Optics measurement and correction studies at the Large Hadron Collider

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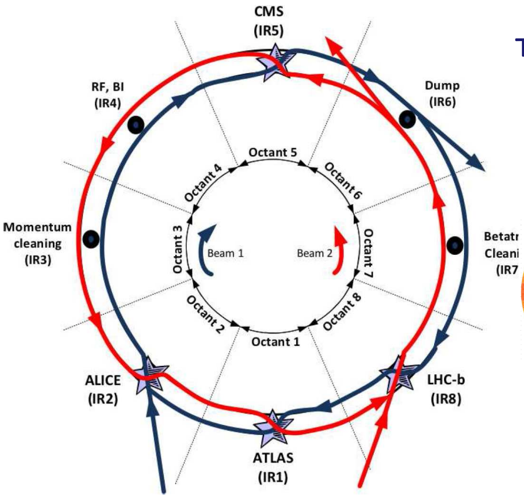
with many thanks to

the LHC **O**ptics **M**easurement and **C**orrection (**OMC**) Team
& M.Giovannozzi

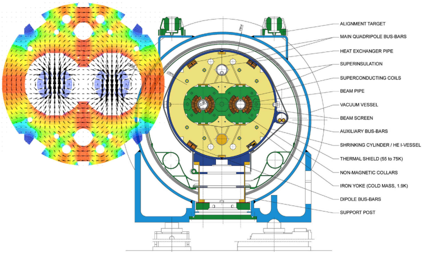
L-Università ta' Malta

The Large Hadron Collider (LHC)



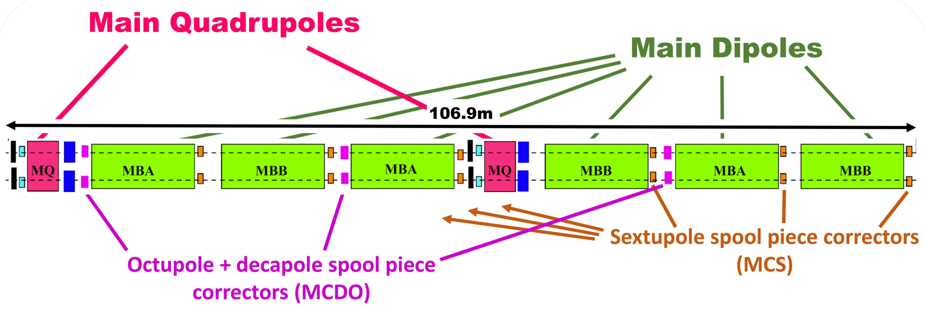
Twin-ring synchrotron collider

- **2 counter-rotating beams**
- **Collides** p, $^{208}\mathrm{Pb}^{82+}$, $^{129}\mathrm{Xe}^{54+}$



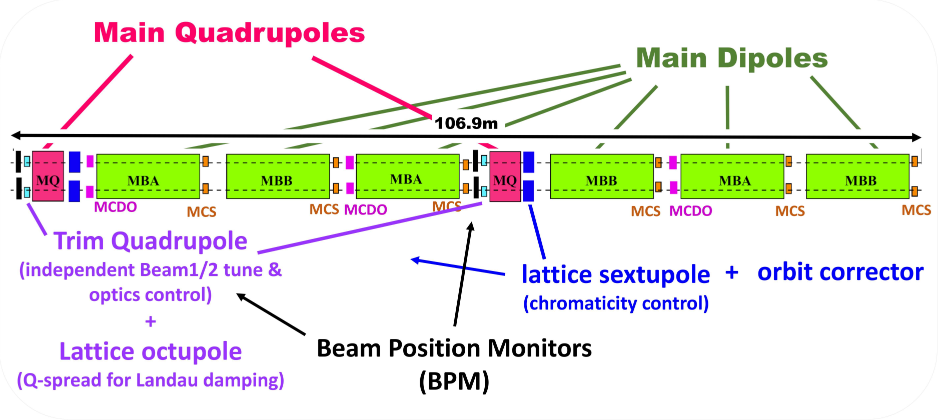
- **8 straight insertion regions** (IRs) **& 8 bending Arcs** *'A12 → A81'*

23 repeating ‘cells’ per Arc



- Linear & nonlinear optics errors at injection dominated by errors in main dipoles (MB) & main quads (MQ)

23 repeating 'cells' per Arc



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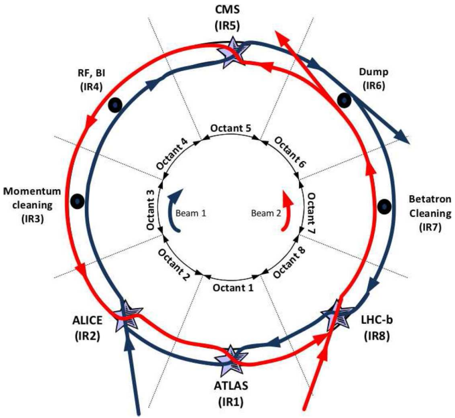
The Large Hadron Collider (LHC)



8 insertions:

- **IR2:** LHB1 injection + HEP (ALICE)
- **IR8:** LHB2 injection + HEP (LHCb)

- **IR1:** HEP (ATLAS)
- **IR5:** HEP (CMS)

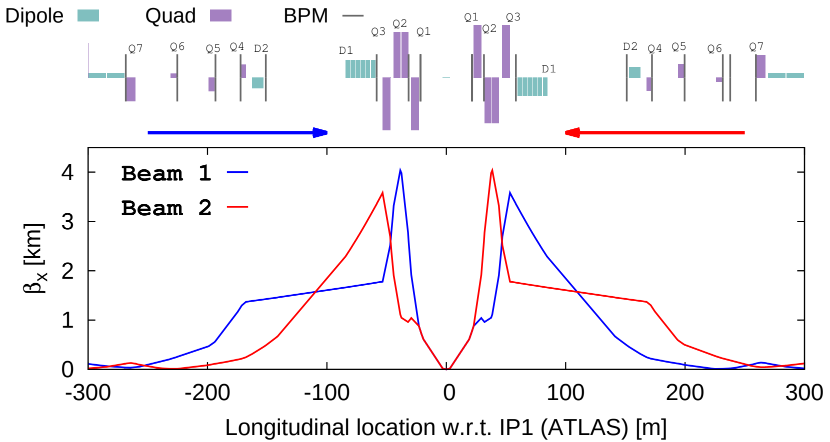
- **IR3:** COLLIMATION (momentum)
- **IR7:** COLLIMATION (transverse)

- **IR4:** Acceleration + instrumentation

- **IR6:** LHCB1+B2 BEAM DUMP

For luminosity production squeeze β^* in experimental IRs

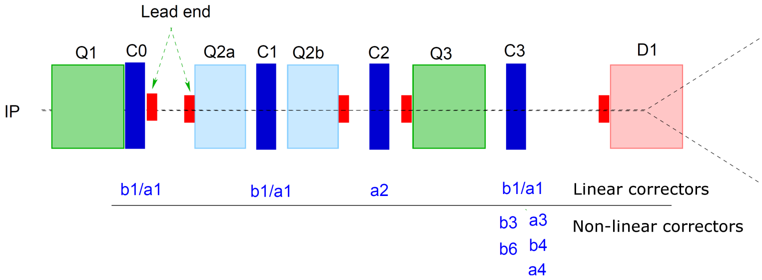
$\rightarrow$ **Run1** $\beta^* \geq 0.6\,\mathrm{m}$, **Run2** $\beta^* \geq 0.25\,\mathrm{m}$



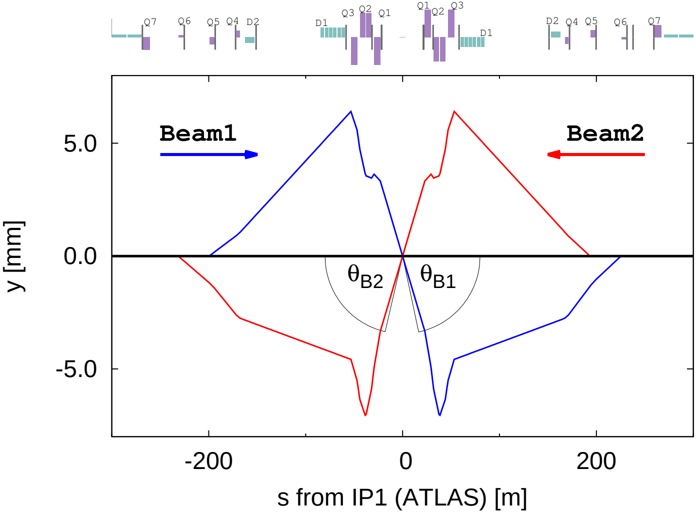
- **Linear & nonlinear optics errors at end-of-squeeze dominated by errors in IR-magnets**

Dedicated nonlinear correctors for sextupole→dodecapole, located left/right of all experimental IRs

- **LHC:** b_3, a_3, b_4, a_4, b_6
- **HL-LHC:** b_3, a_3, b_4, a_4, b_5, a_a5, b_6, a_6



Never used in operation prior to 2017

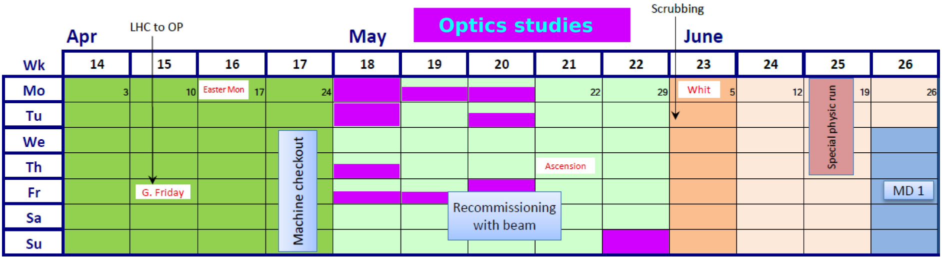


- **Crossing-angle orbit bumps prevent parasitic collisions during luminosity production**

Linear & nonlinear optics studies at the LHC

First optics activity every year is commissioning

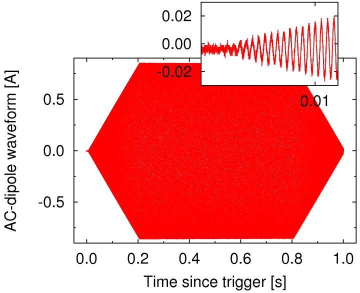
- **Essential studies to prepare for Luminosity production**
- **around 1 month at start of each year**
  $\longrightarrow$ extra commissioning for special runs (Heavy Ion, High-β...)

