Compensation of beam-beam driven RDTs in the LHC

E.H.Maclean, T.H.B Persson, F. Burkhardt, R. Tomas, K. Paraschou, X. Buffat, G. Sterbini

and the OMC team:

Y. Angelis, F. Carlier, J. Dilly, V. Ferrentino, M. Le Garrec, W. Van Goethem, S. Horney, J. Keintzel, E. Kravishvili, K. Skoufaris, F. Soubelet, K. Ujani

Many thanks to the LHC EICs, OP, Collimation, and BI teams!

Resonance driving terms measured with an AC-dipole are used extensively in LHC to study and correct linear coupling and various nonlinear RDTs

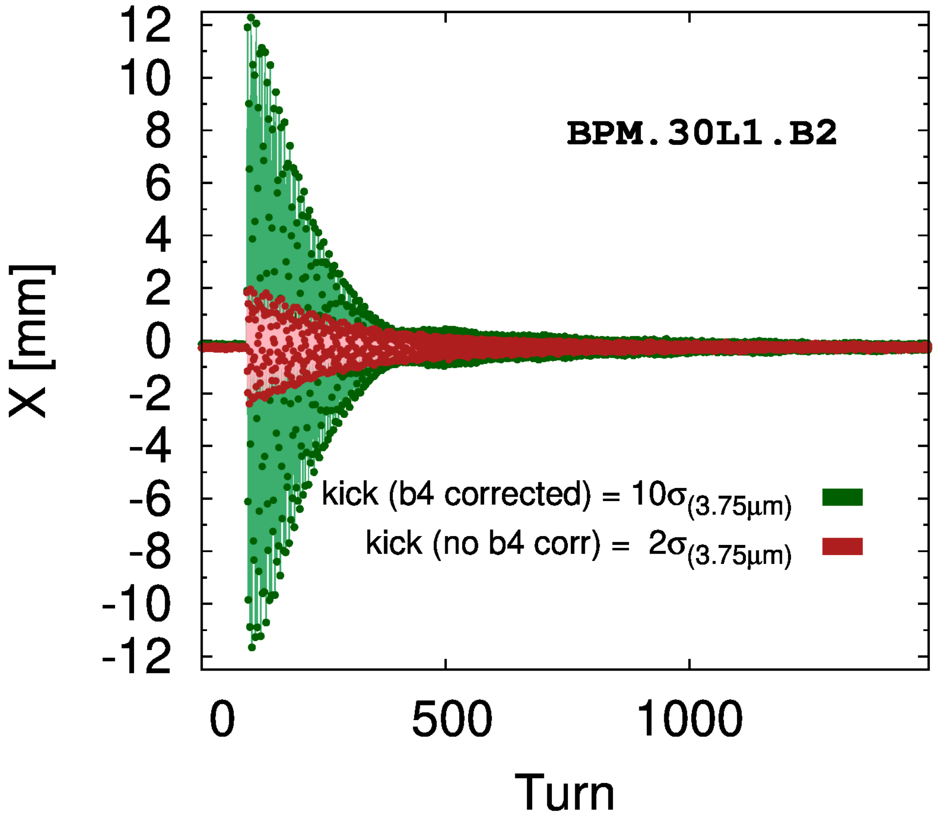
→ **Can we apply the typical OMC techniques to some of the beam-beam driven RDTs in the LHC?**

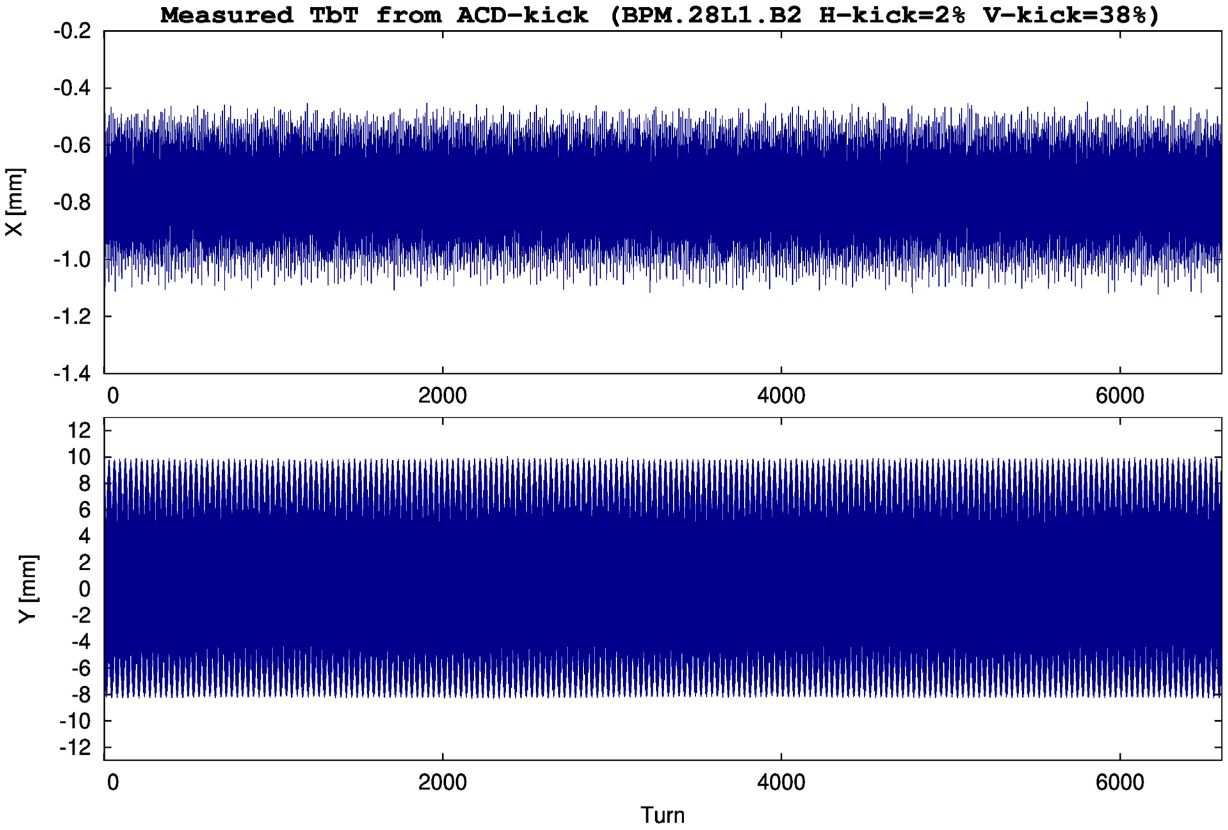
Overview:

- Resonance Driving Term measurements and corrections in the LHC
- Measurement of beam-beam driven RDT in the LHC & comparison to simulation
- Potential to correct the beam-beam driven RDT

LHC has dedicated kicker magnets for Optics studies and commissioning: can operate as kicker or AC-dipole

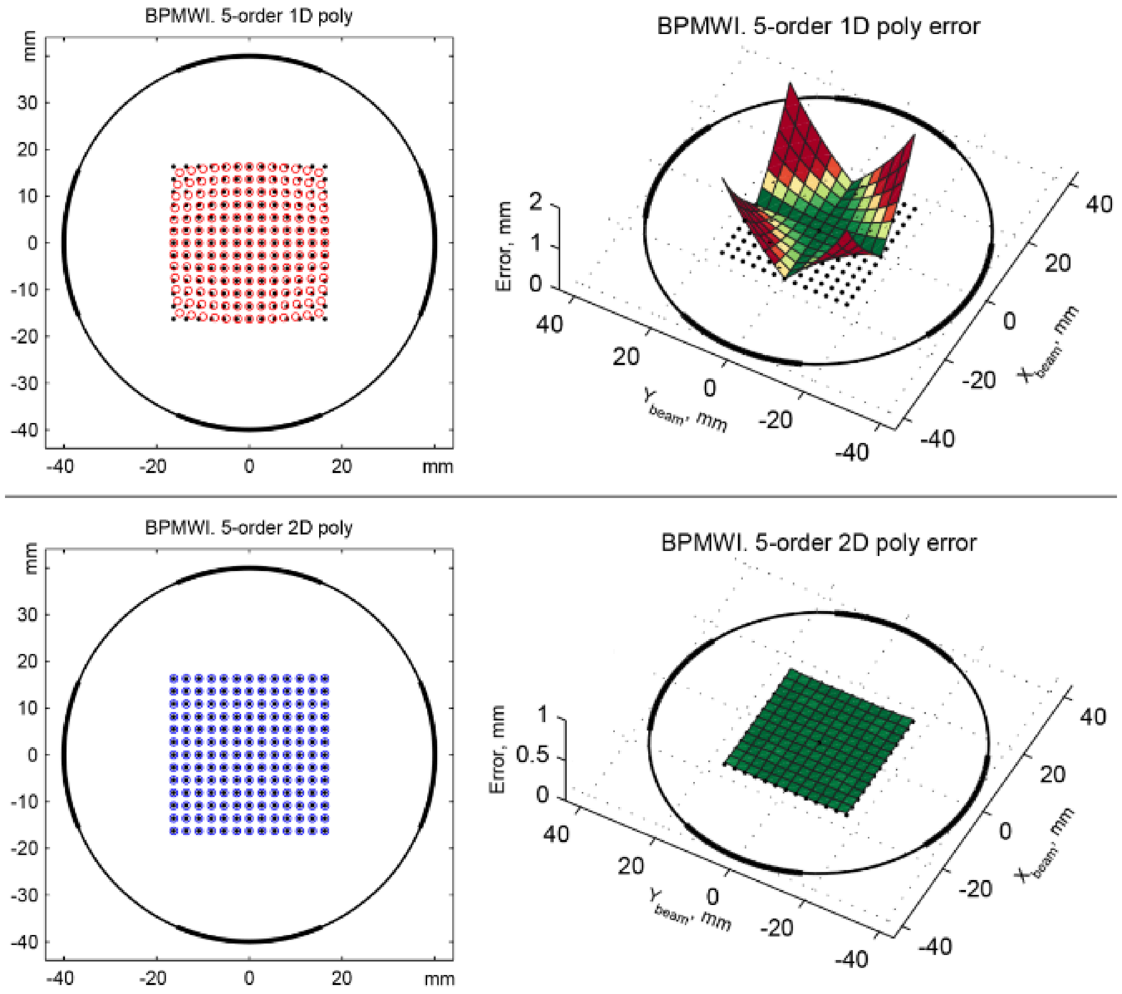
- Almost all optics studies today performed with AC-dipole
- Ramps adiabatically allowing repeated kicks of same beam + slow ramp satisfies machine protection
- Forced oscillation doesn't decohere (6600 turn analysis flattop)





Approximately 550 dual plane BPMs per ring in the LHC

- **Log pre-calibrated turn-by-turn (TbT) bunch position during the 6600 turn AC-dipole flattop**



Corrections for geometrical and electrical BPM nonlinearity pre-applied to TbT data by BI teams

- **From simulations + measured avg responses of the cards**
- **Since 2015 geometrical nonlinearity corrected via 2D polynomial to 5th order**

SVD decomposition/recombination of TbT data used to further reduce uncorrelated noise between BPMs

T.Persson et al., PRAB 17 0511004
Improved control of the betatron coupling in the LHC

R.Calaga et al., PRAB 7 042801
Statistical anlaysis of RHIC BPM performance

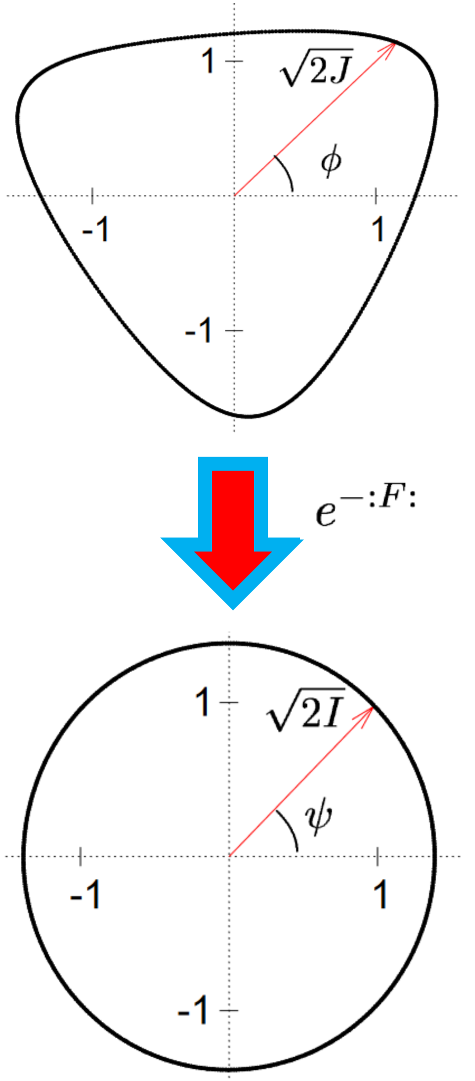
For nonlinear optics studies, we characterize how strongly a given resonance perturbs the turn-by-turn motion via Resonance Driving Terms (RDT): f_{jklm}

Linear motion

[R. Tomas, CERN-THESIS-2003-010, Direct Measurement of Resonance Driving Terms in the Super Proton Synchrotron (SPS) of CERN using Beam Position Monitors]

$$\hat{x} - i\hat{p}_x = \sqrt{2I_x}e^{i(2\pi\nu_x N+\psi_{x0})} - 2i\sum_{jklm} j f_{jklm}(2I_x)^{\frac{j+k-1}{2}}(2I_y)^{\frac{l+m}{2}} \times e^{i[(1-j+k)(2\pi\nu_x N+\psi_{x0})+(m-l)(2\pi\nu_y N+\psi_{y0})]}$$

