Instrumentation & optics measurements at LHC - what is used and what has been achieved

F. Carlier, J. Coello, A. Garcia-Tabares, M. Hofer, A. Langner, E. Maclean, L. Malina, T. Persson, P. Skowronski, R. Tomás and A. Wegscheider.

May 13, 2018

BPM signal & Optics parameters

Turn-by-Turn BPM signal in the i^{th} BPM:

$$x_i(n) = C_i\sqrt{2\beta_i J}\cos(2\pi nQ + \phi_i) + \overline{x}_i + \sigma_{noise}$$

Uncertainties on Q and ϕ_i when using FTs on $x_i(n)$:

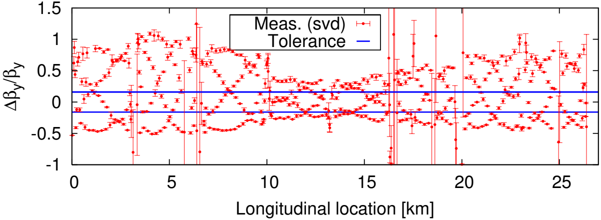
$$\sigma_Q = \frac{\sigma_{noise}}{AN^{\alpha}}$$
$$\sigma_\phi = \frac{\sigma_{noise}}{A\sqrt{N}}$$

where $A = C_i\sqrt{2\beta_i J}$ is affected by the BPM calibration error C_i.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 081002 (2009)

First β-beating measurement and optics analysis for the CERN Large Hadron Collider

M. Aiba, S. Fartoukh, A. Franchi, M. Giovannozzi, V. Kain, M. Lamont, R. Tomás,* G. Vanbavinckhove, J. Wenninger, and F. Zimmermann

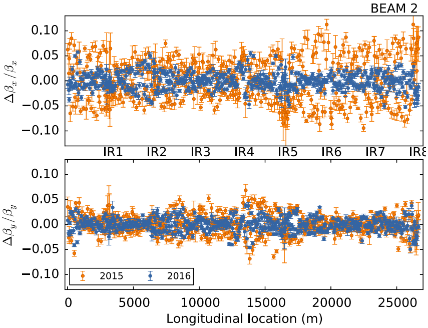


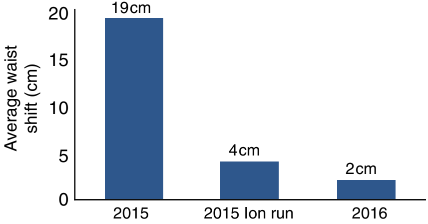
- LHC BPMs worked perfectly in the 1st injections into the LHC!
  - Design performance: σ_{noise}=100μm at 10^{10}ppb in TbT mode
  - 2000 BPM channels working with less than 5% failure
- β-beating of 100%!
- Main quadrupole error identified

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 061002 (2017)

LHC optics commissioning: A journey towards 1% optics control

T. Persson,* F. Carlier, J. Coello de Portugal, A. Garcia-Tabares Valdivieso, A. Langner, E. H. Maclean, L. Malina, P. Skowronski, B. Salvant, and R. Tomás



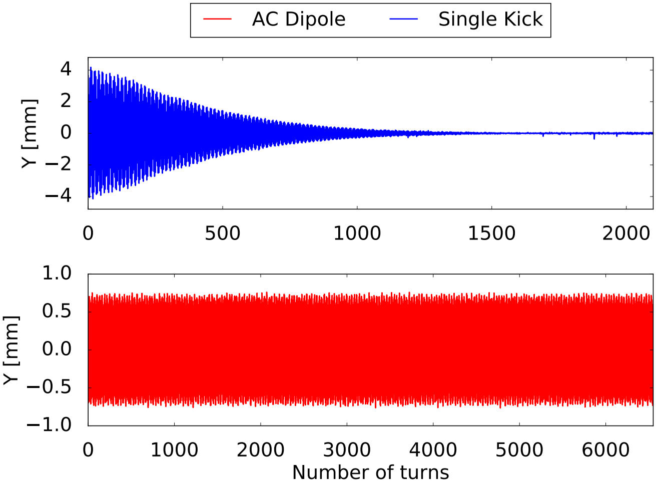


- ★ $\beta^* = 0.4$ m, design was 0.55 m
- ★ rms β-beating below 1.8%
- ★ rms β^*-beating below 1%