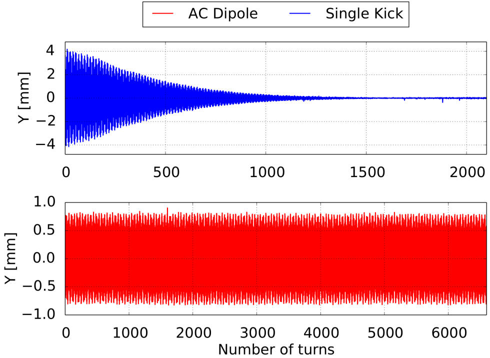


- **Traditionally concerned with linear optics**

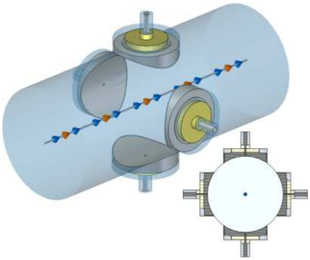
Optics measurement via excitation & spectral analysis

→Use driven oscillations of the beam via AC-dipole





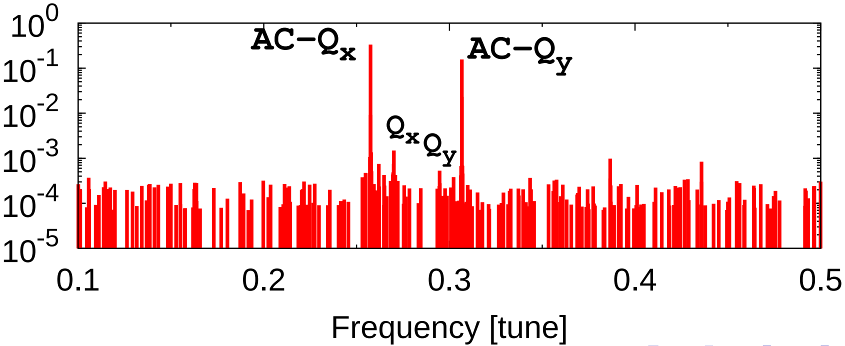
- **No decoherence of forced oscillations**
- **No blow-up due to adiabatic ramp-up/down**
- **Safe**



- ~500 dual plane BPMs record turn-by-turn betatron oscillation data during kicks
- Spectral analysis to obtain phase advances between BPMs
- Reconstruct β-functions via N-BPM method

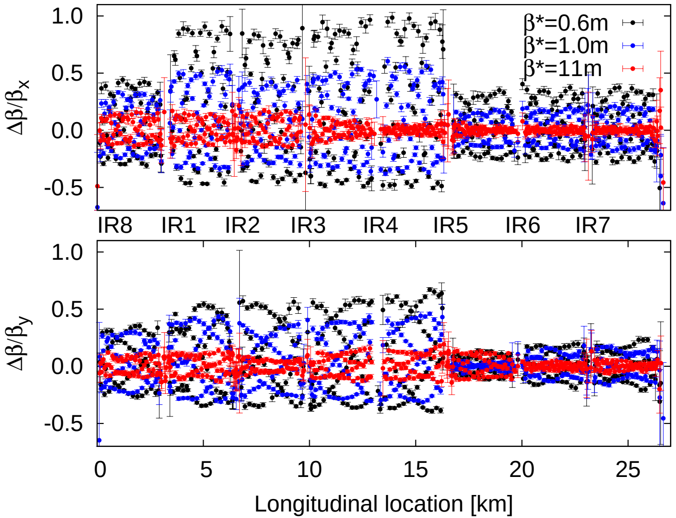
  Phys. Rev. ST Accel. Beams 18, 031002

  Phys. Rev. Accel. Beams 20, 111002

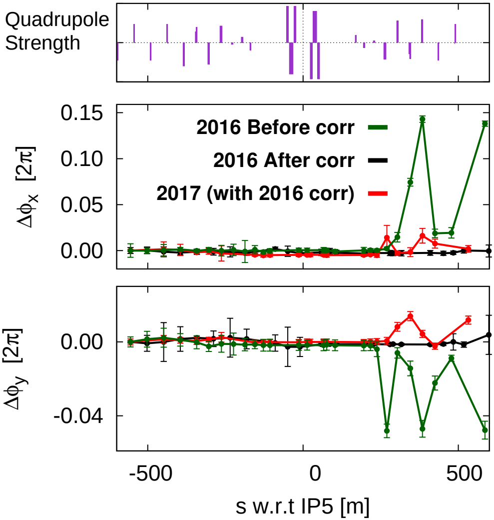


Linear optics errors in LHC are substantial!

LHC not allowed to operate for Lumi-production if $\Delta\beta/\beta \gtrsim 18\,\%$



First corrections are for large local errors (e.g. in IRs)



Correct via betatron phase, not β-from-phase

$\rightarrow$ BPM calibration independent

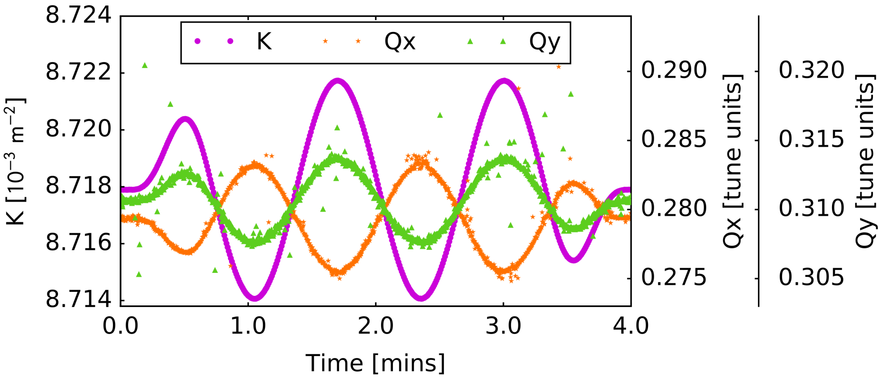
$\rightarrow$ Model independent

- Examine deviation of betatron phase from expected value over segment
- Use LHC models to match quadrupole settings to reproduce errors

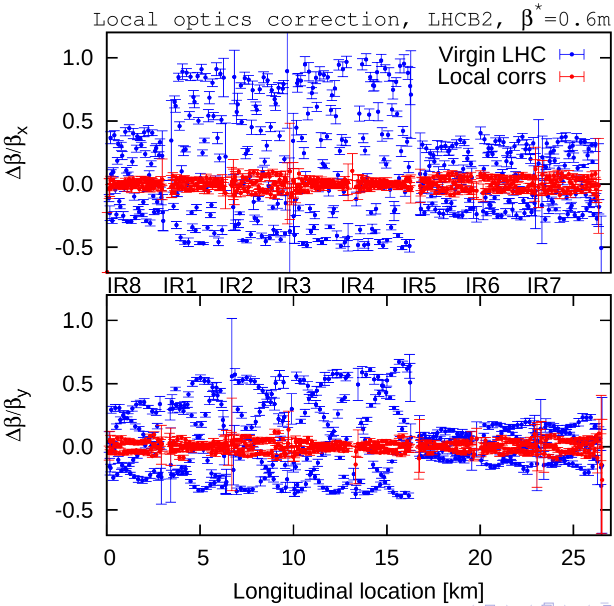
Phys. Rev. ST Accel. Beams 12, 081002

Use complementary observables to better constrain corrections in critical areas such as experimental insertions e.g. ‘K-modulation’

$$\Delta Q_{x,y} \propto \Delta K_1 L \bar{\beta}_{x,y}$$



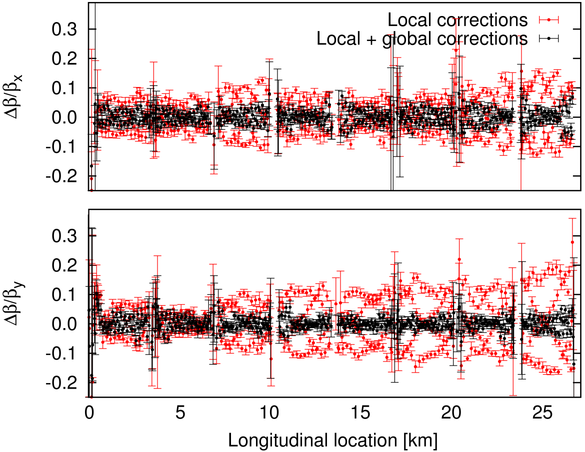
Local corrections remove most β-beating



Global corrections give final optimization

Response matrix adjusts remaining quadrupole circuits

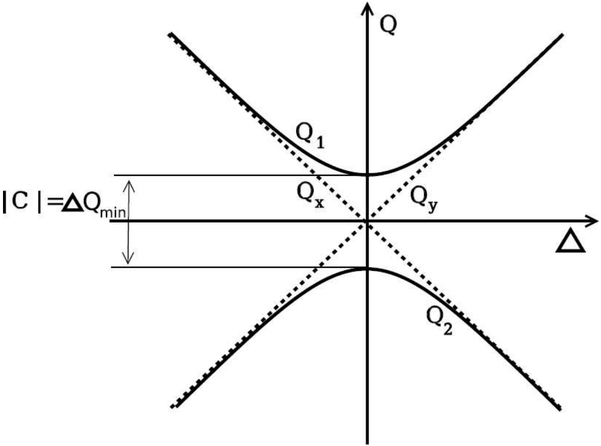
$$\left(\Delta\vec{\phi}_x, \Delta\vec{\phi}_y, \vec{\beta}^*_x, \vec{\beta}^*_y, \Delta\vec{D}_x/\sqrt{\beta_x}, \Delta Q_x, \Delta Q_y, \ldots\right) = \mathbf{R}\cdot\Delta\vec{k}$$