Nonlinear distortion proportional to the RDT



Resonance: $(j-k)Q_x + (l-m)Q_y$

Characterized by RDT f_{jklm}

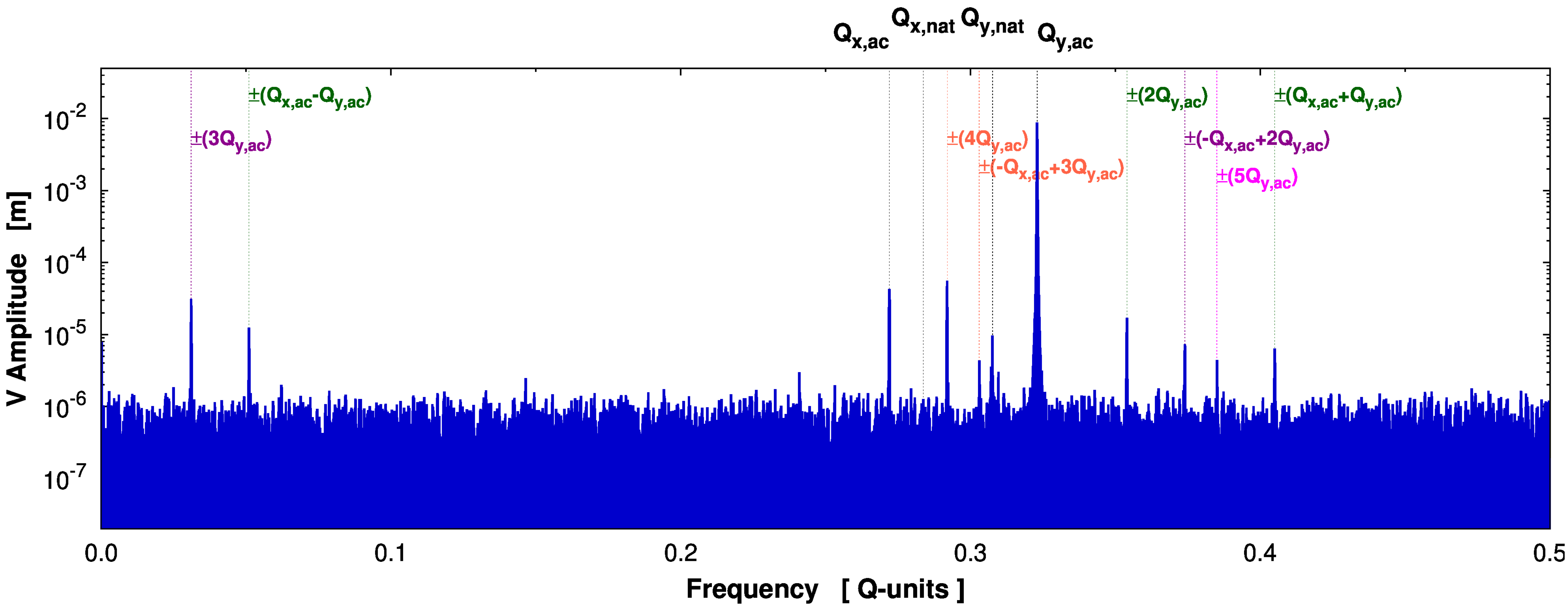
Appears in TbT Q spectra at:

H[$(1-j+k)Q_x + (m-l)Q_y$]

V[$(k-j)Q_x + (1+l-m)Q_y$]

Example of measured TbT spectrum from LHC AC-dipole kicks

- see clear peaks corresponding to combinations of the AC-dipole tunes
- We are measuring the RDTs of the forced-oscillation generated with AC-dipole (f'_{jklm})



Recipe for an LHC RDT measurement:

- **Excite with the AC-dipole and analyse tune spectrum of the 6600 turn flattop**
  → measured phase advance used to reconstruct complex spectrum from BPM pairs with $\Delta\theta{\sim}90^{\circ}$

- **Action of the driven oscillation ($A_{x,y}$) calculated from amplitude of AC-dipole tune lines (no decoherence)**
  → take mean action value over arc-BPMs with choice of model or measured β-functions

- **BPM spectra are normalized to main AC-dipole peak to remove β-dependence or BPM-calibration errors**

- **RDT value per BPM is determined from fit of normalized line amplitude vs AC-dipole kick action**

$$\mathrm{AMP_V}[(k-j),(1-l+m)] \quad = \quad 2l\left|f'_{jklm}\right|(2A_x)^{\frac{j+k}{2}}(2A_y)^{\frac{l+m-1-1}{2}}$$

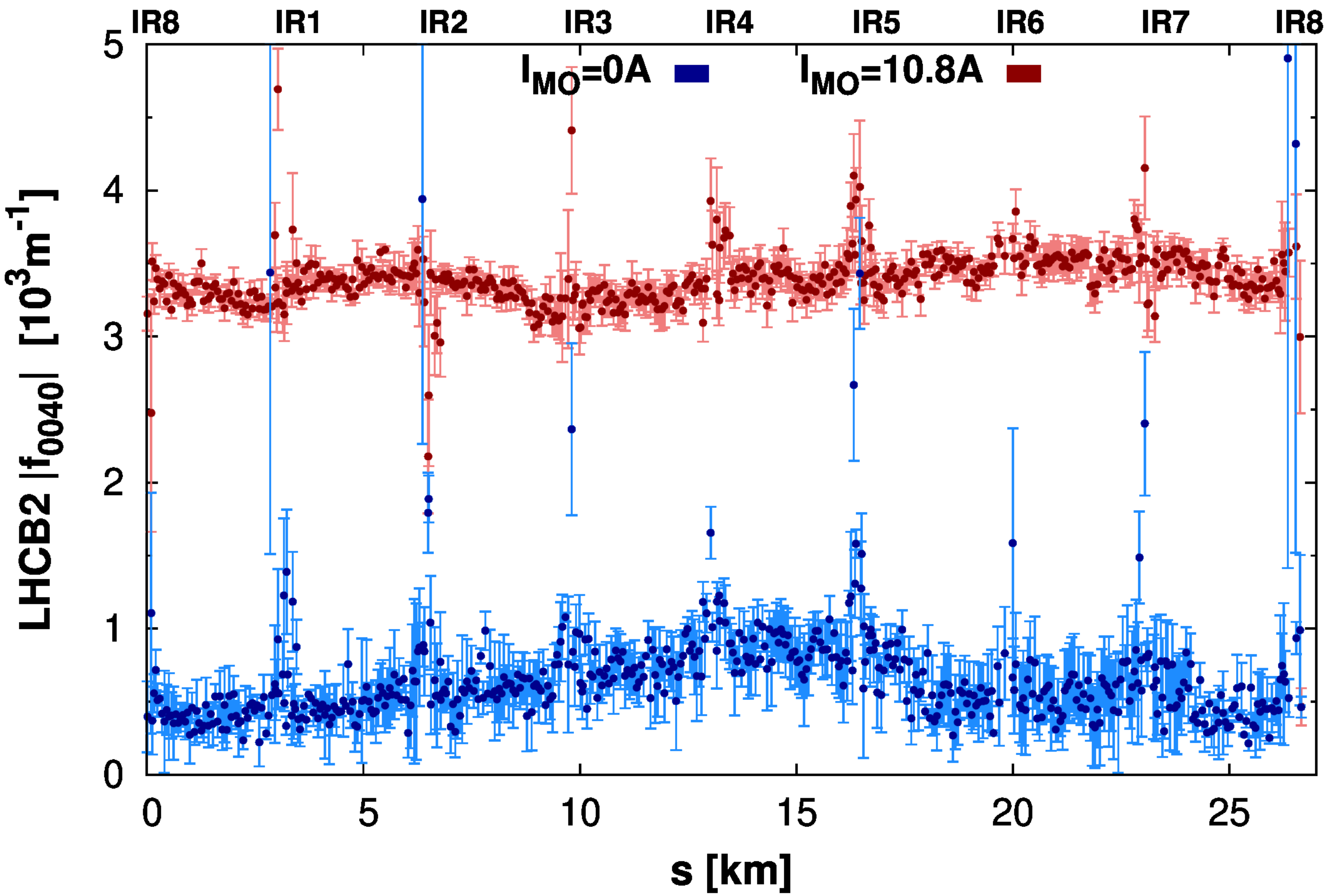
→ assume line-amplitude = 0 at zero action
→ assume only single leading order RDT under-consideration contributes to line amplitude
→ working with RDT of forced oscillation: measured values differ from that of a free-oscillation measurement

R. Tom´as PRAB 5 054001, Normal form of particle motion under the influence of an ac dipole

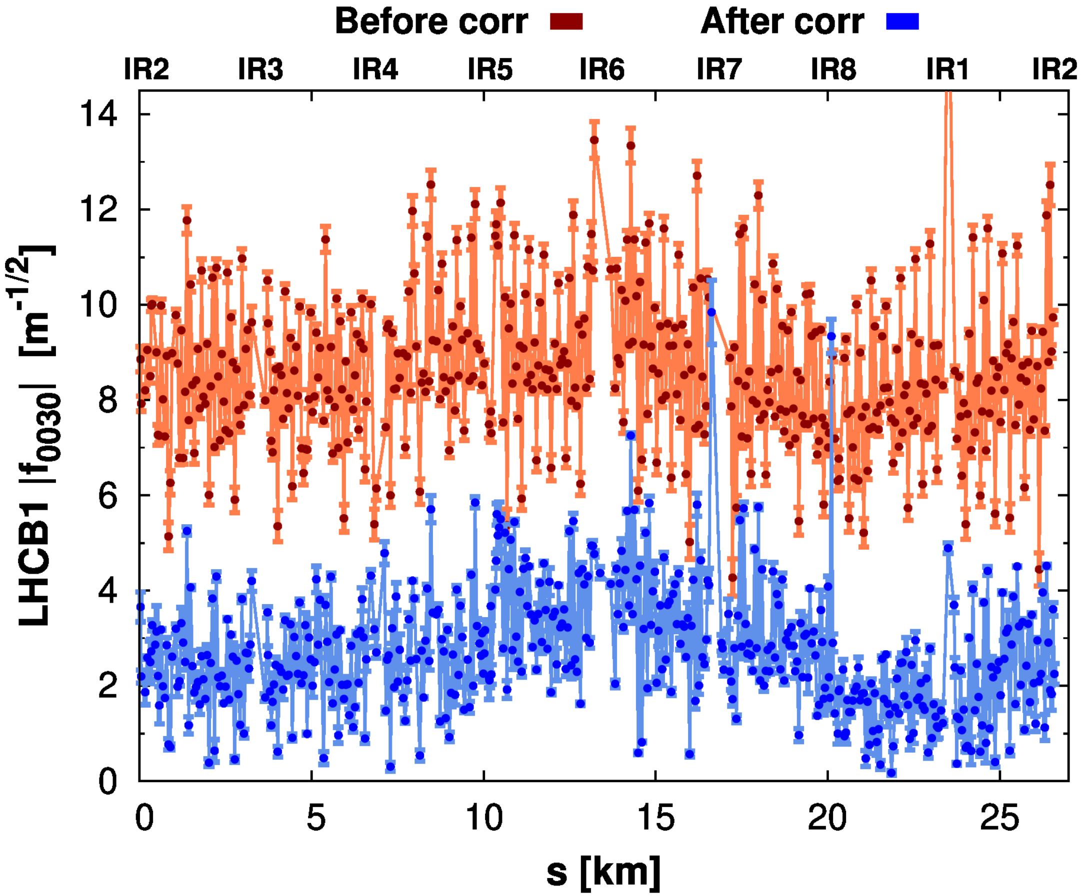
F. Carlier Ph.D. Thesis, CERN-THESIS-2020-025

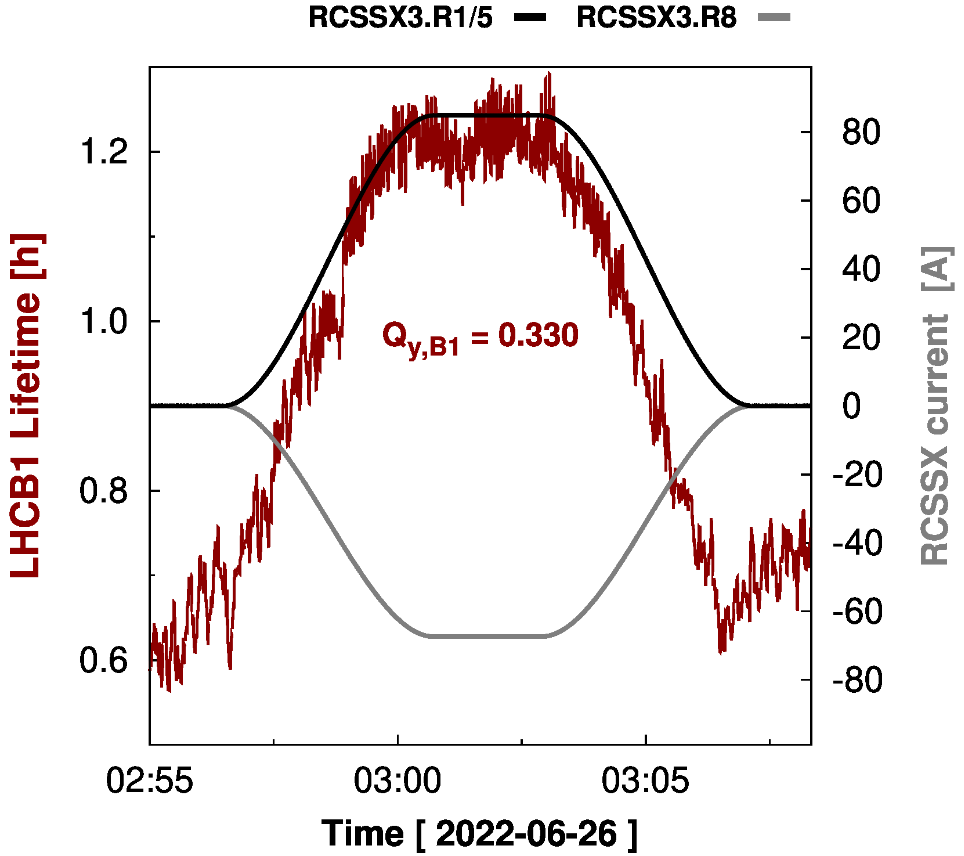
R. Tom´as et al PRAB 8,024001, Measurement of global and local resonance terms

Example of measurement of f'_{0040} (4Qy RDT) with weak and strong octupoles



Having measured the RDT we can calculate a correction using the model response of the corrector packages from simulation → e.g. via response matrix





Can we apply these tools to study/correct RDTs from beam-beam?