Main ingredients:

- ★ AC dipole for TbT
- ★ β from phase (BPM calibration poor)
- ★ K-modulation for β^* & IR4

AC dipole Vs Single kick



$$Q^{AC}_{x,y} = Q_{x,y} \pm 0.012$$

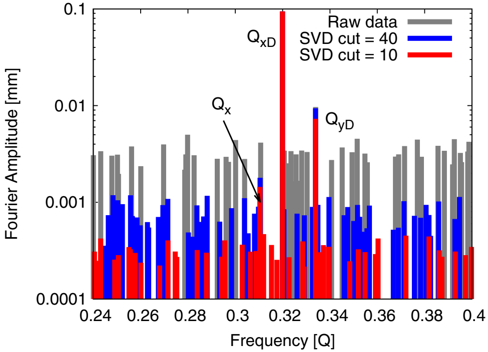
AC dipole gives more turns for analysis and it is non-destructive.
Limitations: Maximum 6600 turns & 1 min. wait for cool-down.

Singular Value Decomposition cleaning

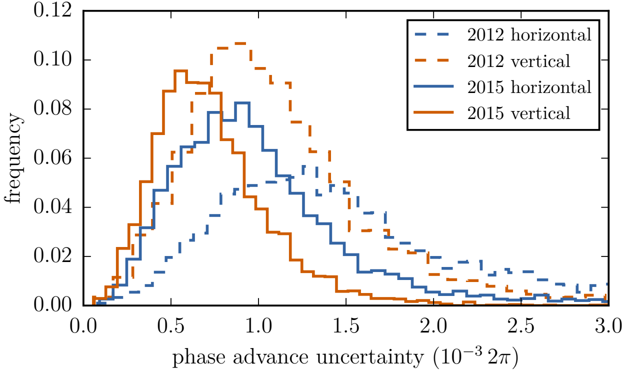
Removing uncorrelated noise from the 1000 BPMs/beam with SVD improves Q and phase measurement uncertainties:

$$BPM_{matrix} = \sum_i u_i \sigma_i v_i^T$$

Clean: Keep $i \leq$ cut

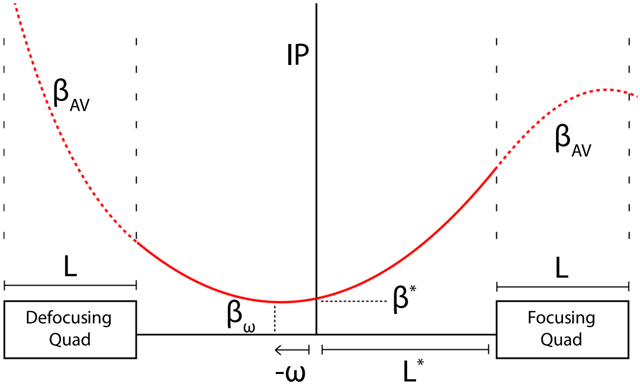


Phase measurement uncertainty



Phase uncertainty of about 2π mrad tipically achieved.

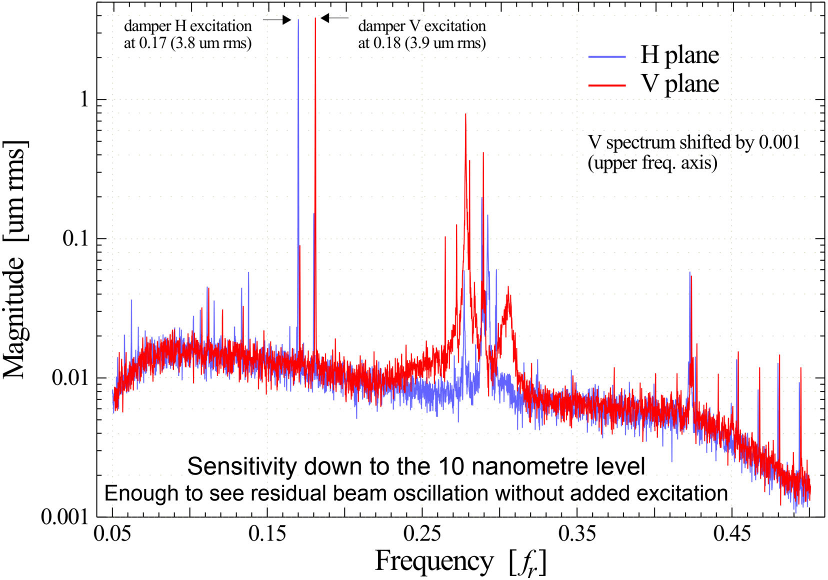
K-modulation



$\beta_{AV} \approx \pm 4\pi \dfrac{\Delta Q}{\Delta K_{quad}}$, β^* and waist ω are interpolated.

