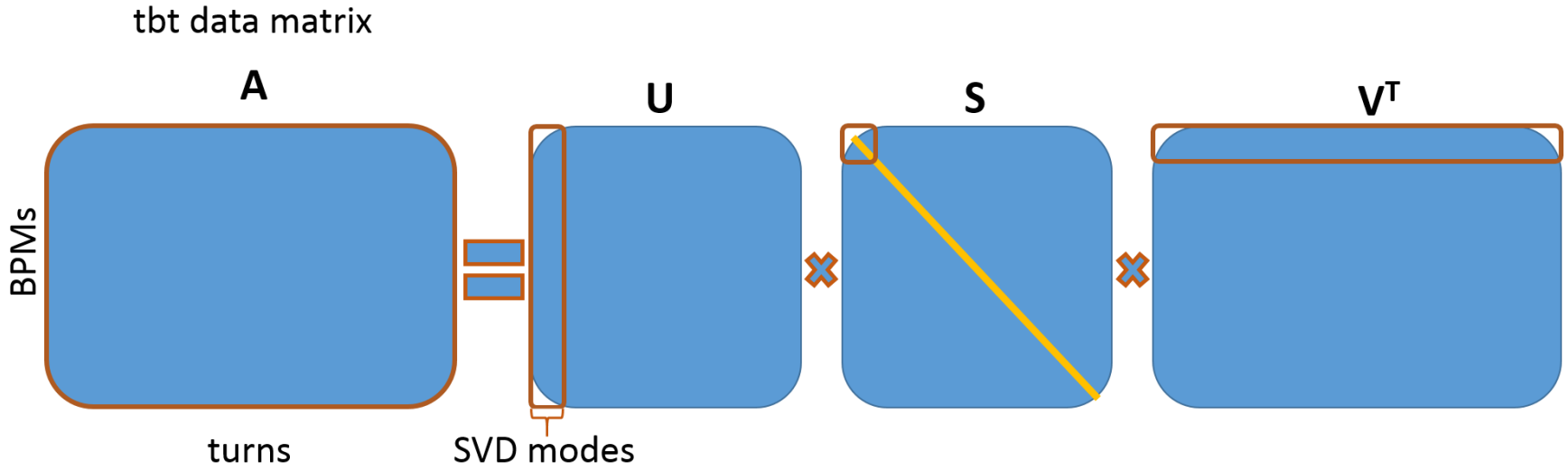
1) A. García Tabarés Valdivieso, Optics-measurement-based Beam Position Monitor calibration, PhD thesis.
2) J.-P. Koutchouk, Measurement of the beam position in the LHC main rings, https://cds.cern.ch/record/1068133/files/cer-002724157.pdf
3) T. Persson et al., Linear coupling dependence on intensity and a next step towards a feedback (MD1850), https://cds.cern.ch/record/2255976/files/CERN-ACC-2017-0008.pdf
4) M. Hofer et al., K-modulation in future high energy colliders, IPAC 19, paper MOPMP022.
5) J. Coello de Portugal et al., New local optics measurements and correction techniques for the LHC and its luminosity upgrade, submitted to Phys. Rev. Accel. Beams.

Backup slides

LHC BPM calibration from ballistic optics



SVD cleaning - review



- Use few largest singular values (modes) to remove noise
- Columns of U and V matrices are orthonormal vectors
  - Bad BPMs dominate modes (limit typically > 0.9)