Very interesting question in general!

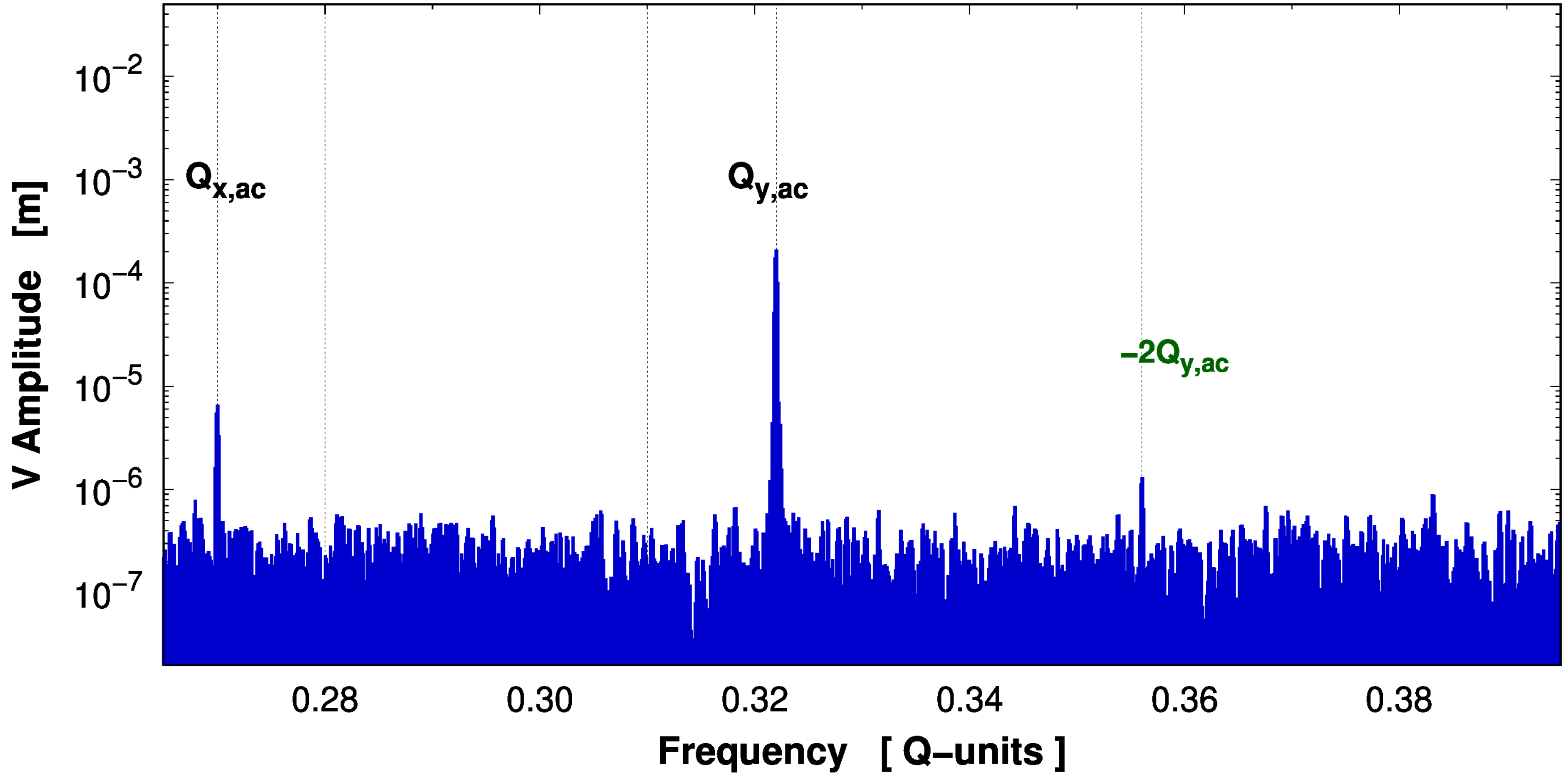
Extra motivation for this came from collimator hierarchy problem in LHC this year, which seemed to be linked to phase-space distortion from 3Qy

In collision LHC sees significant lifetime dependence on Qy → signature of 3Qy issues

→ Can we measure/correct the 3Qy RDT driven by long-range beam-beam?

Operational procedure for weak-strong measurements was developed by T. Persson and tested earlier this year → **presented in detail in the previous talk by Tobias**

- Exciting a weak-pilot bunch with the AC-dipole, while it experiences the full long-range interactions in the IPs (beams separated to avoid head-on)



Kick amplitude possible was extremely limited compared to usual optics measurements

3Qy resonance appears at $-2Q_y$ in the TbT spectrum

Dedicated kicks approaching closer to 3Qy resonance allowed for cleaner RDT measurement

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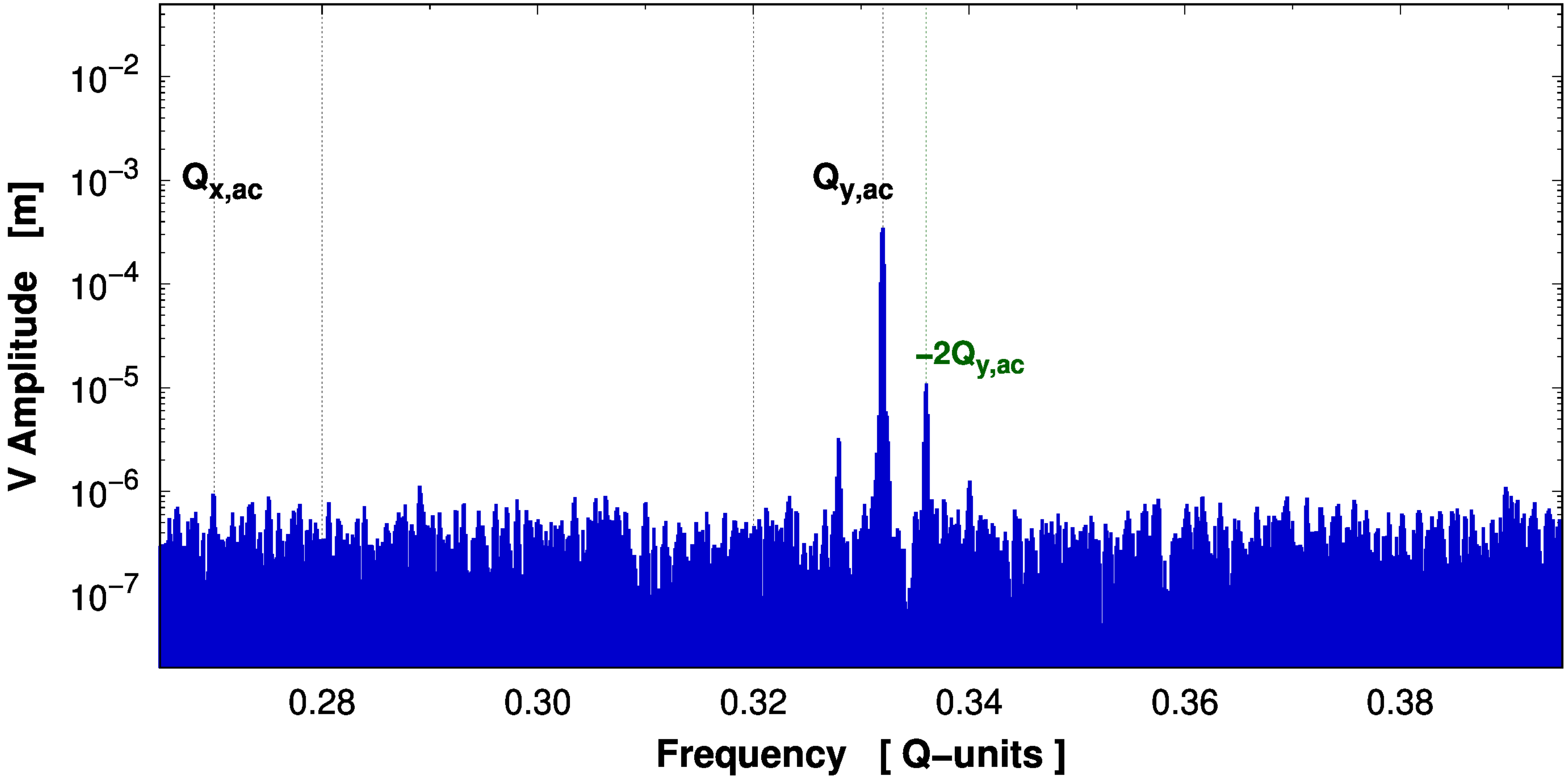

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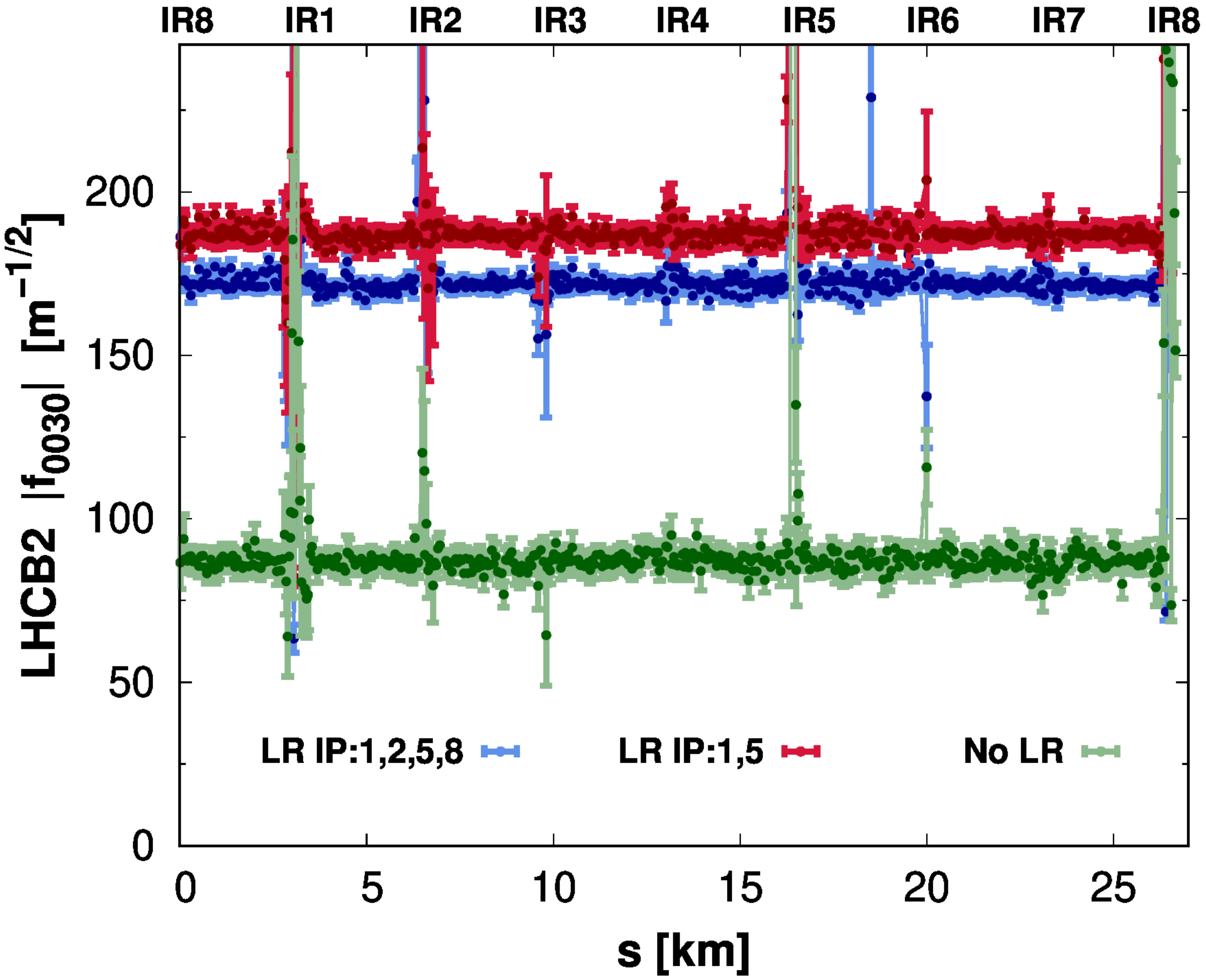


f'_{0030} simultaneously measured for bunches with no-LR, full-LR in ALTAS/CMS, and full-LR in all IPs

Contribution coming from lattice:

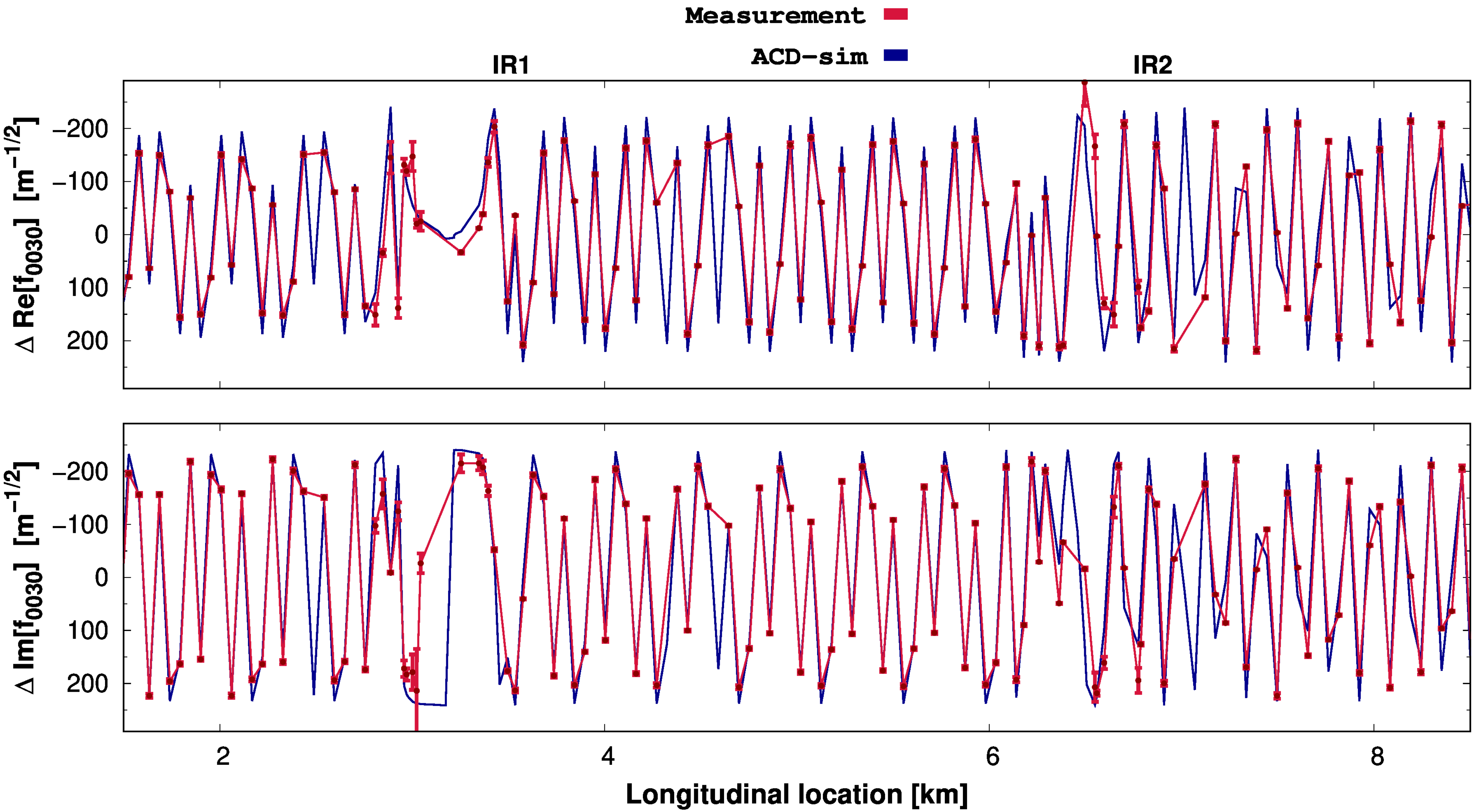
- skew-sextupole errors and skew-octupole feed-down
- Normally corrected during commissioning

Contribution coming from LR-beam beam:

- Only small contribution from IP2/8

Measurements of 4Qx RDT were also performed

Measured shifts to real and imaginary parts of f'_{0030} between bunch with and without the LR-BB have been benchmarked against Mad-X & Xsuite tracking (single-particle simulations with head-on kicks turned off)



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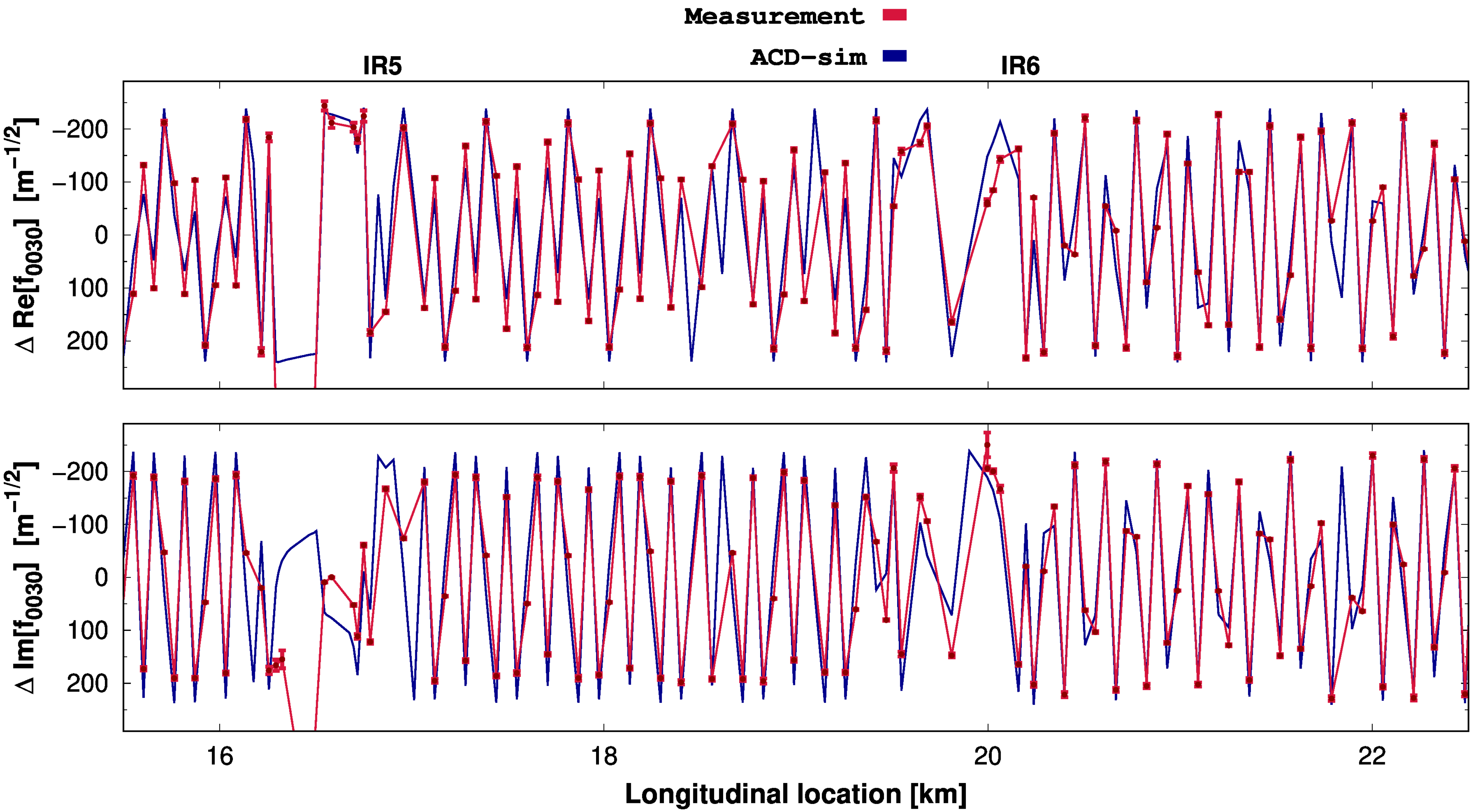

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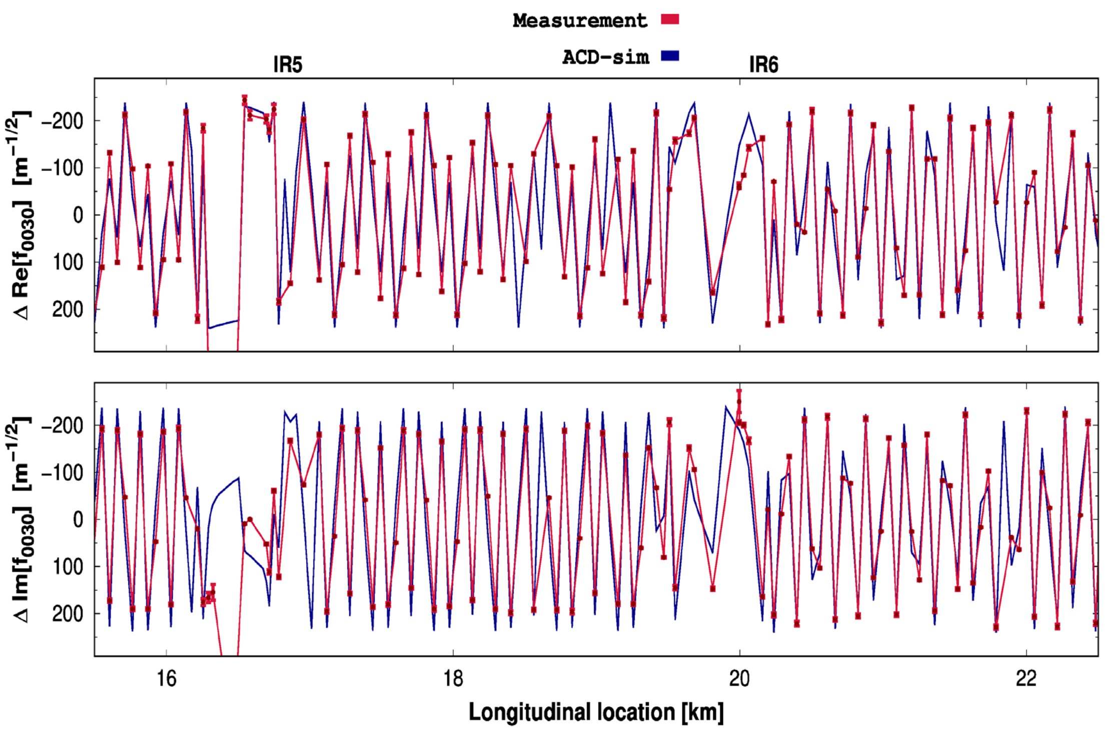
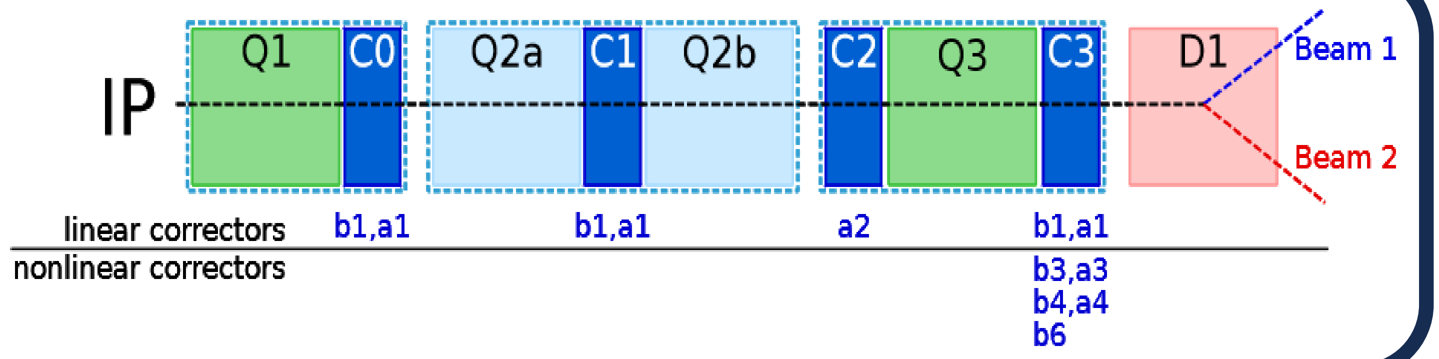
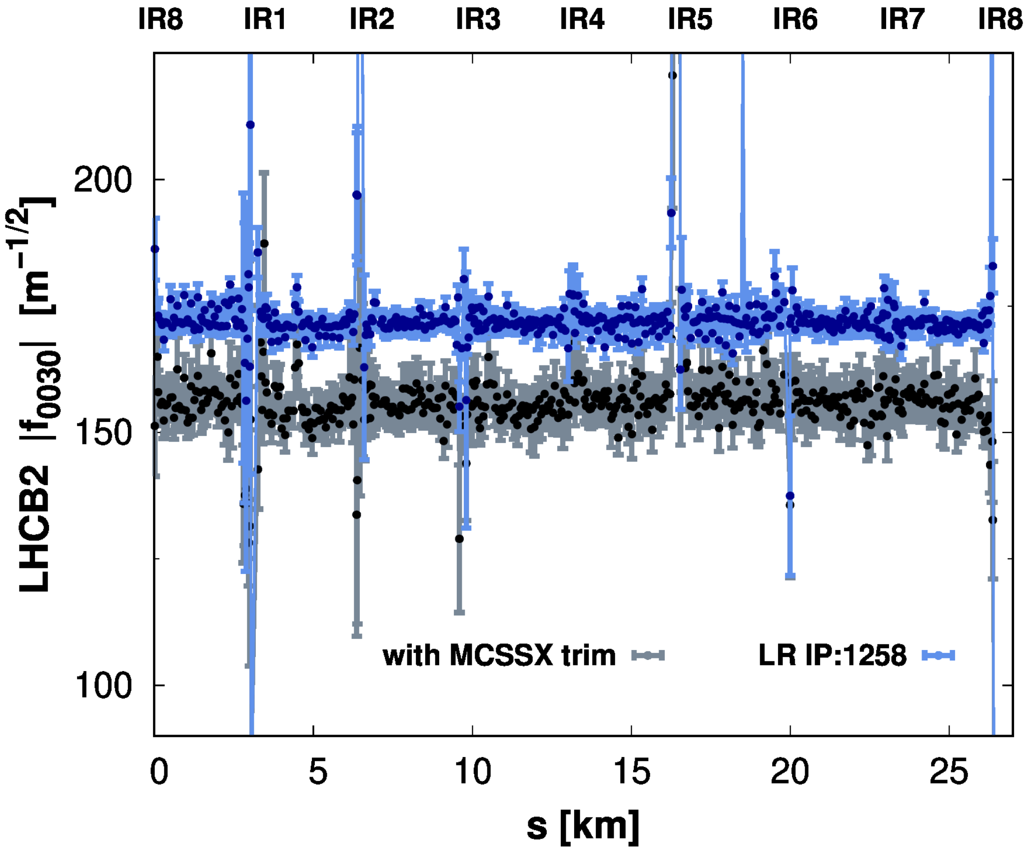


- **Good agreement between predicted and measured shifts in the RDT**
- **Similar level of agreement observed all around the ring**
- **Both amplitude and phase of the RDT are consistent between model and measurement**
- **Necessary to including the AC-dipole in simulation when comparing to measurement**
  (free and forced RDT showed differences)