Having accurate tune measurements is fundamental.

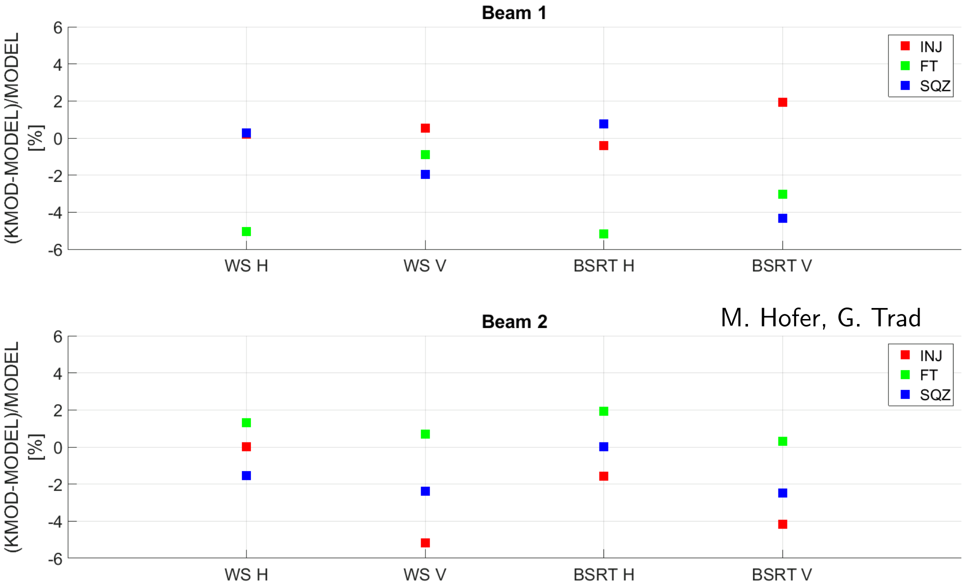
LHC Tune System Performance



Sensitivity down to the 10 nanometre level

Enough to see residual beam oscillation without added excitation

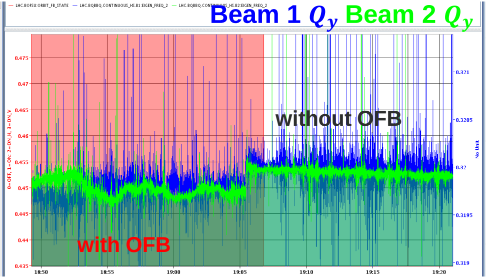
K-modulation to measure β @ instruments

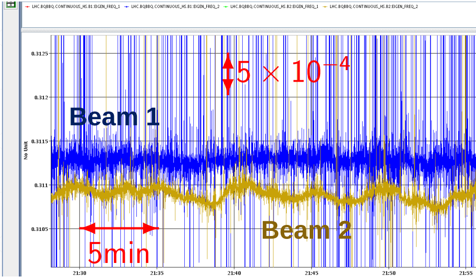


Issues with β^* from K-modulation this year

β^* measurements less reproducible than before. Possible reasons:

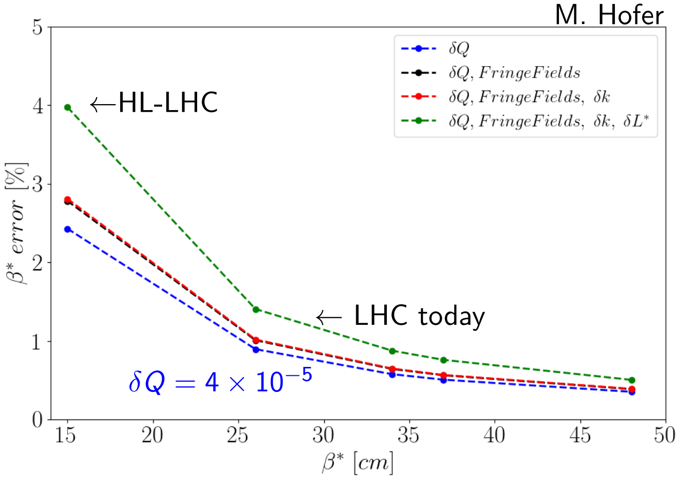
- ★ Change in amplitude detuning (non-linearities)
- ★ Poorer tune stability. Related to Orbit Feedback?





Further investigations needed in 2018.
→Search for alternative β^* measurement techniques is required.

β^* from K-modulation: challenge in HL-LHC



In HL-LHC, expected β^* error is 4% with only machine uncertainties, while goal is 2%. *If* $\delta Q > 4 \times 10^{-5}$ *disaster*.

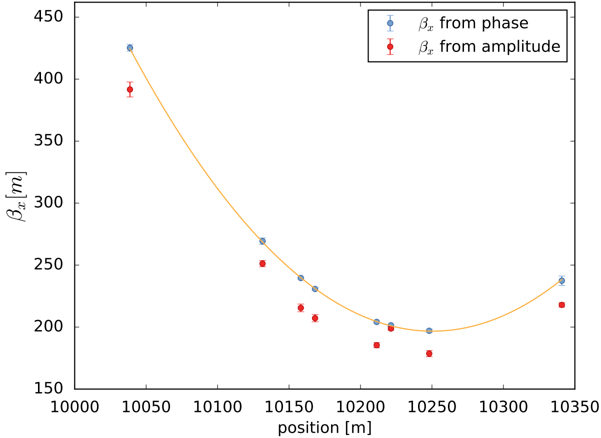
→Search for alternative β^* measurement techniques is required.

β^* from amplitude $A = C_i\sqrt{\beta_i 2J}$

- Using Q1 BPMs betatron amplitude measurement
- Requirement is about 1% accuracy in calibration, i.e. $|C_i - 1| < 0.01$

BPM Calibration with ballistic optics

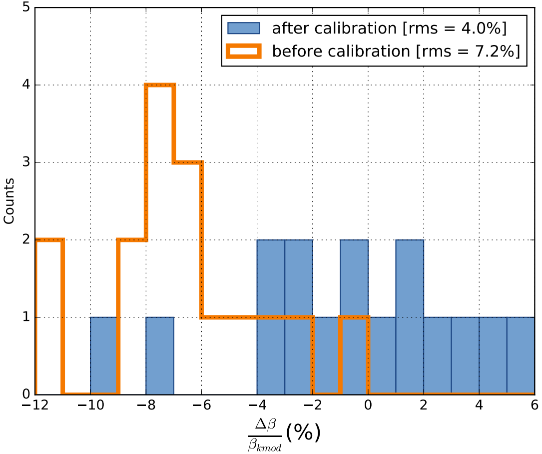
Switching off IR quadrupoles $\beta(s) = \beta^* + s^2/\beta^*$ and a very precise β-measurement is possible to even compute C_i:



A. García-Tabarés Valdivieso et al., IPAC 2016

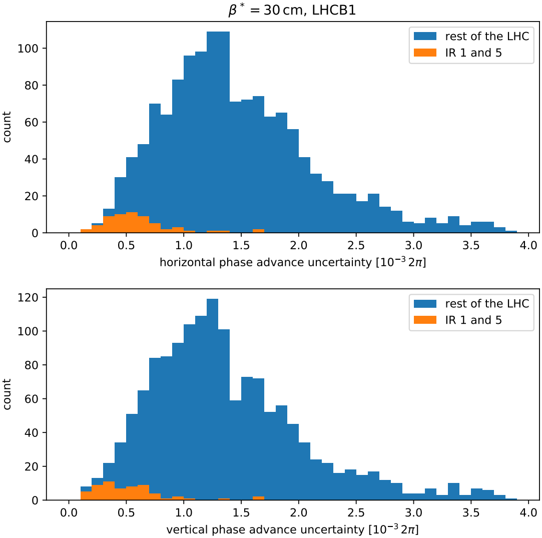
BPM Calibration with ballistic optics

BPM calibration errors are well above requests



This optics-based calibration reduces rms calibration errors by about a factor 2 but does not reach 1%. Changes over time observed.