Typical RMS $\frac{\Delta\beta}{\beta} \approx 2\,\%$

PEAK $\frac{\Delta\beta}{\beta} \approx 5 - 10\,\%$

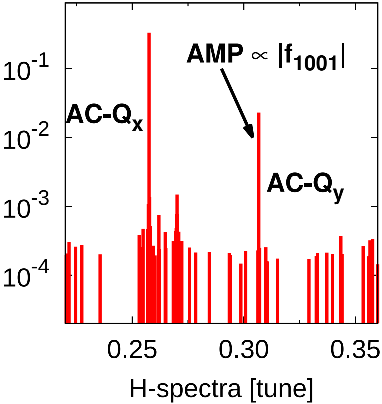
Also correct linear transverse coupling ($|C^-|$)

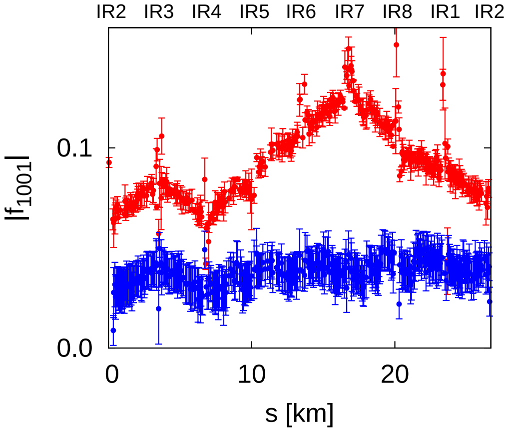


- Drive $Q_x - Q_y$ resonance
- Generates a closest tune approach

Correct coupling by minimizing strength of $Q_x - Q_y$ resonance

$\rightarrow$ characterized by $|f_{1001}|$ *Resonance Driving Term*





$$|\Delta Q_{min}| = |C^-| \approx 4 \times \Delta Q |f_{1001}|$$

Why the concern with hadron collider optics?

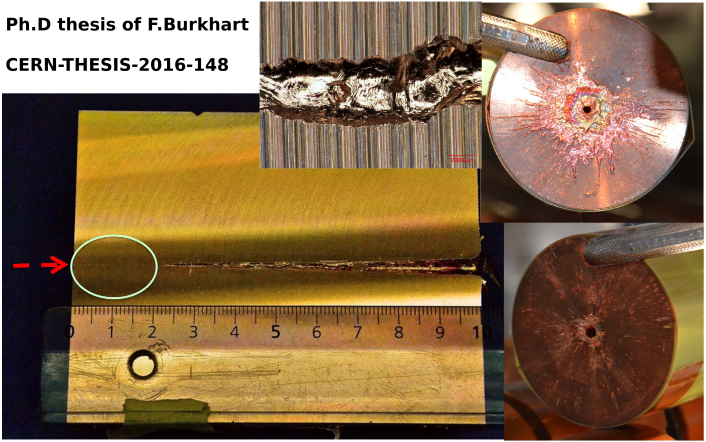
Why the concern? $\longrightarrow$ machine protection

LHC beams store a huge amount of energy (360 MJ, 1 MJ $\approx$ 0.25 kg of TNT)

- **can quench superconducting magnets**
- **can physically damage materials in the ring**

Ph.D thesis of F.Burkhart

CERN-THESIS-2016-148



Why the concern?→ performance

Key figure of merit for us is of-course Luminosity

$$R_p = L\sigma_p$$

$$L = \frac{N_1 N_2 \left(f_{ref}\, n_{coll}\right)}{2\pi\sqrt{\left(\sigma_{x,1}^2 + \sigma_{x,2}^2\right)}\sqrt{\left(\sigma_{y,1}^2 + \sigma_{y,2}^2\right)}} \times \left(reduction\ factors\right)$$

$$\sigma_{z,b} = \sqrt{\beta_{z,b}^{*}\epsilon_{z,b}} \qquad \text{where } z = x, y \text{ and } b = 1, 2$$

- **Optics errors can reduce data delivered to HEP experiments**
- **Create Luminosity imbalance between HEP experiments**
- **Aim for β^*-beat $\leq 1\,\%$**

  Record low β beating in the LHC, PRSTAB 15, 091001

  LHC optics commissioning: A journey towards 1% optics control, PRAB 20, 061002

High quality optics corrections provide clean baseline upon which to begin the study of nonlinear optics errors!

Nonlinear optics not traditionally part of LHC commissioning $\rightarrow$ studied in dedicated Machine Development (MD) beam tests

- 4-5 LHC MD blocks per year ($\sim 1\,\mathrm{week/block}$)
- Allocated a block of time for MD ($6-12\,\mathrm{hours}$)

First task (circa. 2011-2012): how large are nonlinearities at injection? $\rightarrow$ two key observables used:

<u>Nonlinear Chromaticity</u>

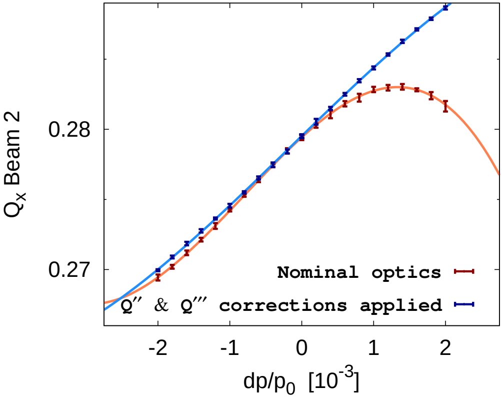
$$Q_z\left(\frac{\delta p}{p_0}\right) = Q_{z0} + Q'_z\left(\frac{\delta p}{p_0}\right) + \frac{1}{2!}Q''_z\left(\frac{\delta p}{p_0}\right)^2 + \frac{1}{3!}Q'''_z\left(\frac{\delta p}{p_0}\right)^3 + \ldots$$

- **Change of tune with momentum. Measure by varying RF-frequency**
- **Different orders of NL-chromaticity can provide information on different multipole errors** (subject to some complications)

Measure with nominal spool-piece correction already applied (red)

(based on magnetic measurements during construction)

- **Second-order chromaticity 10× worse than expected**
- **Third-order chromaticity 2× worse than expected**



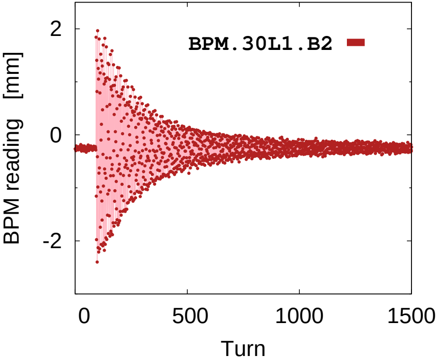
- **Beam-based minimization of Q'' & Q''' with global trims of octupolar/decapolar-spools respectively (blue)**

Amplitude detuning

$$Q_z(\epsilon_x, \epsilon_y) = \ Q_{z0} + \left(\frac{\partial Q_z}{\partial \epsilon_x}\epsilon_x + \frac{\partial Q_z}{\partial \epsilon_y}\epsilon_y \right) + \frac{1}{2!}\left(\frac{\partial^2 Q_z}{\partial \epsilon_x^2}\epsilon_x^2 + 2\frac{\partial^2 Q_z}{\partial \epsilon_x \partial \epsilon_y}\epsilon_x\epsilon_y + \frac{\partial^2 Q_z}{\partial \epsilon_y^2}\epsilon_y^2 \right) + \ldots$$

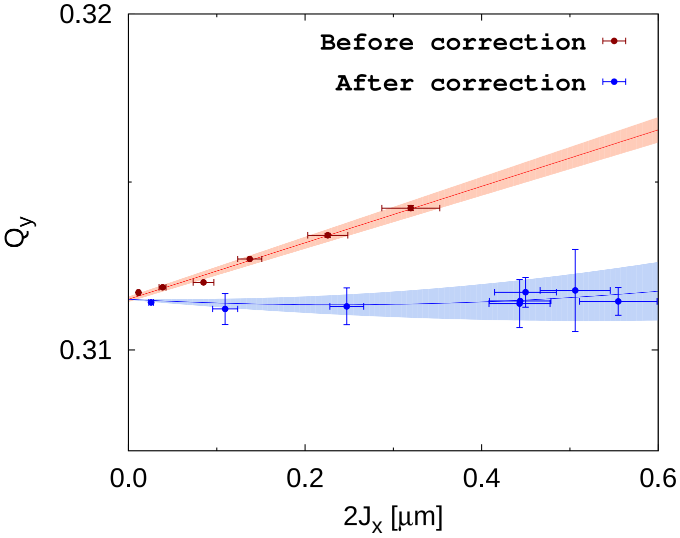
where (Courant-Snyder invarient) $\epsilon = 2J$ $(x = \sqrt{2J\beta}\cos\phi_x)$

- **Change of tune with betatron oscillation amplitude**
- **Excite betatron oscillations of a bunch to various amplitudes**