LHC is equipped with nonlinear-corrector package in common-region of IRs

→ Intended for local correction of triplet errors





MCSSX trim

During the weak-strong MD tried applying correction for part of lattice 3Qy

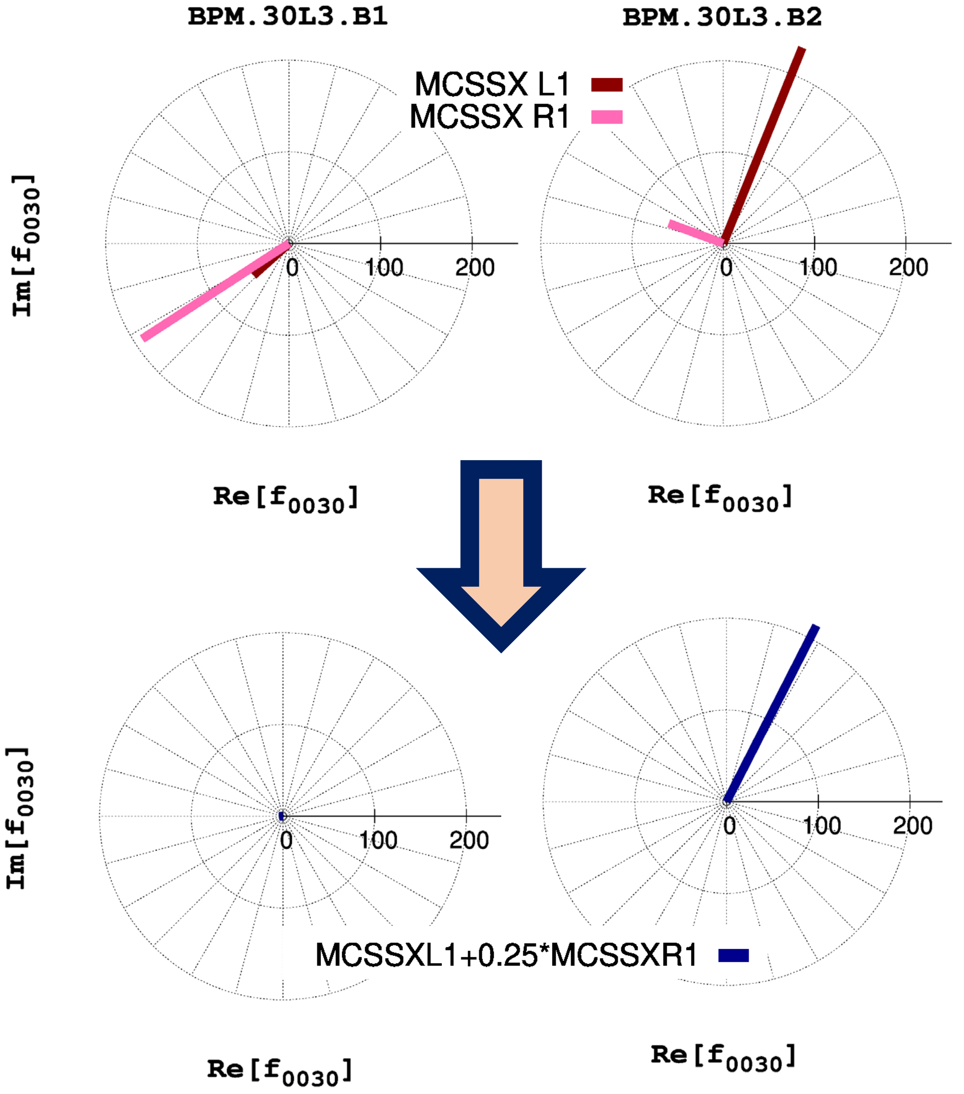
- Trim of a_3 (skew-sextupole) corrector magnet (**MCSSX**)
- Shift to RDT of bunches with LR-BB could be measured
- Shift to RDT from MCSSX trim agreed well with expected response

Since both BB-LR contribution and response of correctors agree with model, can use simulation to try and find viable correction for the long-range contribution to 3Qy using the MCSSX correctors

- **Want to independently control LHCB1 and LHCB2**
  → separate knobs allow to adjust for different intensities
  → challenging as only skew-sextupoles are in common region
- **Want to compensate with different β^***
- **Don't want to spoil linear optics**

For initial studies taken similar approach to successful 3Qy correction at injection

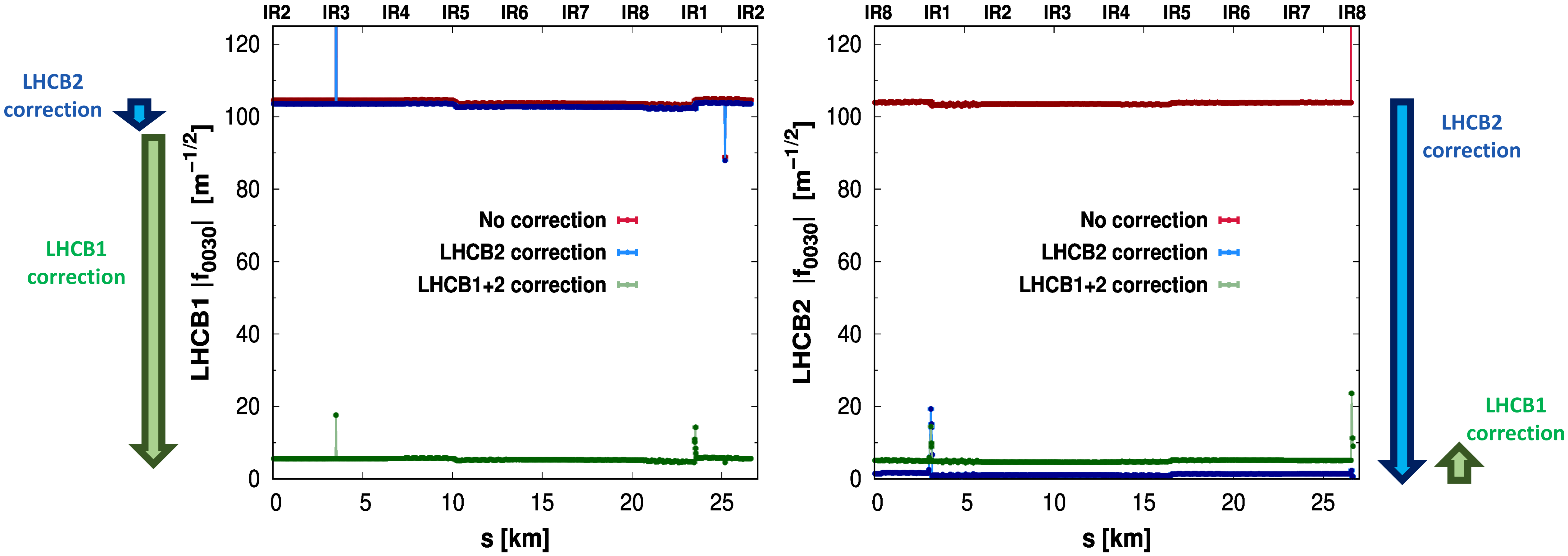
- **Define knobs for LHCB1/2 which self-cancel for other beam**
- **Find knob setting which globally minimizes RDT amplitude**



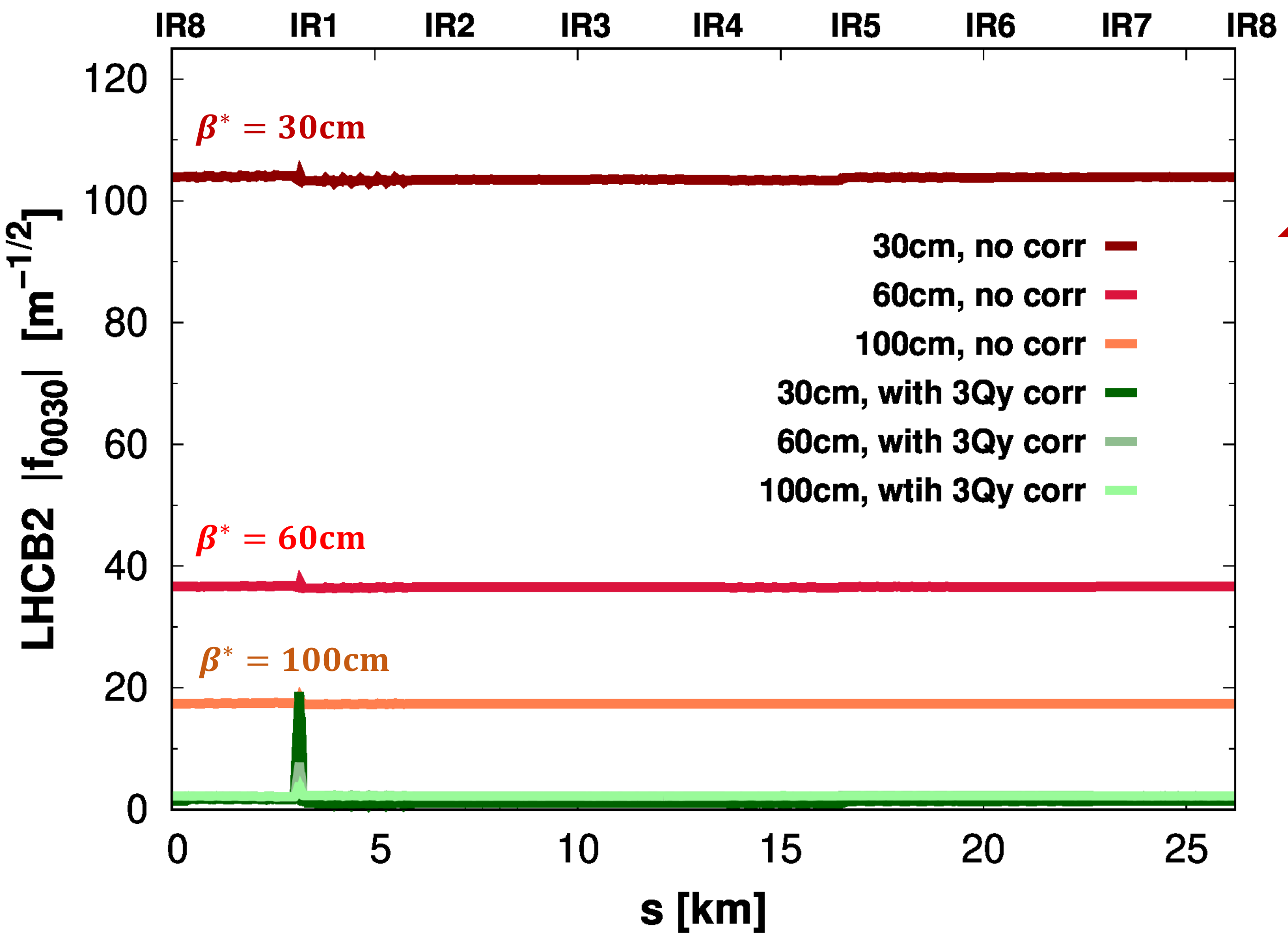
Using MAD-NG find knobs of the common MCSSX to independently control 3Qy of LHCB1 and LHCB2

→ can compensate the long-range contribution to 3Qy in X-suite using ≤ 45% of maximum MCSSX strength

LHCB1 | **LHCB2**

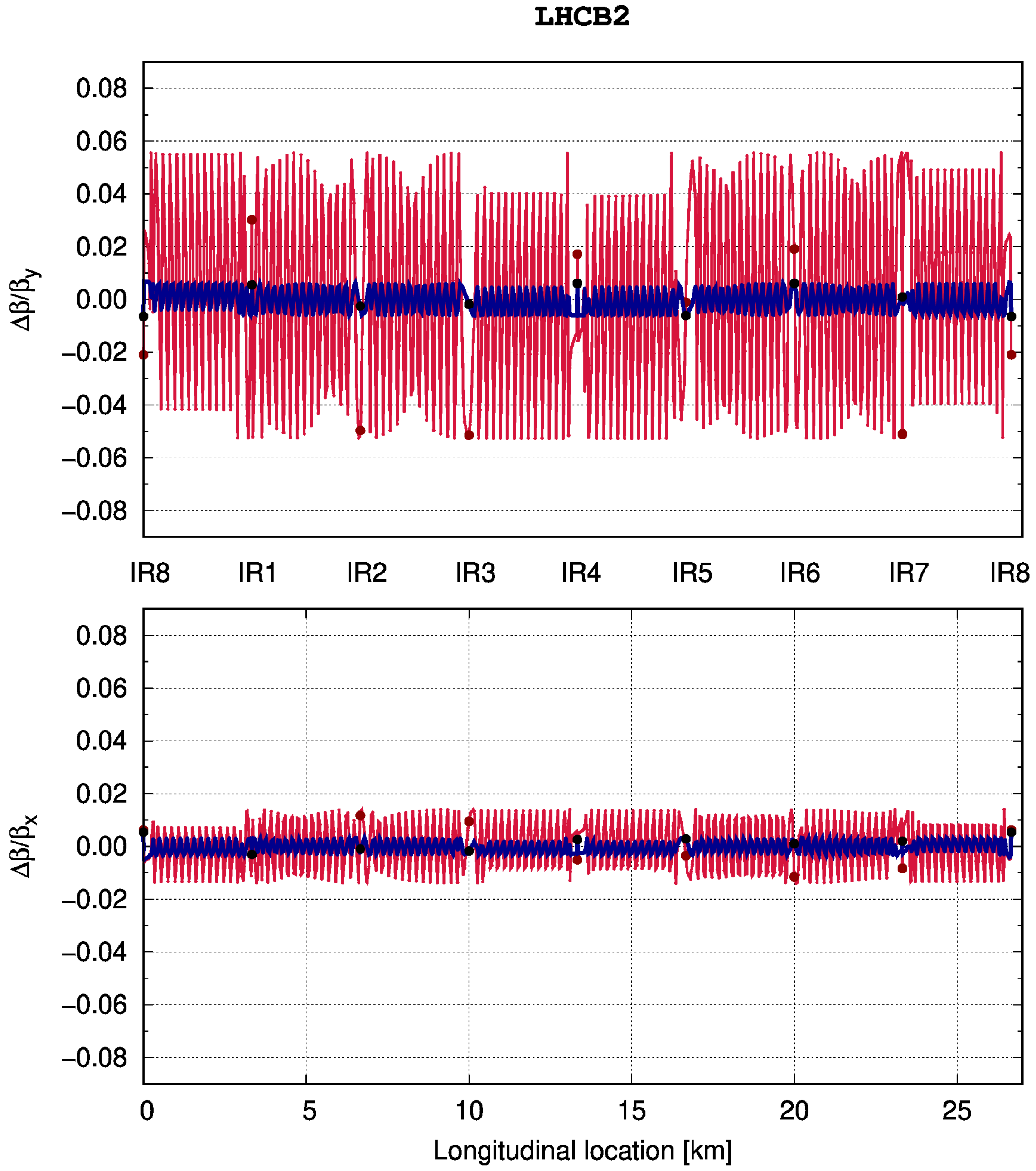


Static setting of the MCSSX knobs work well over large β^* range (adjustment for crossing-angle changes may be needed)