Phase advance for β^*?



A. Wegscheider

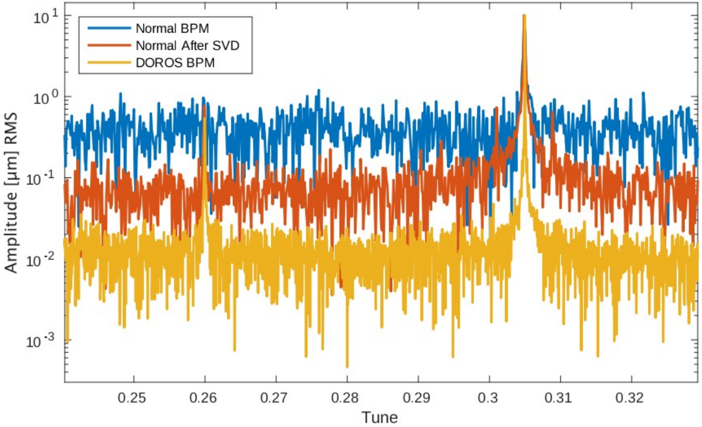
IR BPMs have better phase uncertainty, $\sigma_\phi \approx 5 \times 10^{-4}$, thanks to the larger β.

In order to use phase for β^* calculations we need $\sigma_\phi \leq 10^{-4}$, a factor 5 improvement in σ_{noise}.

We have not checked DOROS BPMs for this.

DOROS BPMs (see Jakub Olexa's talk)

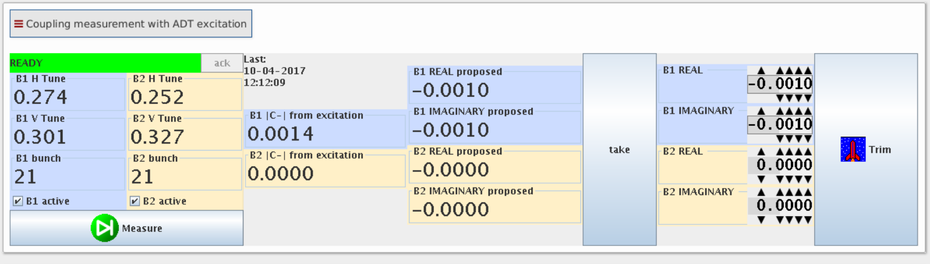
T. Persson, M. Gasior et al. CERN-ACC-NOTE-2015-0033



Noise level after SVD improves by about a factor 5!
Need to check DOROS for measuring β^* from phase.

Automatic coupling correction tool

The ADT is used as an AC dipole to excite the beam. All normal BPMs are used to measure coupling, computing a correction:

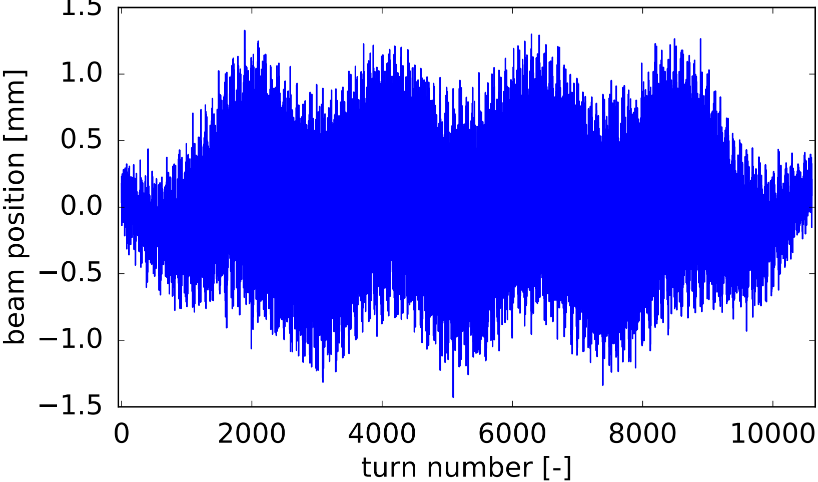


T. Persson et al., IPAC 2018

3D kicks

Combined AC dipole + fast RF modulation speeds up off-momentum optics measurements:

L. Malina, J. Coello, IPAC 2018



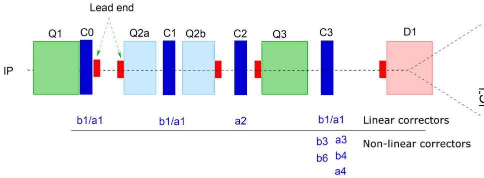
PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 121002 (2015)

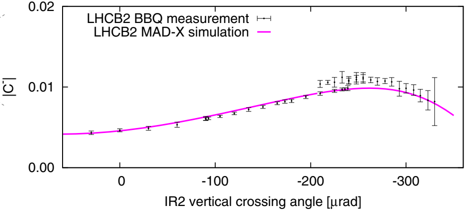
First measurement and correction of nonlinear errors in the experimental insertions of the CERN Large Hadron Collider

E. H. Maclean*

CERN, CH-1211 Geneva, Switzerland; Cocroft Institute, Daresbury WA4 4AD, United Kingdom; University of Manchester, Manchester M13 9PL, United Kingdom

R. Tomás, M. Giovannozzi, and T. H. B. Persson





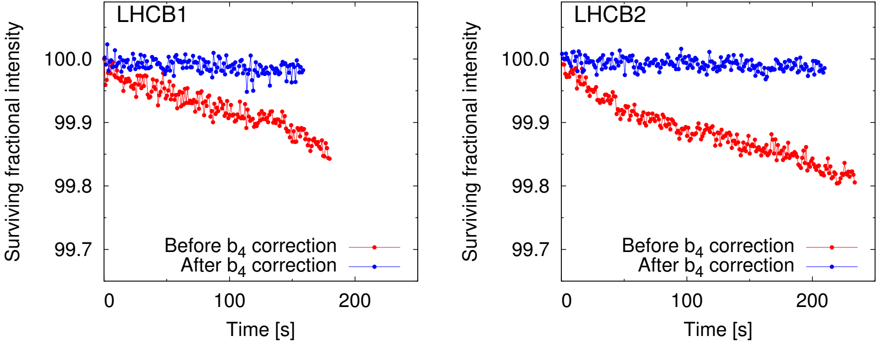
Observables:

- ★ Tune & coupling shifts versus orbit bumps
- ★ Amplitude detuning $Q = Q(J)$
- ★ Resonance Driving Terms
- ★ Lifetime

IR octupolar corrections & lifetime

ATS optics at $\beta^* = 0.14$m:

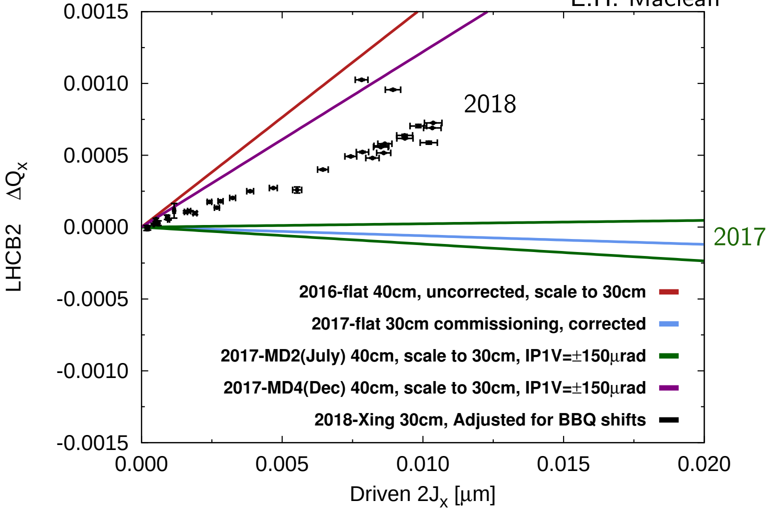
E.H. Maclean



Non-linear corrections are critical for integrated luminosity, specially for HL-LHC.