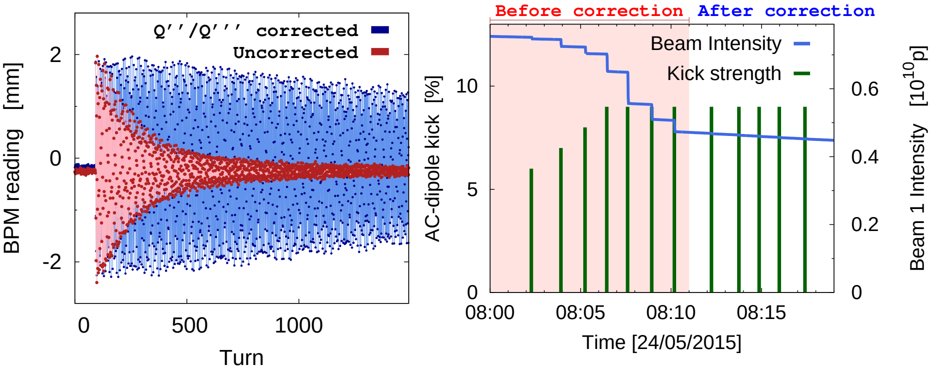


- Excite via kicker dipole (ramp up/down in $\frac{1}{2}$ turn)
- Spectral analysis of TbT data to fit tune vs action
- Oscillations **do not** decay (hadrons) $\rightarrow$ **Oscillations decohere**
- Re-inject after every kick

- Q'' **correction also corrected first-order amplitude detuning**



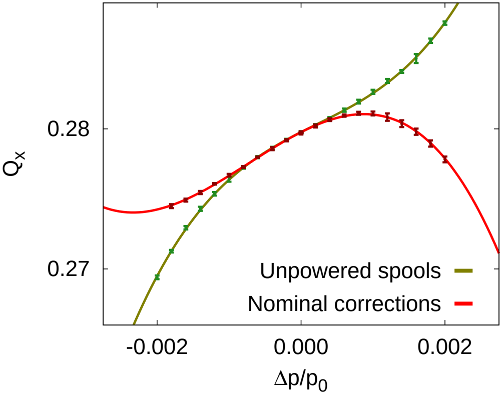
Also observe improved decoherence of single kicks and reduced beam-losses with AC-dipole



- **Simultaneous correction of chromaticity, detuning, decoherence and losses implies quasi-local correction**
- **Points to broadly distributed octupole sources in the arcs**

- When correcting Q''' with decapoles observe significant $\Delta Q''$
- Scaling observed $\Delta Q''/I_{MCD}$ to nominal corr' explains most missing Q''
- Improved estimate of hysteresis in MCO explains remainder

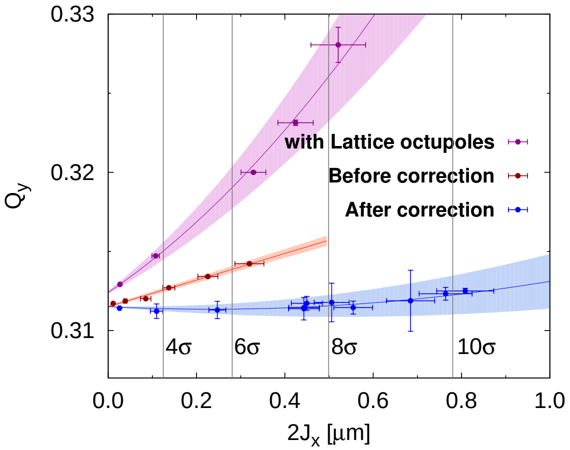
Measure without octupole or decapole spools



Spool piece 'correction' actually made errors worse!

During operation for Lumi-production nonlinearities at injection dominated by detuning introduced by Lattice octupoles (MO)

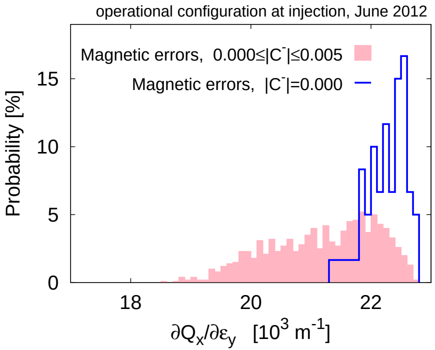
$\rightarrow$ Provides Landau damping for collective instabilities

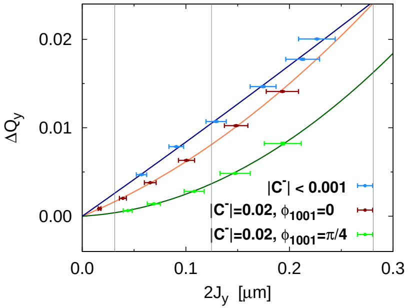


- **Detuning in operation within** $10\,\%$ **of model at injection**
- **Subject to 1 big caveat: transverse coupling**

Simulated detuning shifts from typical OP-range of $|C^-|$ significantly larger than uncertainty on magnetic measurements

$\rightarrow$ Backed up by measurements with different $|C^-|$ and RDT





Linear coupling is biggest source of uncertainty/variability in LHC NL-observables Effect of linear coupling on nonlinear observables at the LHC, IPAC'17, WEPIK092

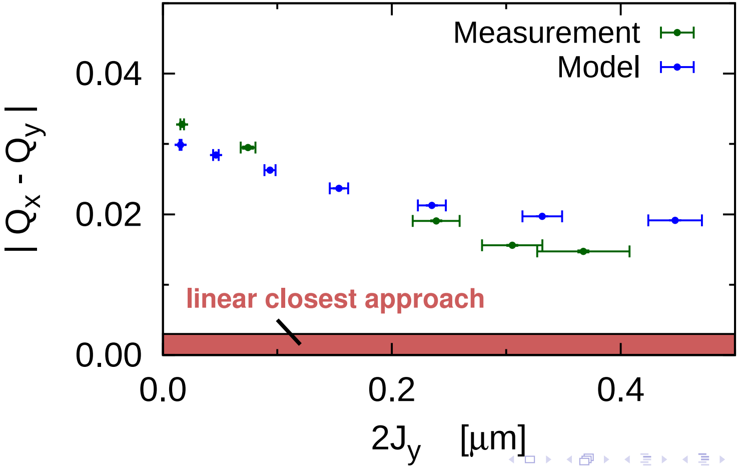
- Must be accounted for whenever performing NL-measurements & correction

Care needed when detuning towards the $Q_x - Q_y$ resonance

$\longrightarrow$ **Observe saturation of Q-split vs J far above linear ΔQ_{min}**

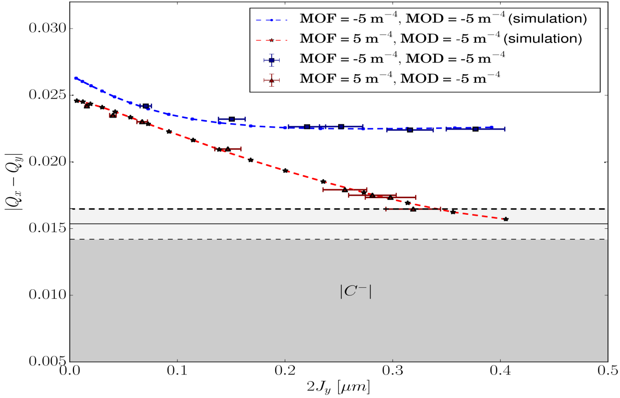
$\longrightarrow$ **Interpret as an Amplitude Dependent Closest Tune Approach**

Measurement of nonlinear observables in the Large Hadron Collider using kicked beams, PRAB 17, 081002



- Model shows large contribution to NL-ΔQ_{min} from combination of Landau octupoles + $|C^-|$ Non-linear coupling studies in the LHC, IPAC'15, TUPTY042
- Theoretical description proposes additional contribution to ΔQ_{min} which is $\propto \kappa$ (linear ΔQ_{min}) and $\propto h_{1111}$ (cross-term detuning)

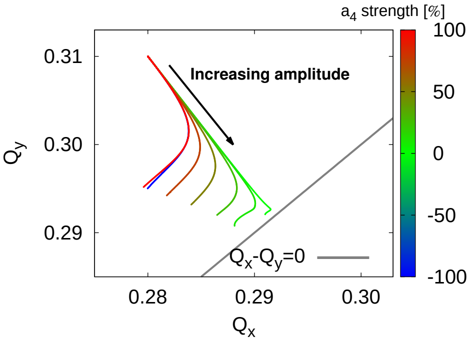
  Amplitude dependent closest tune approach, PRAB 19, 071003



Validated by canceling cross-term detuning (h_{1111})

Normal and skew octupoles together also generate amplitude dependence of closest tune approach

Amplitude dependent closest tune approach generated by normal and skew octupoles, IPAC'17, WEPIK091



Model shows increasing closest approach with skew octupole (a_4) strength

First attempt at validation (artificially increase a_4)

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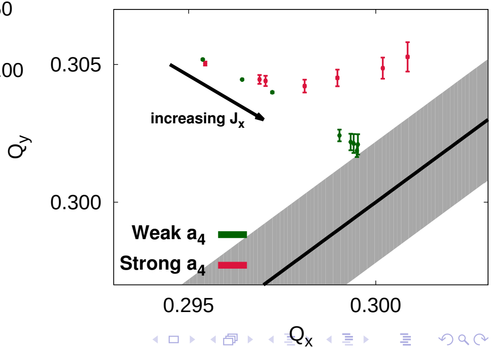
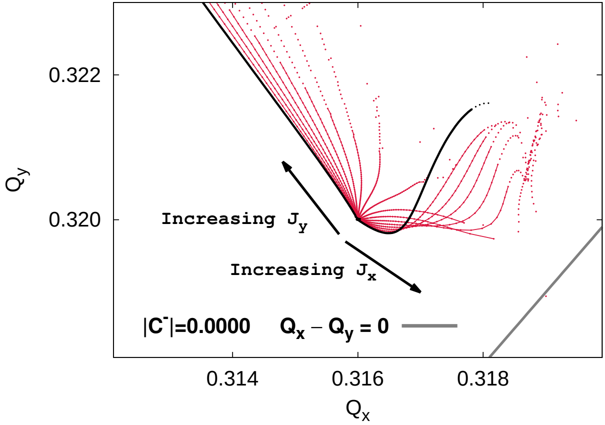
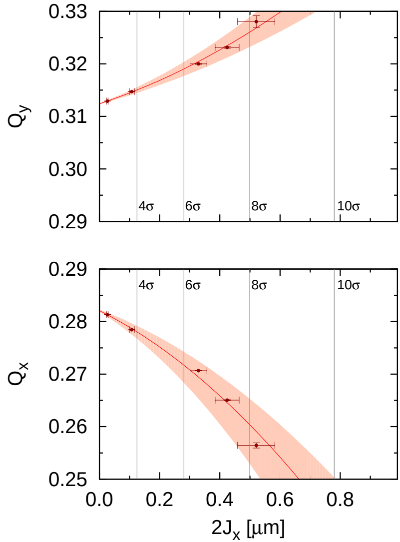