Without MCSSX correction, 3Qy strength from LR-BB increases substantially through squeeze
(simulation assumes constant beam-parameters)

Static MCSSX strength keeps 3Qy corrected through squeeze



Feed-down from MCSSX corrections for LR-BB RDT are expected to generate up to 6% β-beat at $\beta^* = 30\text{cm}$

- **Can be corrected independently for LHCB1/2 using the Q5-7 quads either side of the IP**

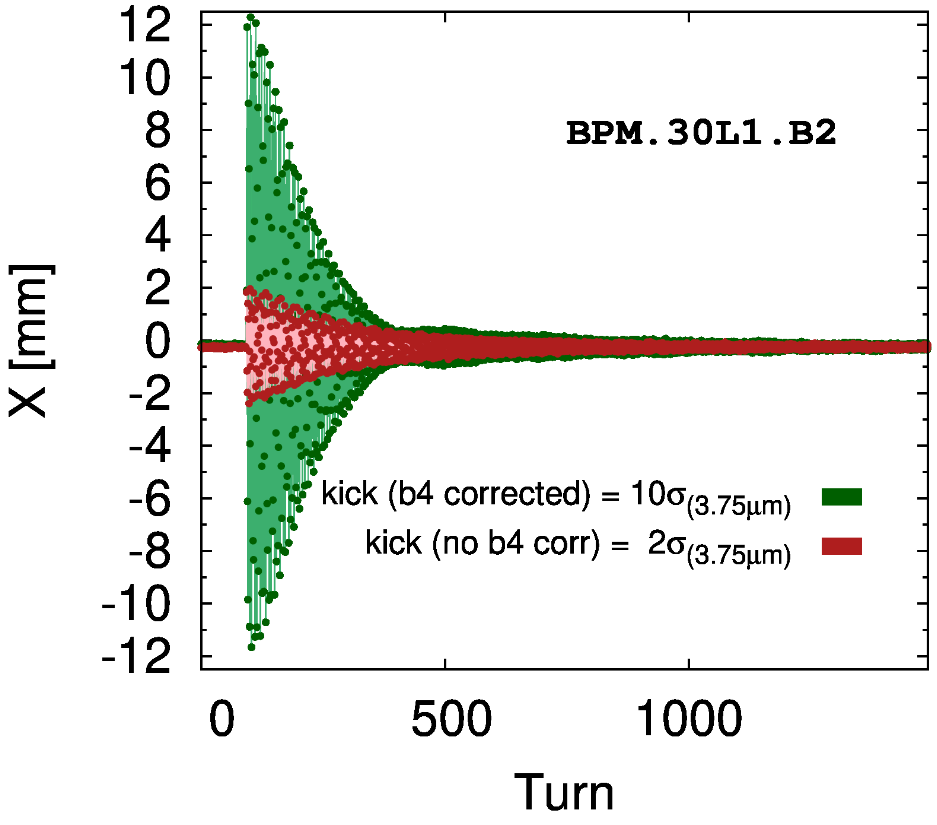
Conclusions:

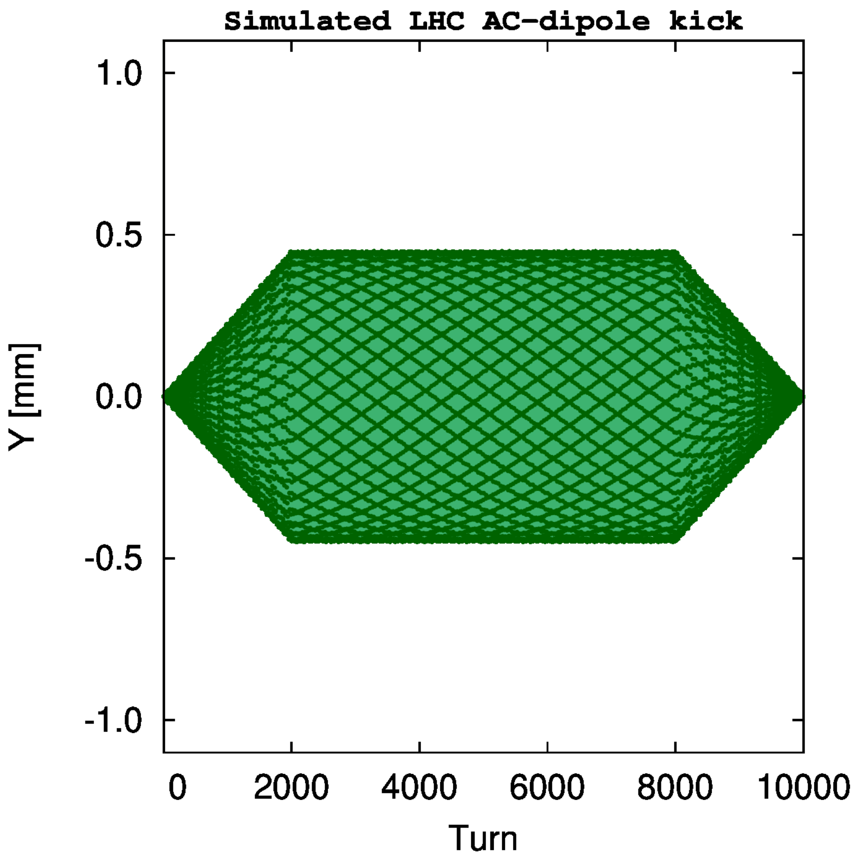
- Resonance Driving Terms now well established in LHC as method to study and correct nonlinear optics
- Measurement of shifts to the 3Qy RDT from LR-BB have been performed for the first time with new OP-procedure (see previous talk)
- LR contribution to 3Qy matches well with model predictions, as do corrector responses
- Corrections for the long-range contribution have been found in simulation
  → independent LHCB1 / LHCB2 corrections with IR-skew-sextupole correctors
  → applicable over large β^* range
  → feed-down appears correctable
- Plan to test in the real machine!

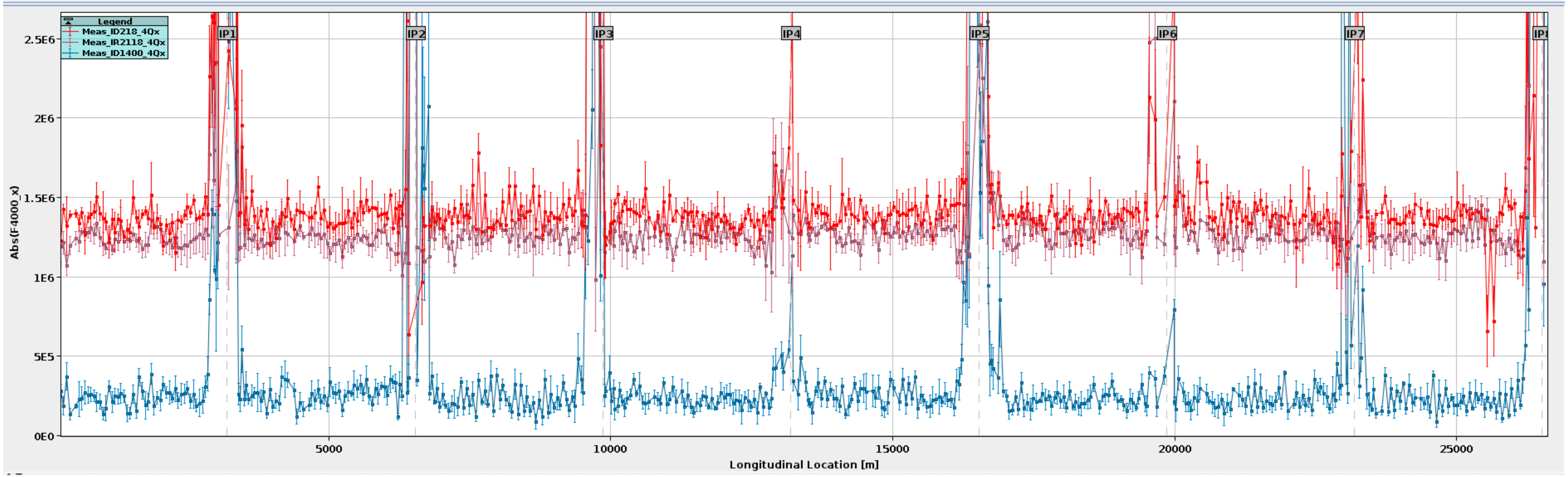
Reserve

LHC has dedicated kicker magnets for Optics studies and commissioning: can operate as kicker or AC-dipole

- Almost all optics studies today performed with AC-dipole
- Ramps adiabatically allowing repeated kicks of same beam + slow ramp satisfies machine protection
- Forced oscillation doesn't decohere (6600 turn analysis flattop)

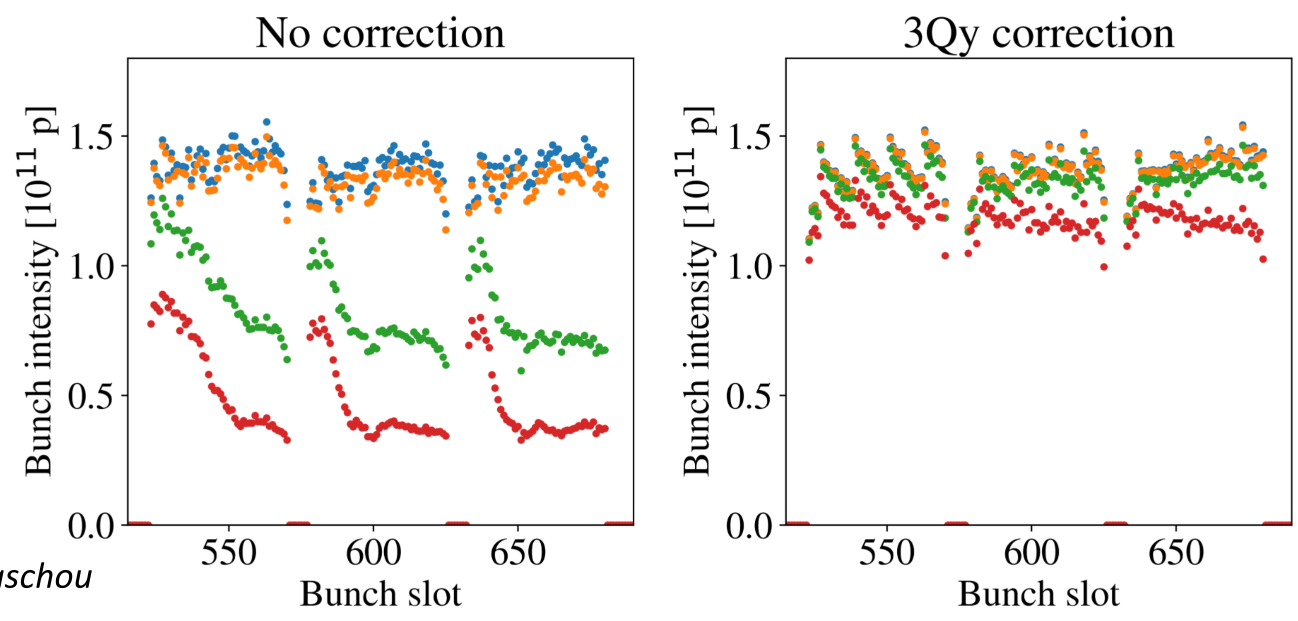




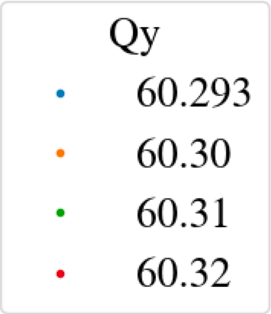


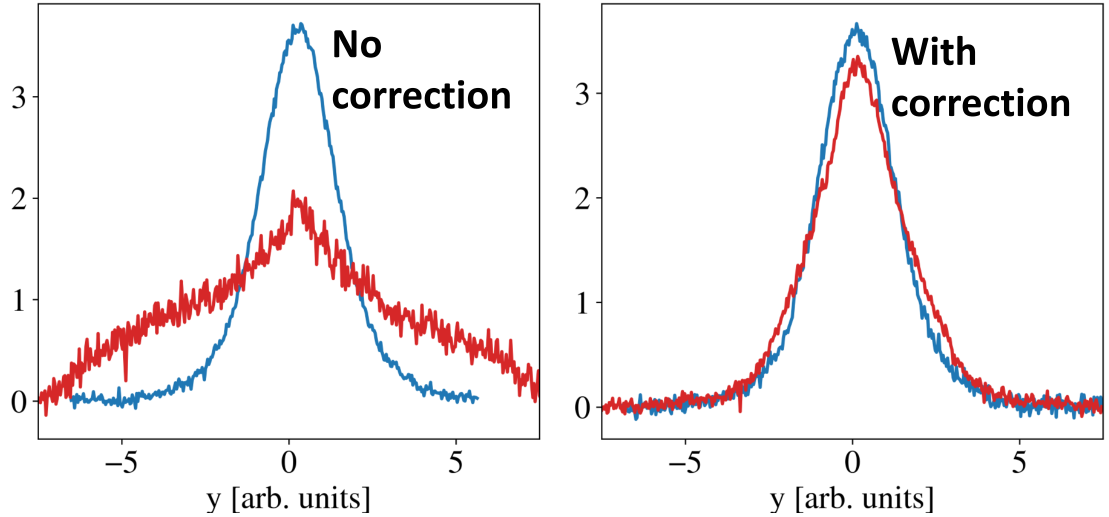
Legend
Meas_ID218_4Qx
Meas_IR2118_4Qx
Meas_ID1400_4Qx
IP1
IP2
IP3
IP4
IP5
IP6
IP7
2.5E6
2E6
1.5E6
1E6
5E5
0E0
Abs(F4000_x)
5000
10000
15000
20000
25000
Longitudinal Location [m]