Issue with non-linear corrections in 2018

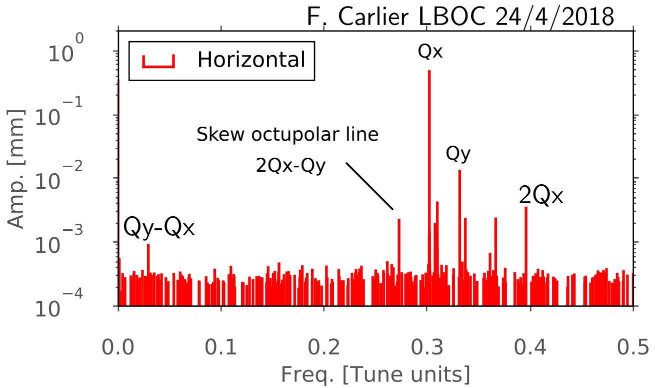
E.H. Maclean



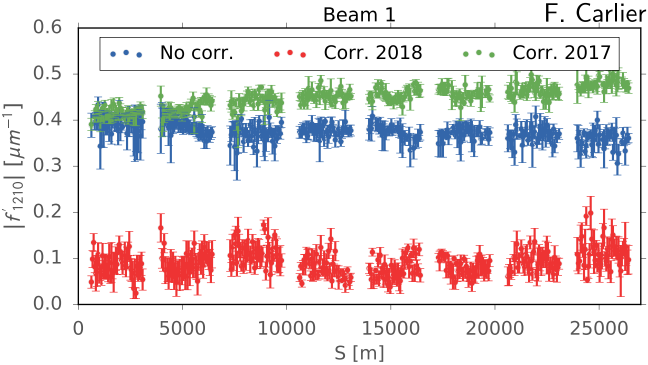
Larger amplitude detuning than in the past measured in 2018.
Need further investigations and new corrections.

Resonance Driving Terms

For the first time in 2018 we implement IR skew octupolar corrections from Resonance Driving Terms measurements.



Skew octupolar resonance driving term



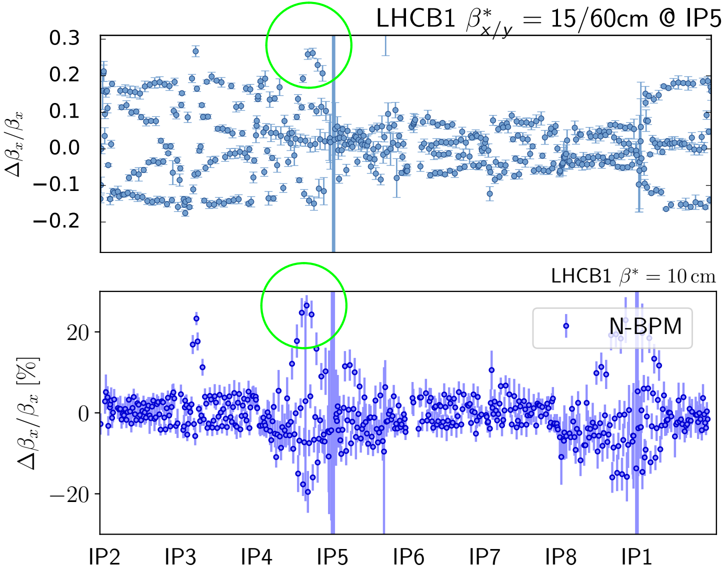
Successful correction in Beam 1 (Beam 2 limited by missing corrector). Many sextupolar, octupolar and decapolar resonance terms to explore!

Outlook

- ★ β^* control is highly challenged:
  - K-mod distorted by orbit feedback? Maybe needs more stable BPM orbit readings and better tune measurements?
  - β^* from amplitude distorted by Q1 BPM calibration error. Can we reach 1% BPM calibration accuracy?
  - β^* from phase needs a factor 5 lower σ_{noise} $\rightarrow$ Explore DOROS
- ★ Control of non-linearities is critical, specially for HL-LHC:
  - Many resonances to study
  - Relying on BPMs with very low aberrations
  - What changed amplitude detuning in 2018?
- ★ Looking forward other techniques presented in the workshop: Schottky, BTF & beam size from BPMs.