Linear coupling & skew octupoles can significantly distort the Q-footprint introduced to provide Landau damping



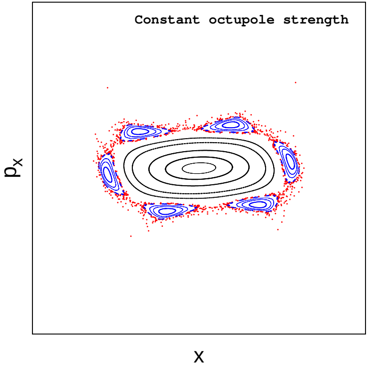
- **Potentially a significant challenge in regard to dealing with collective effects in LHC/HL-LHC**

Introduction of large detuning by Landau octupoles also causes approach to low-order 1D resonances)

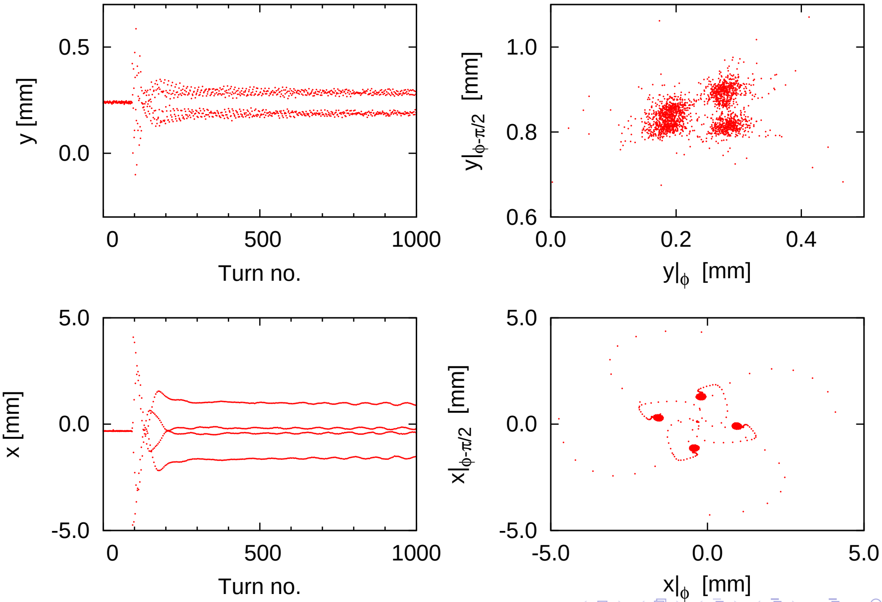


Detuning towards $4Q_x$ & $3Q_y$

$\longrightarrow$ expect to encounter stable islands in phase-space

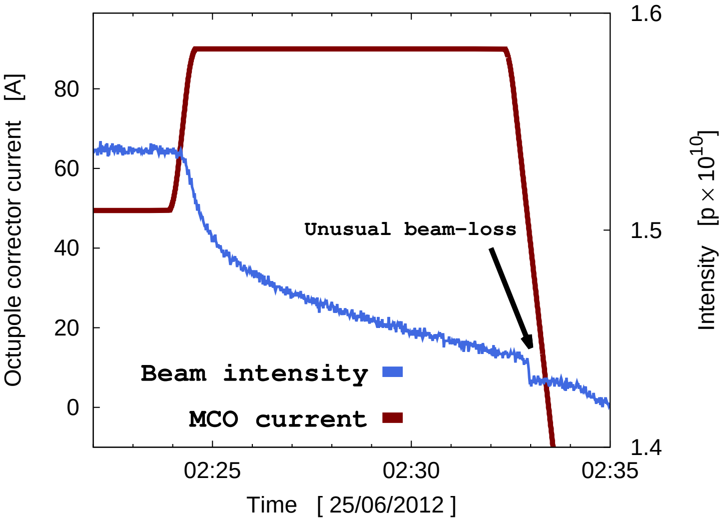


Simultaneously hitting $4Q_x$ & $3Q_y$



Some interesting consequences from low-order resonances

→ e.g. abrupt beam-losses during octupole trim

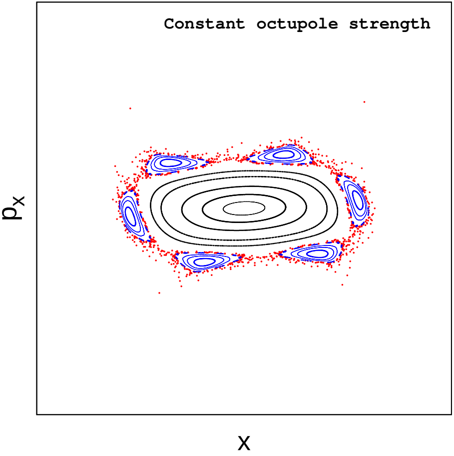


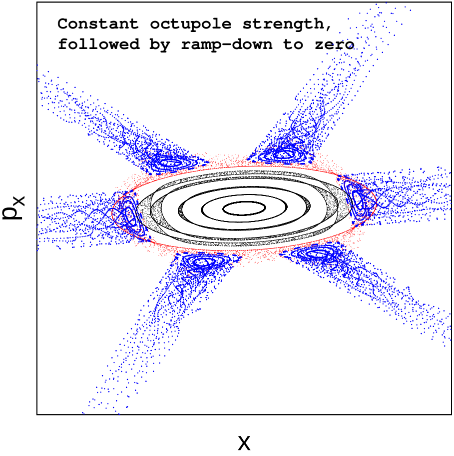
Consider 'toy' model

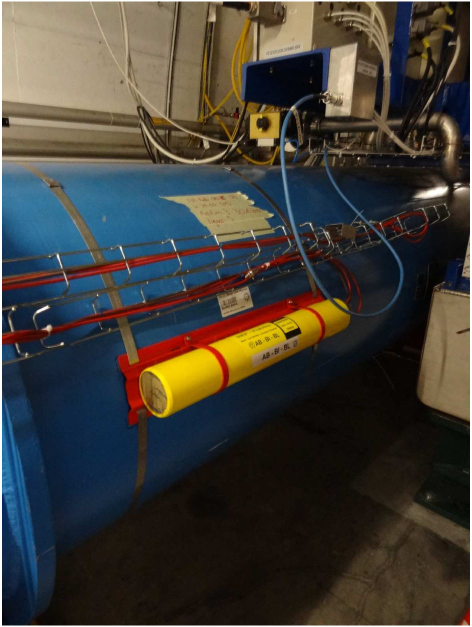
→ slowly reduce octupole kick strength

→ **Central orbits restored to elliptical trajectories**

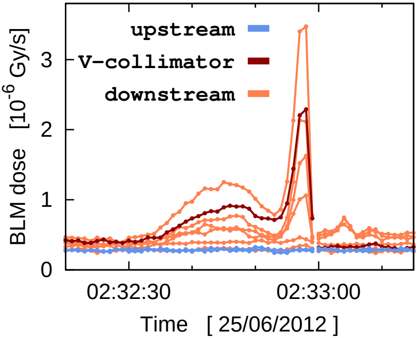
→ **Particles in islands transported out to larger amplitude**





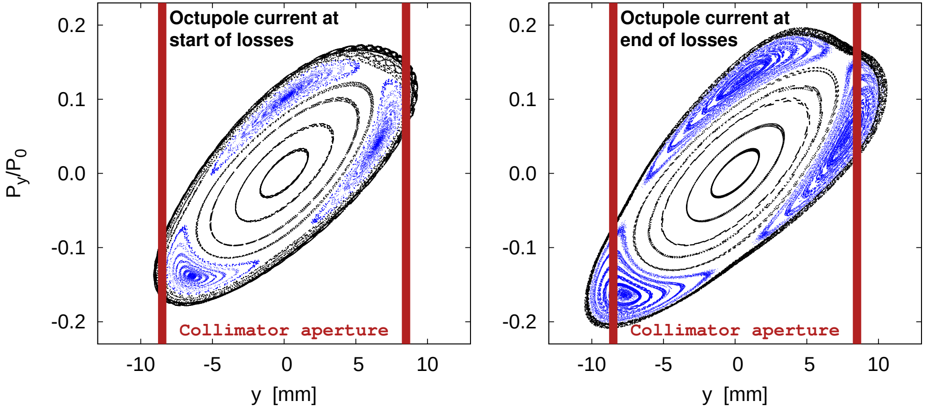


Beam Loss Monitors (BLM) show losses at the vertical collimator



Poincaré section at vertical collimator via numerical tracking

→ losses explained by transport of particles in $3Q_y$ islands to collimator
(expect complete loss of island once any core touches collimator)



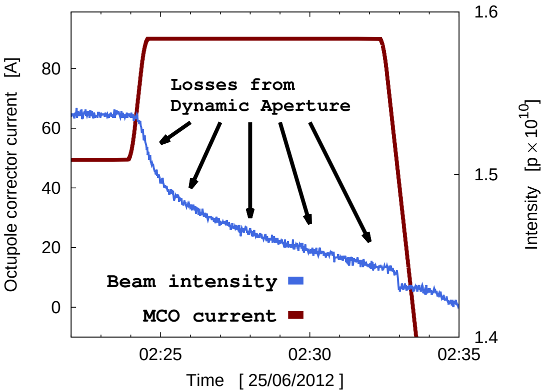
Very similar to multi-turn extraction procedure used in SPS

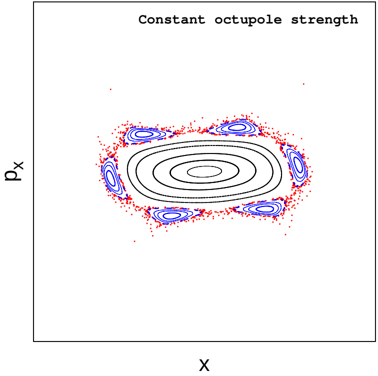
Exploring as a potential mechanism for
beam loss & emittance growth in LHC ramp

Dynamic aperture (DA)

→ amplitude below which particles will survive for a specific number of turns

→ **can reduce beam lifetime causing lower delivered luminosity**



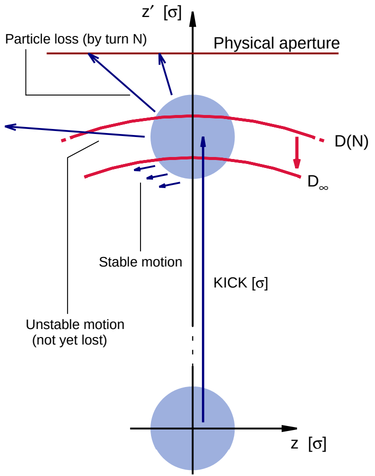


- volunteer computing essential for tracking studies of CERN accelerators

  → **BOINC / LHC@home**: **http://lhcathome.web.cern.ch/**

Important task in MD is to understand how well simulation codes agree with the real world!