LHC injection – 3Qy RDT correction impact



K.Paraschou





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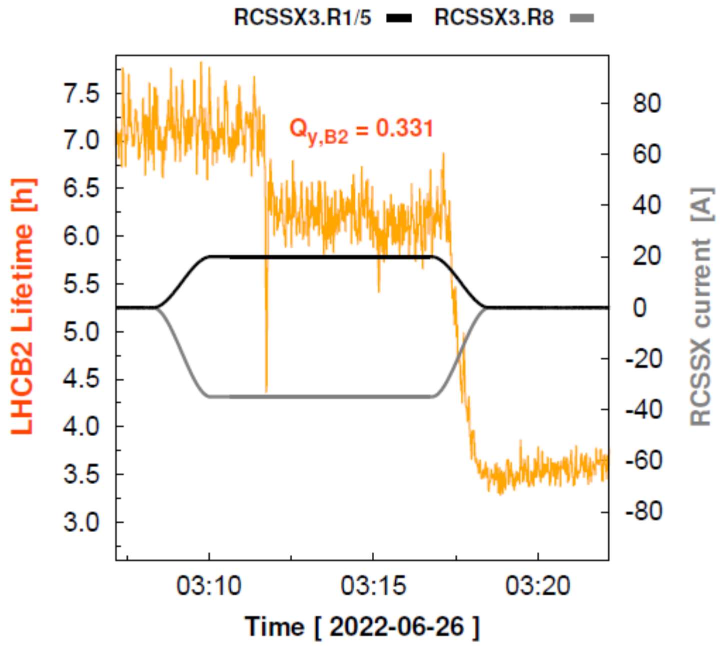
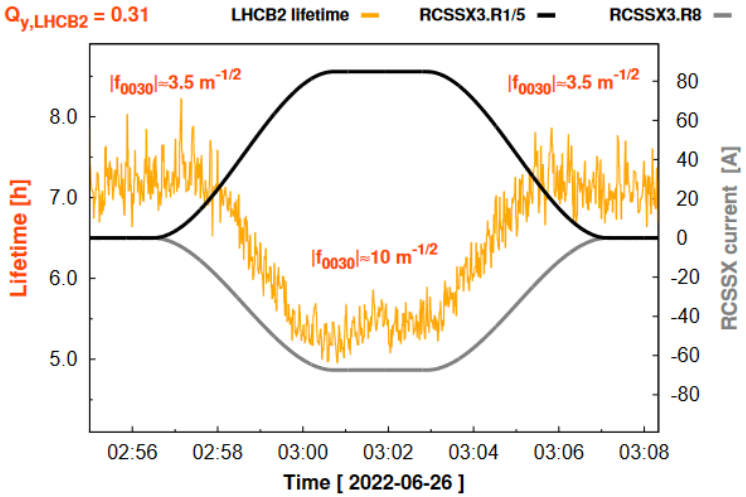
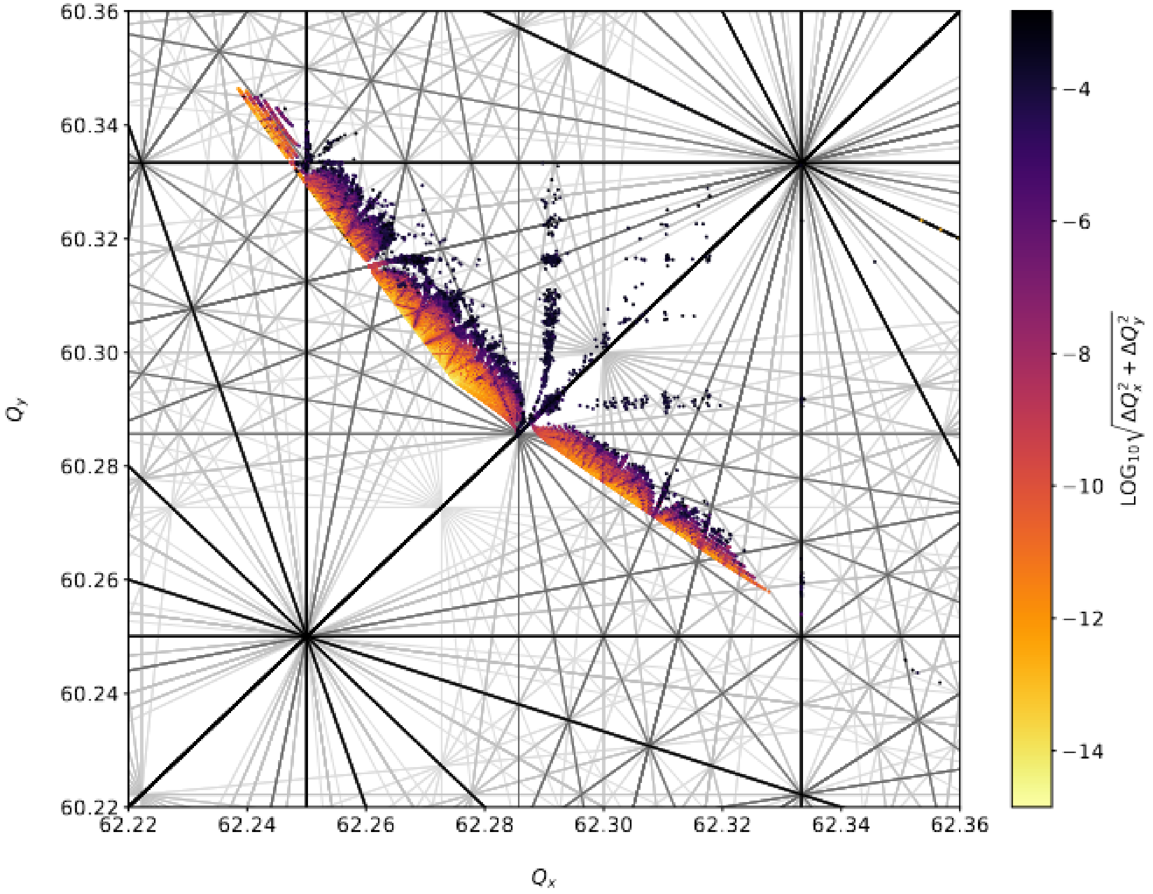
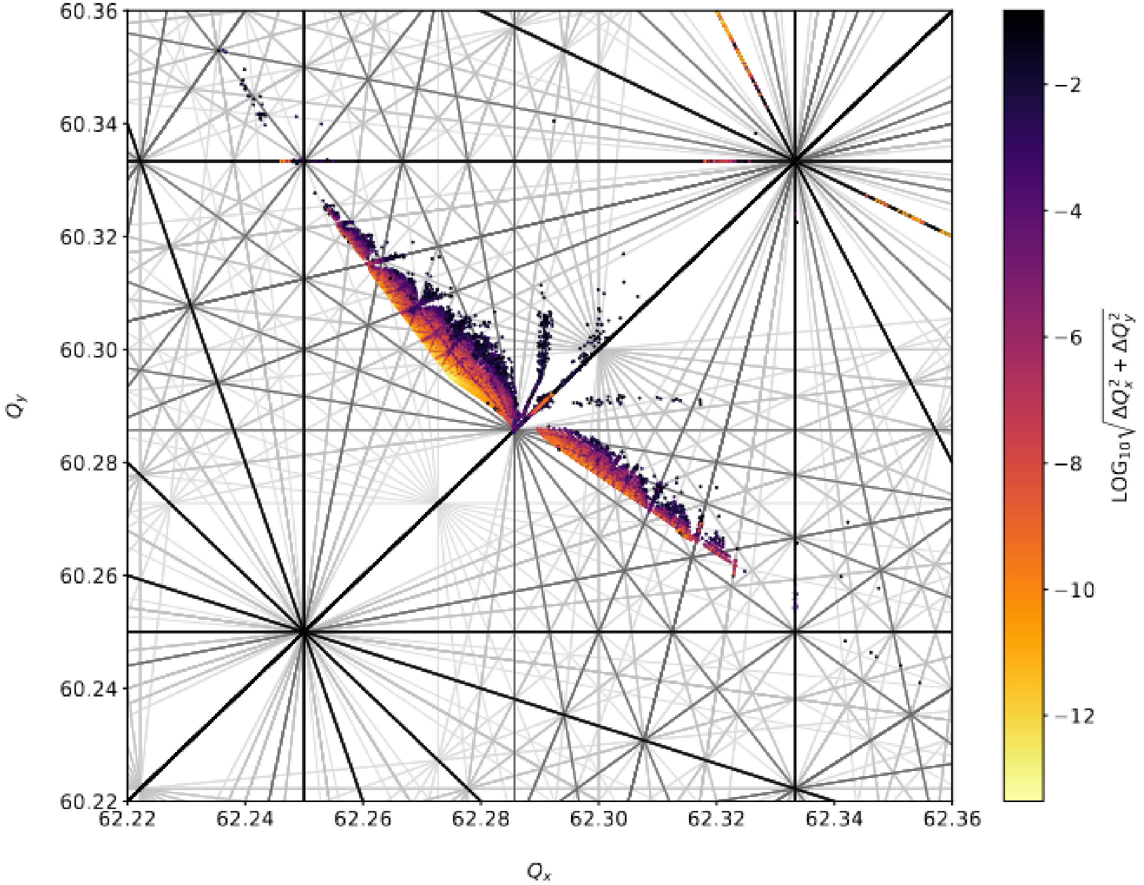