Back-up slides

Flat and round ATS optics ($\beta_{arc} \times 4$)



$\Delta\beta/\beta$ not under control for ATS large β_{arc}

BPM non-linear aberrations

Let $\hat{x}(N)$ be the real beam position versus turn:

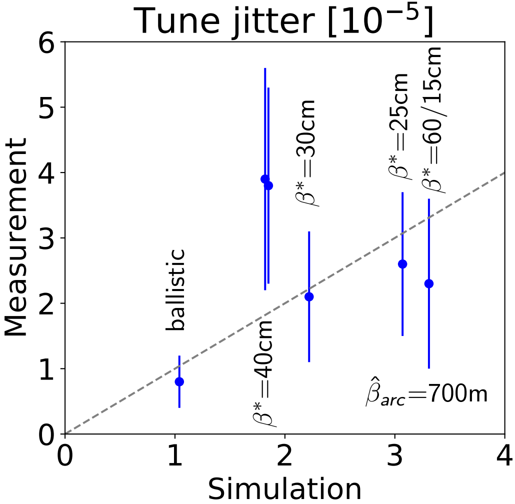
$$\begin{aligned}\hat{x}(n) &= \sqrt{2\beta_x J_x}\cos(2\pi n Q_x + \phi_x)\\ \hat{y}(n) &= \sqrt{2\beta_y J_y}\cos(2\pi n Q_y + \phi_y)\end{aligned}$$

then the BPM reading with aberrations is

$$x(n) = \overline{x} + \sigma_{noise} + C\hat{x}(n) + c\hat{y}(n) + B\hat{x}(n)^2 + D\hat{x}(n)\hat{y}(n) + ...$$

Measured tune jitter in MDs

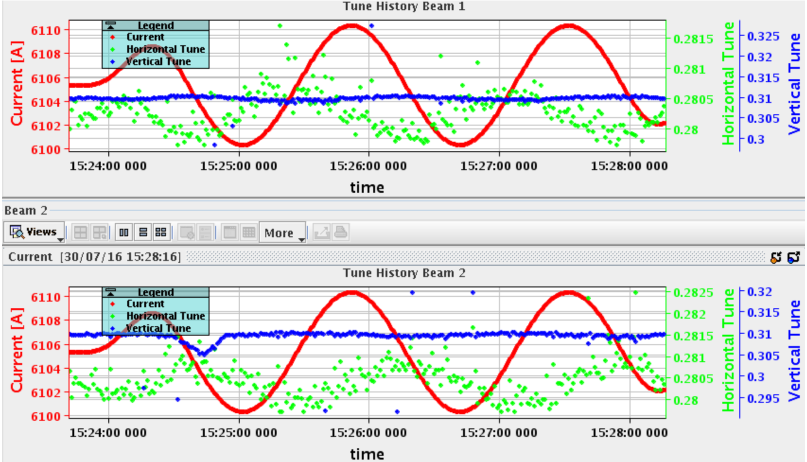
Measurements versus predictions from power converter stability (sampling at 1 minute):



General agreement, need better accuracy →MDs in 2018.

K-modulation with tune feedback I

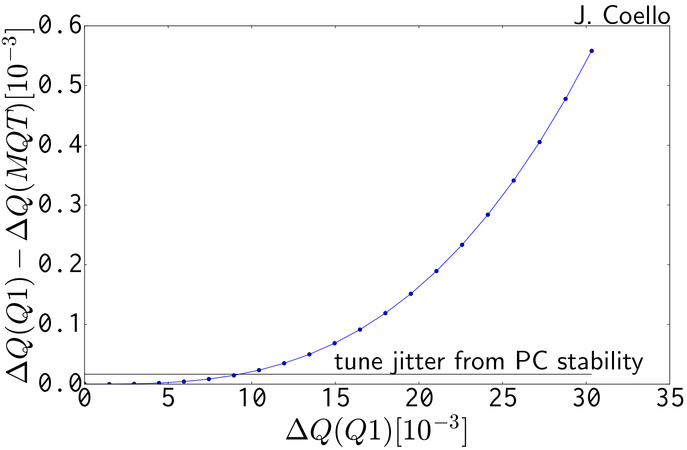
This was tried in the LHC in 2016:



Late response of feedback, partial correction...

K-modulation with tune feedback II

Systematic error from Q1 β-beating in MQTs:



Systematic error above random error for $\Delta Q > 0.01$.