Traditional measurement via single kicks

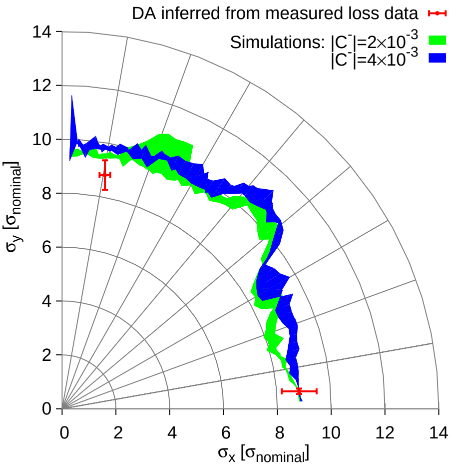


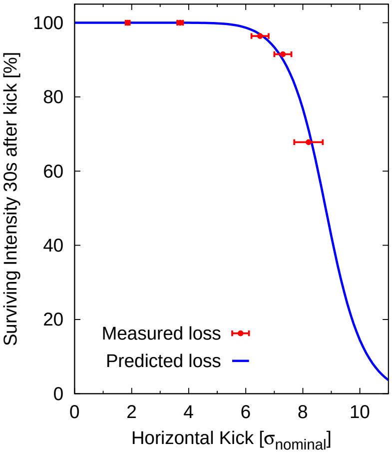
- **LHC ‘aperture kicker’ dipole ramps up/down in $\sim 1/2$ turn**
- **Provide large amplitude displacement of pilot bunch ($\sim 10^{10}p$)**
- **Kick action determined from TbT BPM position data**
- **Beam-loss following kick determines distance between kick and DA(N)**

Compare measured DA to best-knowledge model in SIXTRACK

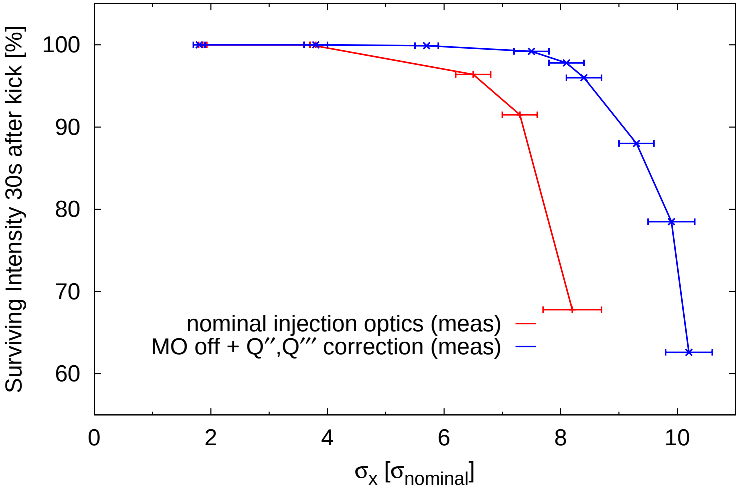
Phys. Rev. ST Accel. Beams 17 081002 (2014)

e.g. $10^5\,\mathrm{turn}$ $(\sim 30\,\mathrm{s})$ DA at injection in OP-configuration

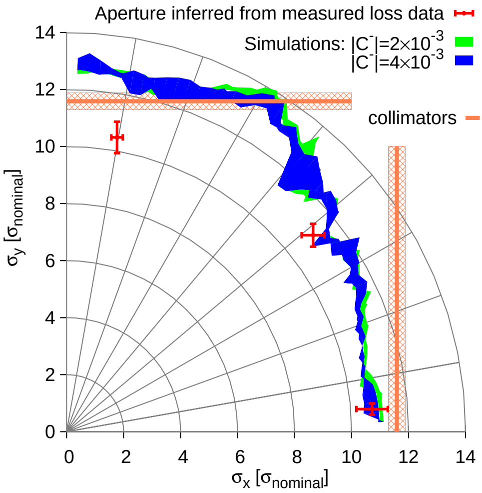


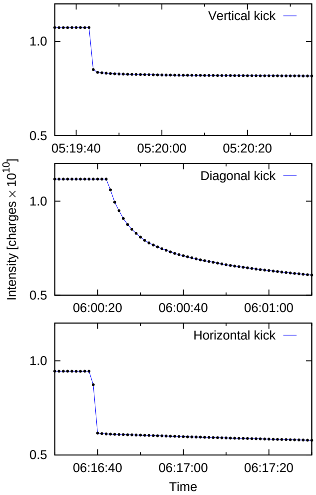


Removing nonlinear sources (turn off lattice octupoles & correct Q''/Q''') improves dynamic aperture



e.g. 10^5 turn ($\sim 30\,\mathrm{s}$) DA at injection after all corrections





Measurement via single-kicks shows excellent agreement to model predictions at injection (within $10\,\%$)

Single-kick DA measurements impossible to apply at $6.5\,\mathrm{TeV}$

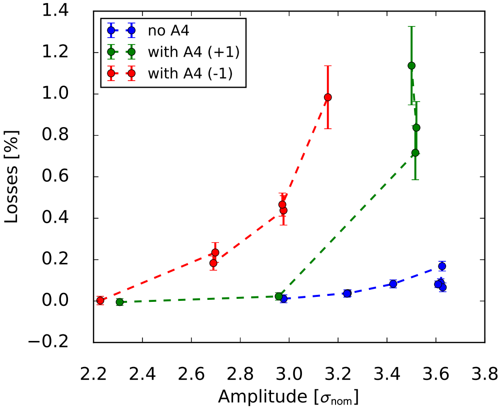
- **Machine protection concerns**
  $\longrightarrow$ large, rapid losses upon kick risk quench, or even damage!
- **Time concerns**
  $\longrightarrow$ require fresh injection after every kick

Two possible alternatives:

- **Short-term DA of driven oscillations with AC-dipole**
- **Long-term DA (free oscillations) of large emittance bunch**

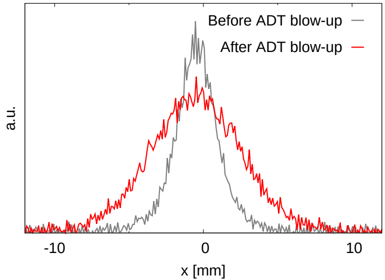
AC-dipole DA → Ph.D thesis of Felix Carlier (CERN)

- **DA of forced oscillations not the same as free oscillations**



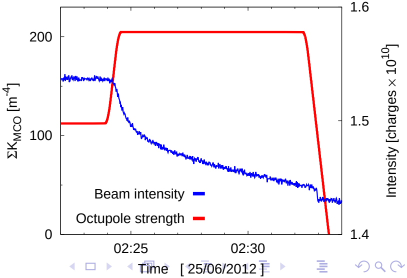
- **Still provides a useful probe to examine nonlinear resonances**
- **Require sufficient driven DA in order to use AC-dipole to commission the LHC/HL-LHC**

Measurement of DA evolution using transverse damper

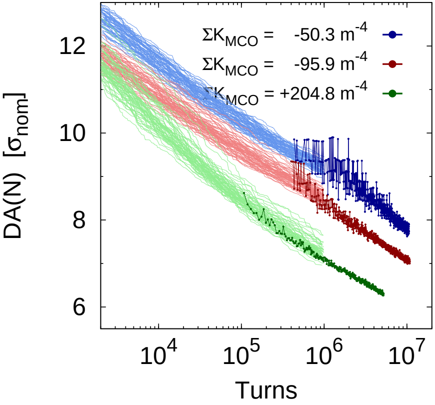


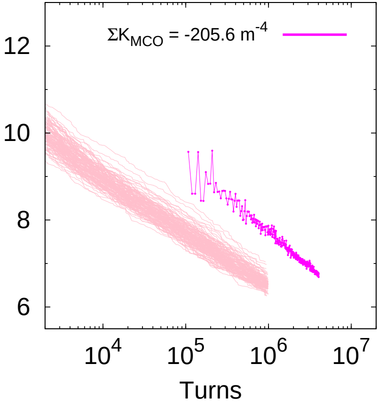
- **LHC transverse damper (ADT) used to blow-up bunch to large emittance**
  - → viable method @ 6.5 TeV
  - → slow heating limits quench risk

- **Examine intensity evolution upon changes in powering of NL-elements**
- **Relate to an average DA after N turns**



Tested at injection with a few large, well known sources (vary octupole spool powering $\sim 10\times$ required b_4 correction)