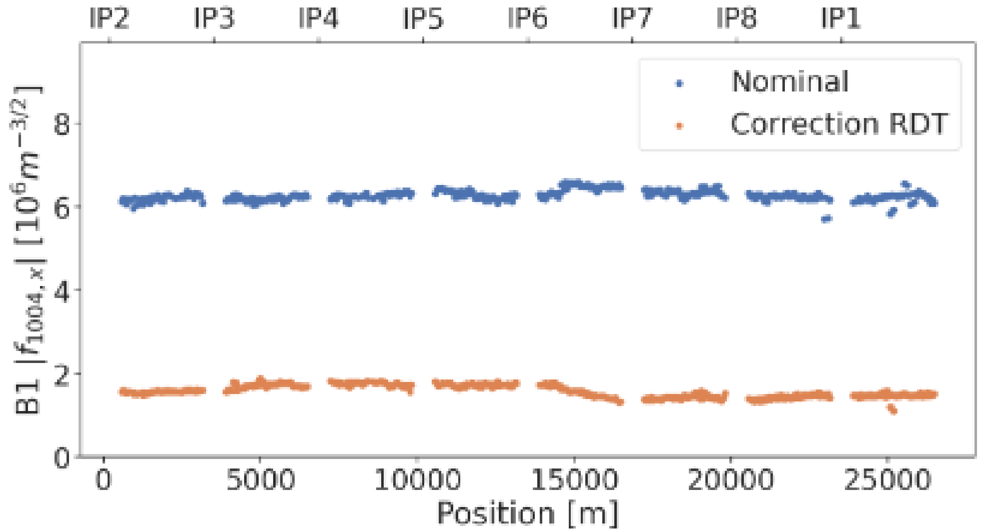
No errors

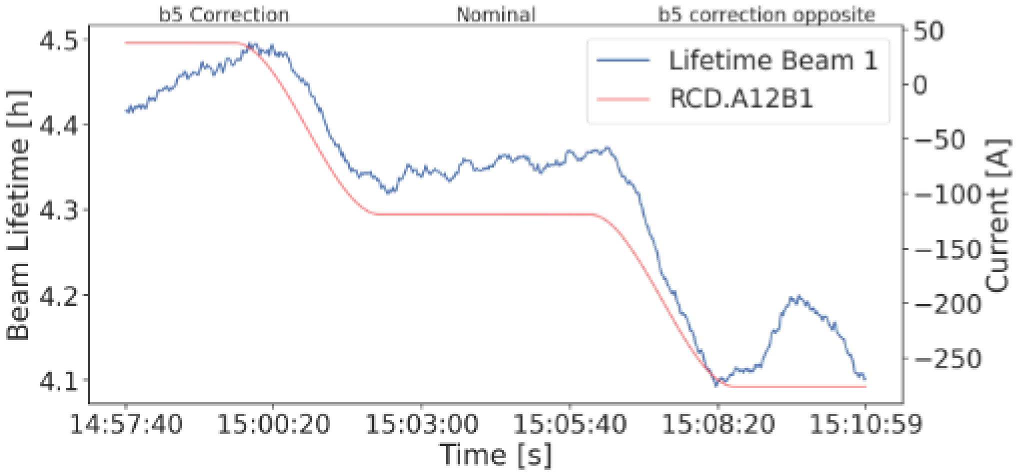


Effective 3QY

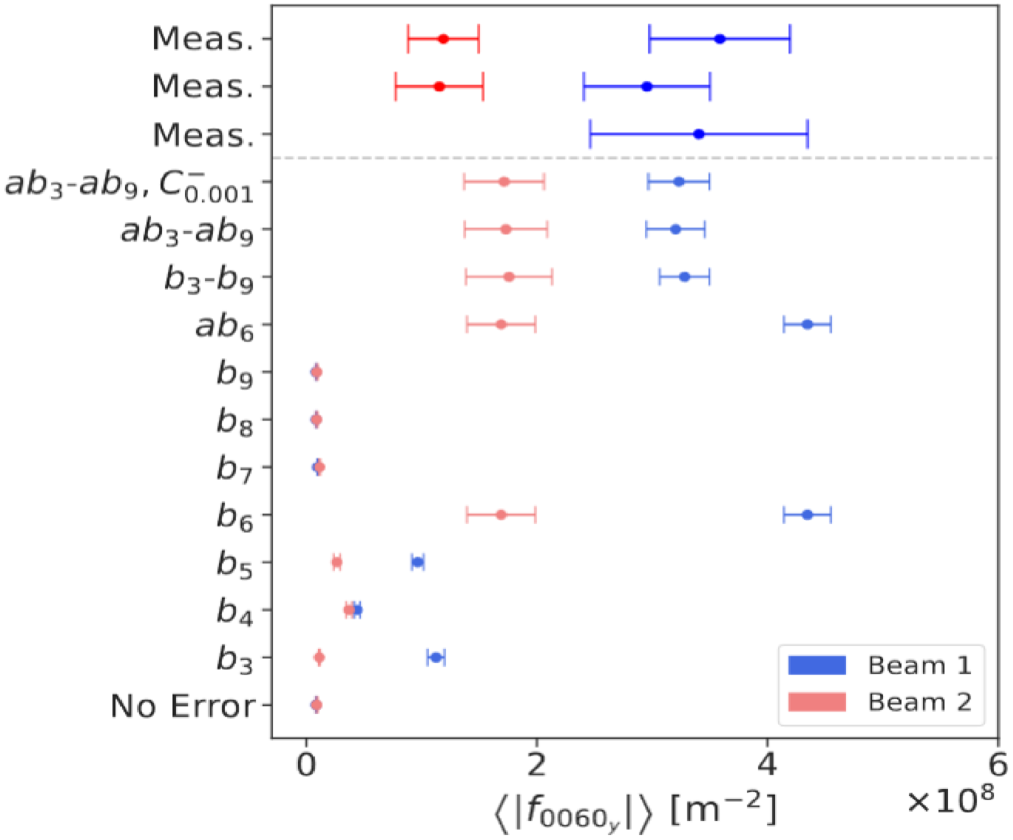


Decapole RDT correction at LHC injection



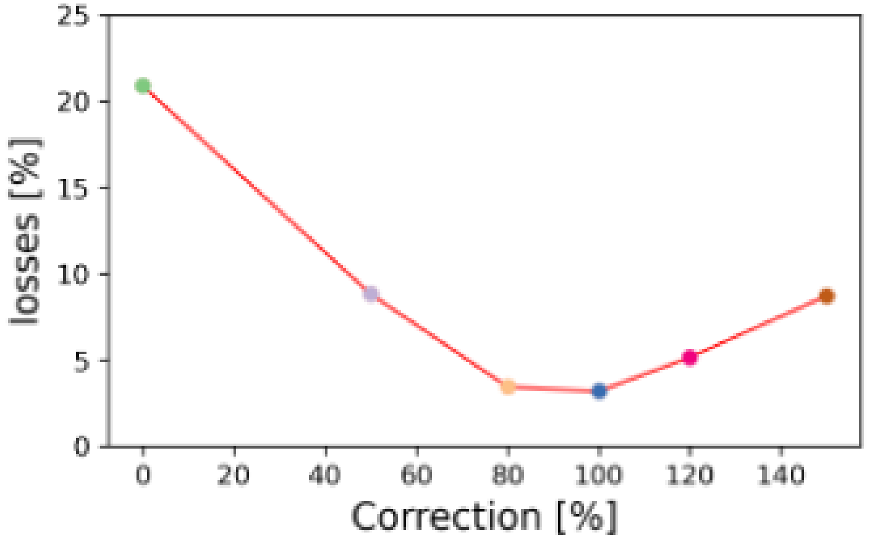


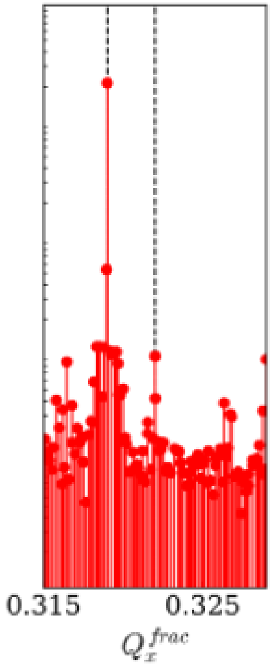
LHC injection – 6Qy RDT (dodecapole) benchmarking

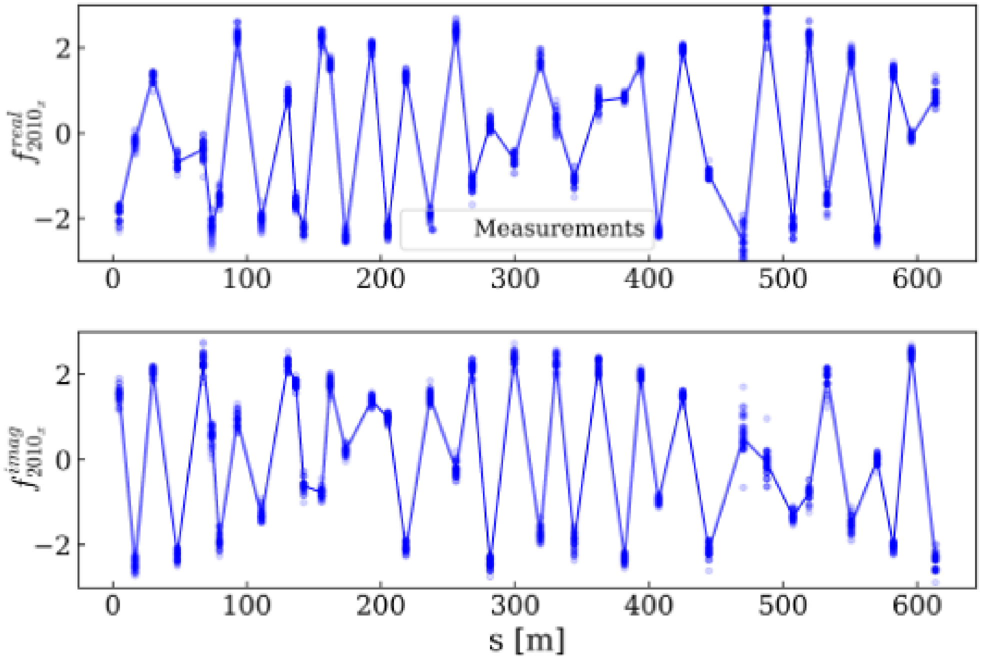


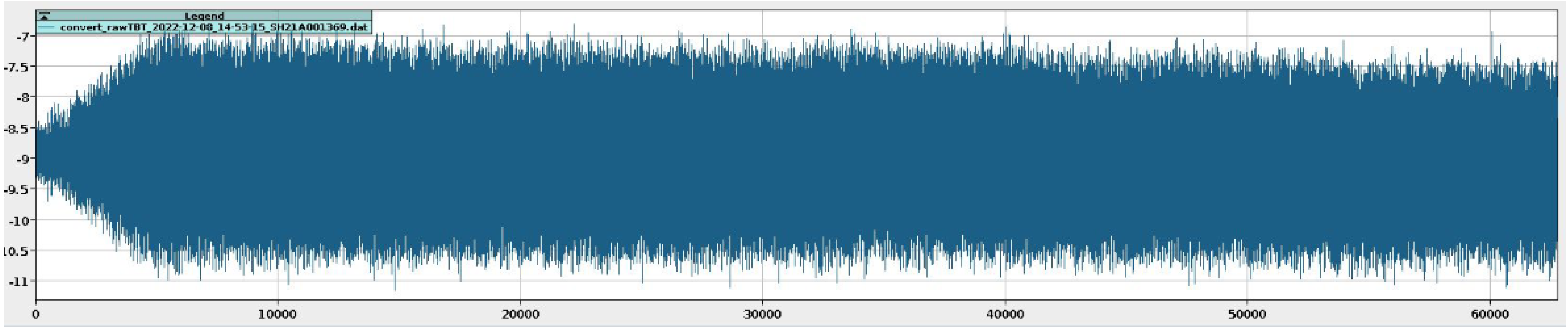
PS RDT studies with ADT-ACD

$2Q_x + 1Q_y$ H(-1,-1) (f_{2010})









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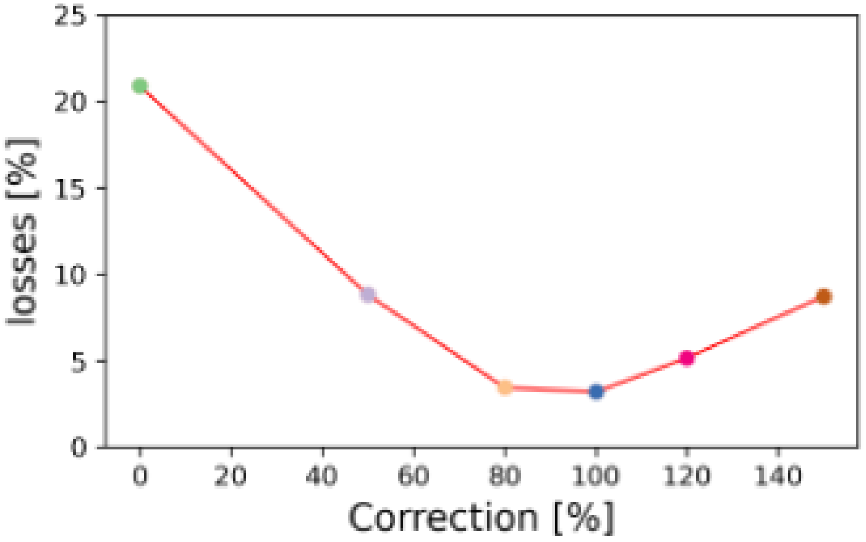

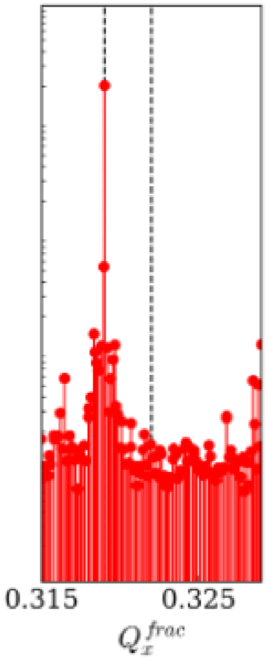

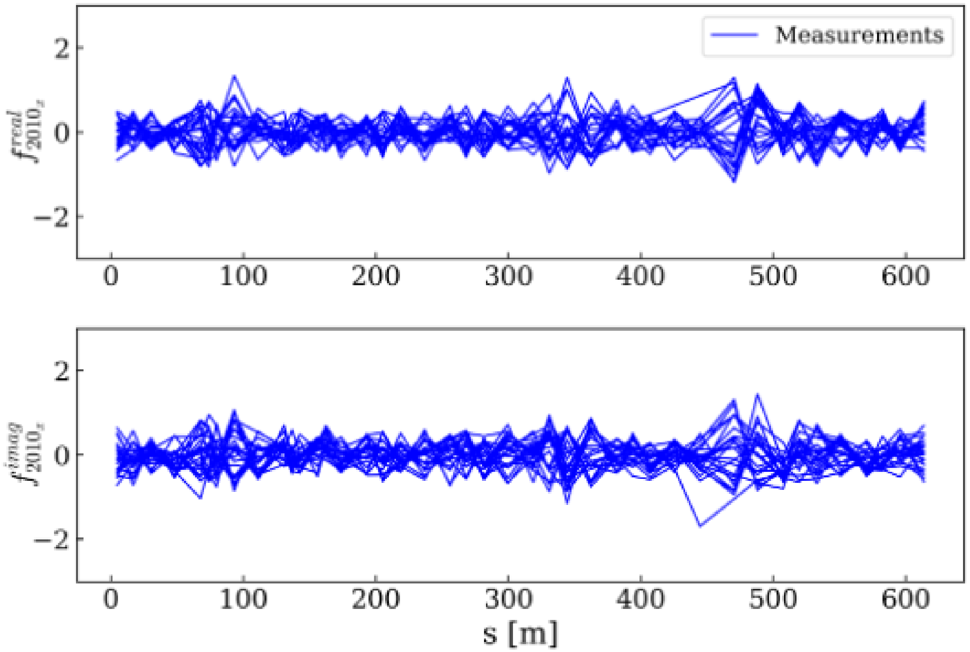

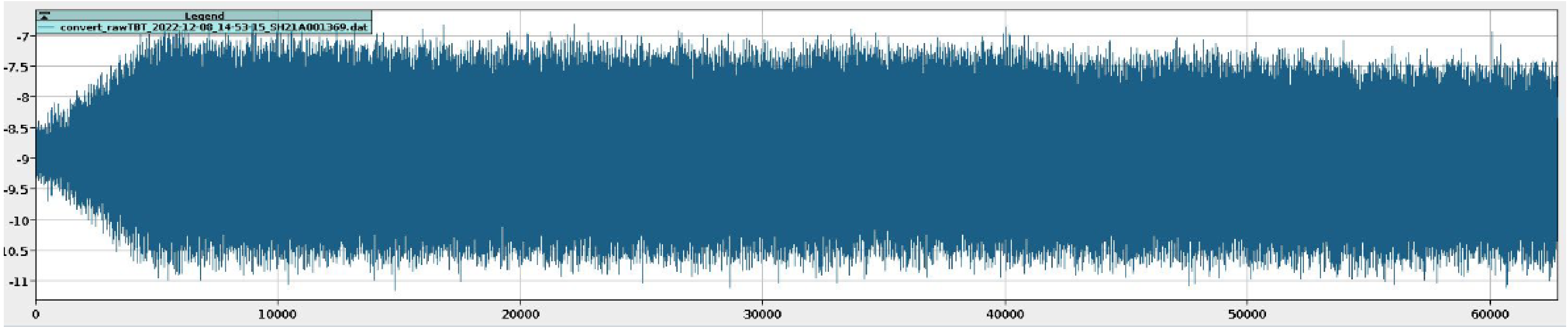

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