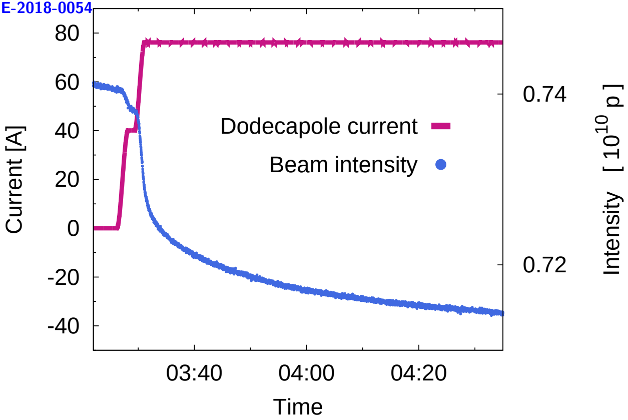




Comparable degree of agreement to model as for single-kicks, at the level of $10\,\%$

First application at $6.5\,\mathrm{TeV}$, $\beta^* = 0.4\,\mathrm{m}$ to asses impact of dodecapole sources in experimental IRs on DA

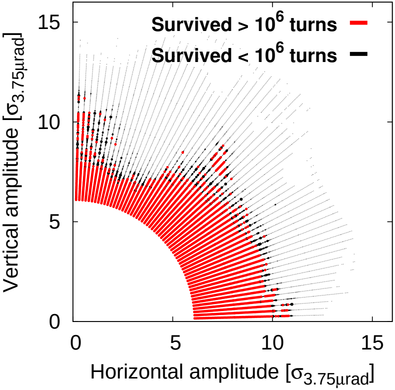
CERN-ACC-NOTE-2018-0054

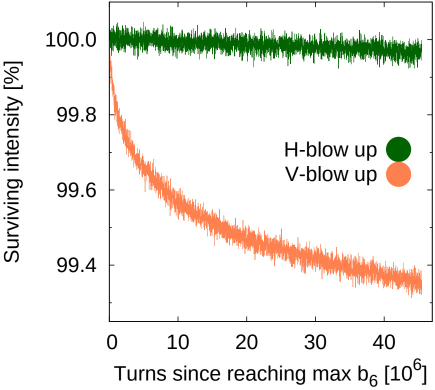


- No significant effect on DA for LHC
- Should expect b_6 to become relevant for very low-β^* in HL-LHC

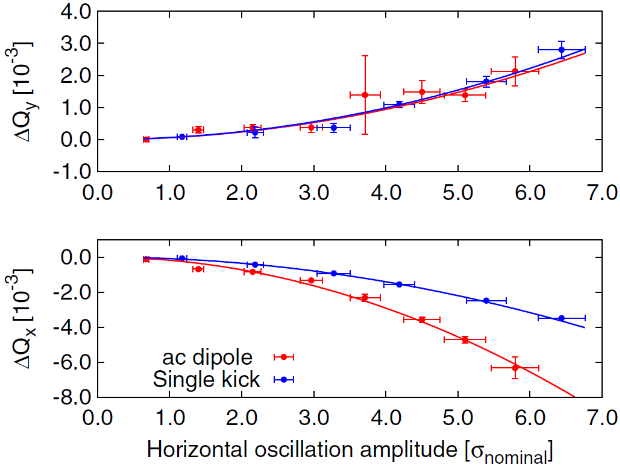
Beams blown up in only H or V give information on shape of DA

- Simulated DA shows clear asymmetry between H and V planes
- Replicated in observed losses for bunches blown up in only 1-plane





DA looks like effective tool to study NL-errors at $6.5\,\mathrm{TeV}$
$\longrightarrow$ experience at injection shows benefit of multiple observables

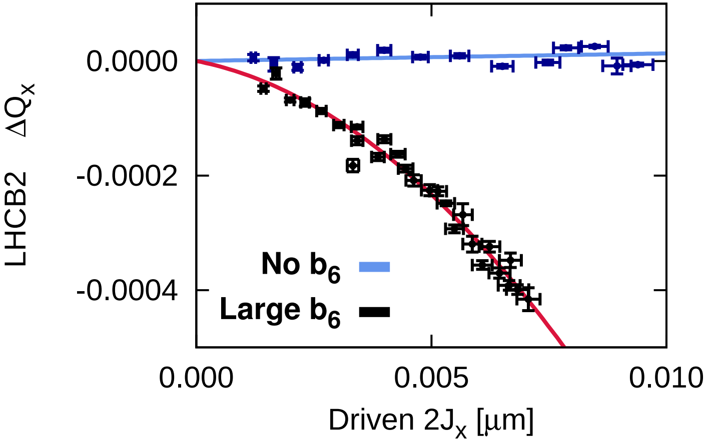


- **Well defined and understood relation between detuning of free & driven betatron oscillations validated at injection**

S. White, R. Tomás, E.H. Maclean Phys.Rev.ST.AB,**16**,071002(2013)

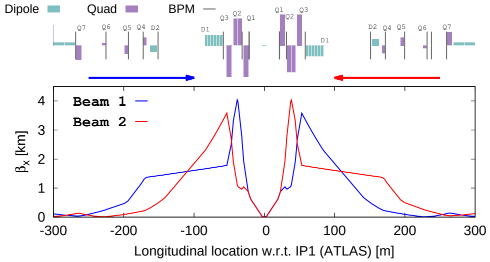
Measure second-order detuning ($\propto J^2$) and feed-down to first-order detuning ($\propto J$) to study decapole/dodecapole errors

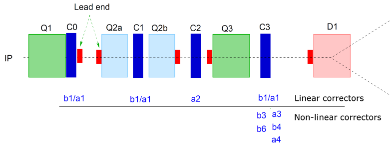
CERN-ACC-NOTE-2018-0021



- Dodecapole errors too small to measure in LHC
- Measurements from deliberately introduced b_6 agree with model

Traditionally LHC commissioning only concerned with linear optics





- Decapole errors are too small to measure in LHC and no correction has been implemented
- As β^* has been reduced sextupole & octupole errors in ATLAS & CMS IRs have become relevant to operation

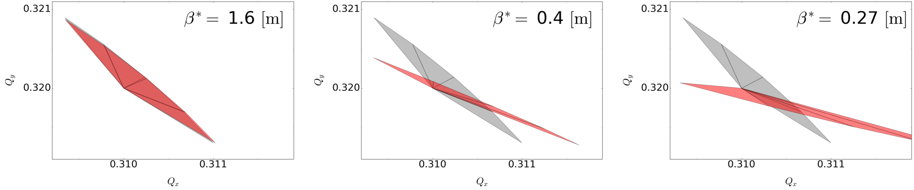
First combined linear and nonlinear optics commissioning of the LHC was performed in 2017

A new activity for the OMC team...

Very large octupole errors identified via amplitude detuning measurements with the AC-dipole

IR-octupole errors distort tune footprint during β^*-squeeze

Desired MO footprint, Obtained footprint

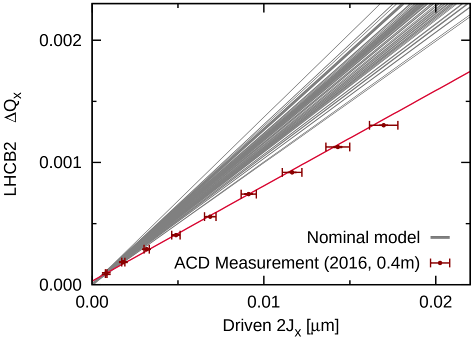


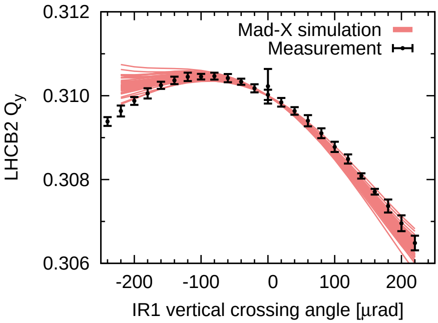
Potential for loss of Landau damping during β^* squeeze if IR-b_4 is not corrected

Design strategy would base corrections on magnetic-measurement

$\rightarrow$ Find significant discrepancies with beam-based measurements

First measurement and correction of nonlinear errors in the experimental insertions of the CERN Large Hadron Collider
PRSTAB 18, 121002

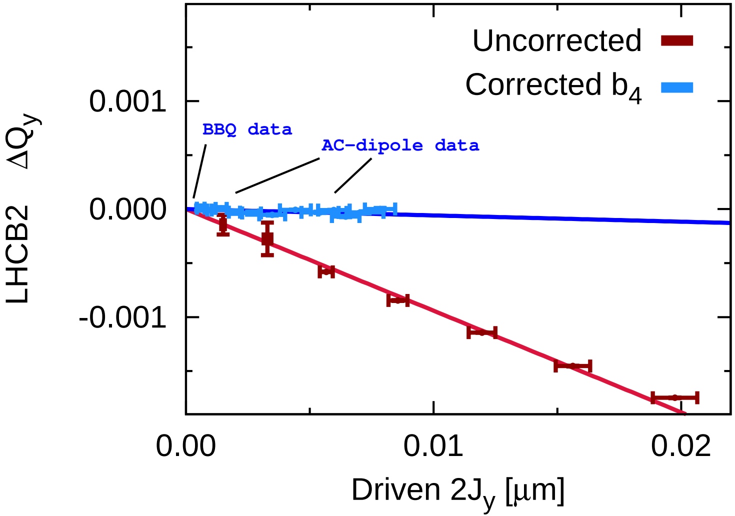




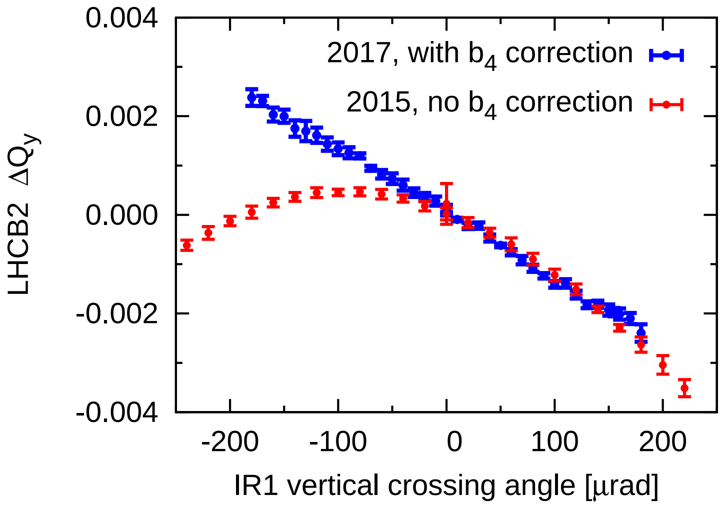
Octupole feed-down agrees with magnetic model of IR1, but not IR5

- **Apply model-based correction to IR1 & minimize remaining detuning via correctors in IR5**

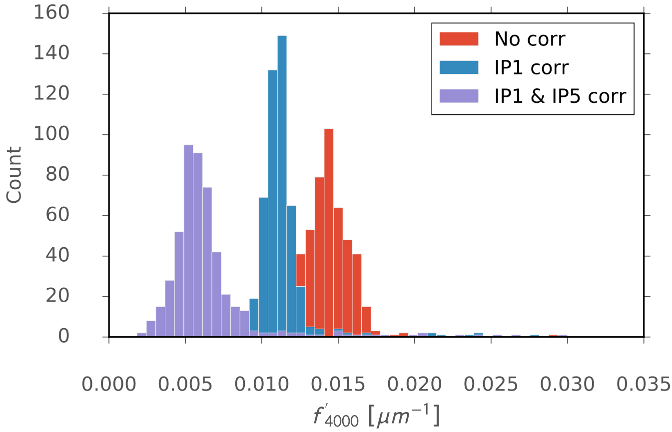
Corrected amplitude-detuning



Corrected feed-down to tune



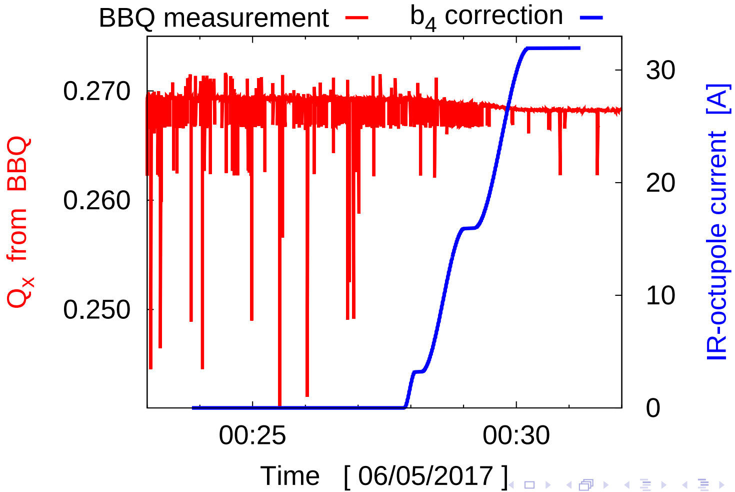
Reduced strength of $4Q_x$ resonance



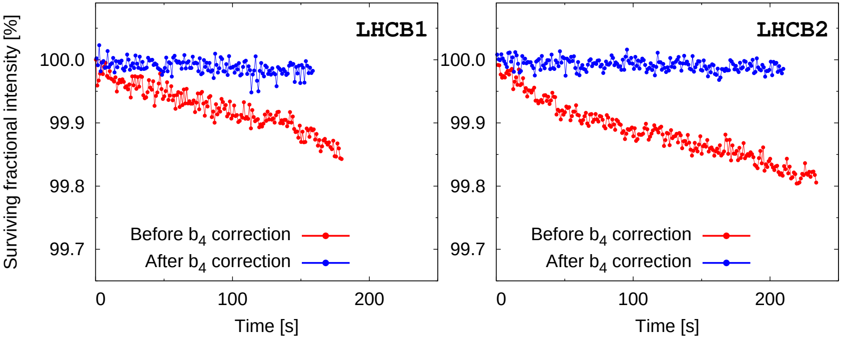
Clear improvement to online tune measurement upon IR-octupole correction:

→ **Mandatory to obtain good K-mod at 30cm!**

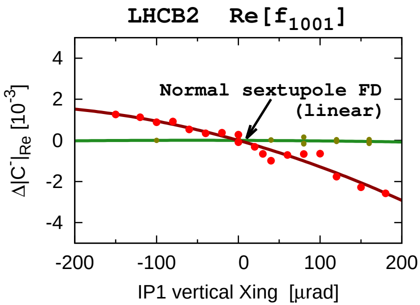
→ **Successful linear commissioning relies on nonlinear corrections!**

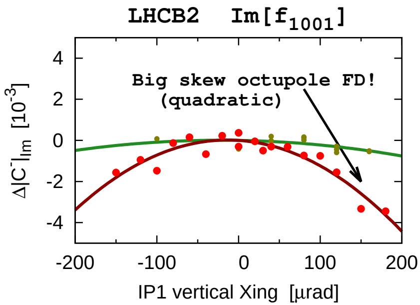


- **No obvious impact on lifetime at $0.4\,\mathrm{m}$**
- **Clear improvement to lifetime at $0.14\,\mathrm{m}$ during dedicated machine tests**



Sextupole & skew octupole corrections reduce feed-down to linear coupling in as a function of crossing-angle

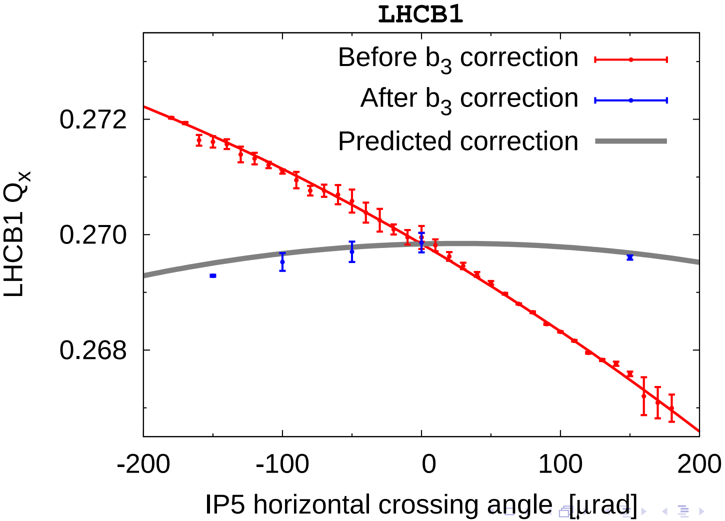




Without correction crossing angle luminosity levelling could lead to loss of Landau damping

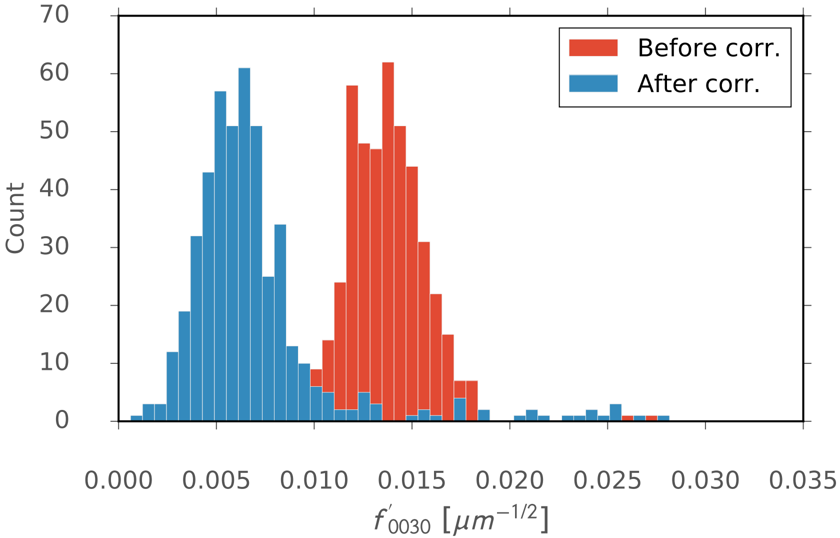
Sextupole corrections applied to minimize feed-down to Q

- Due to orientation of crossing-angle planes performed with skew sextupole in IR1 & normal sextupole in IR5

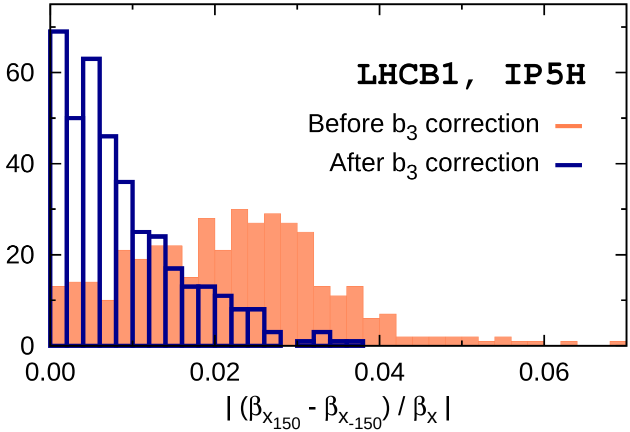


Corrected feed-down to tune in IR1 and IR5

$\rightarrow$ reduced strength of $3Q_y$ resonance



Corrected feed-down to tune in IR1 and IR5
$\rightarrow$ Improved stability of linear optics vs X'ing scheme



- contribution of nonlinear errors to linear optics quality never previously considered in LHC commissioning


Is it worth all the night shifts?

Linear optics in LHC is very well controlled

Has a well developed program to perform beam-based study of the nonlinear optics

- Identify and improve upon any limitations of our understanding of the single-particle beam-dynamics in the LHC
- Develop / refine measurement techniques, with particular emphasis on study at high-energy for LHC/HL-LHC
- Use broad range of beam-based observables to ensure best optics corrections

Inclusion of nonlinear optics corrections into regular LHC commissioning has been of significant benefit to operation

Many thanks for your attention!