Optics correction in HL-LHC:
Experience and implications from the LHC

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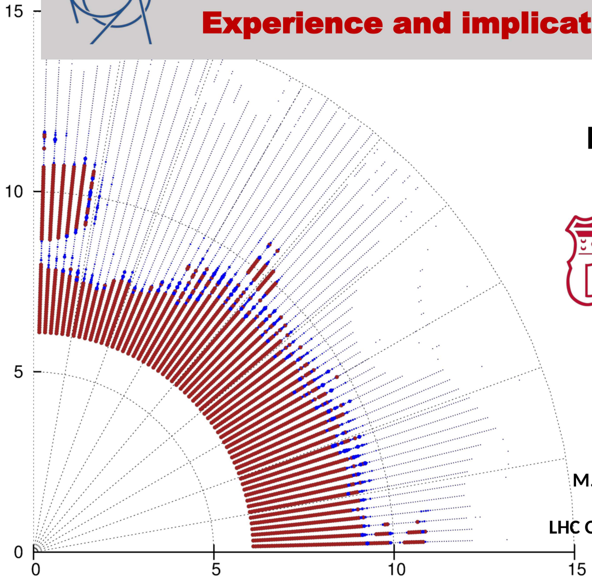
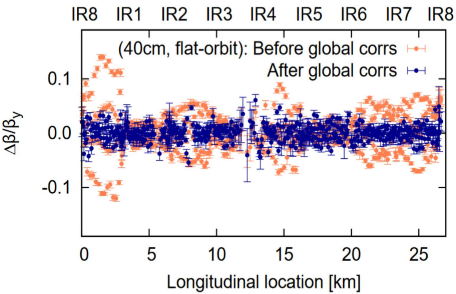


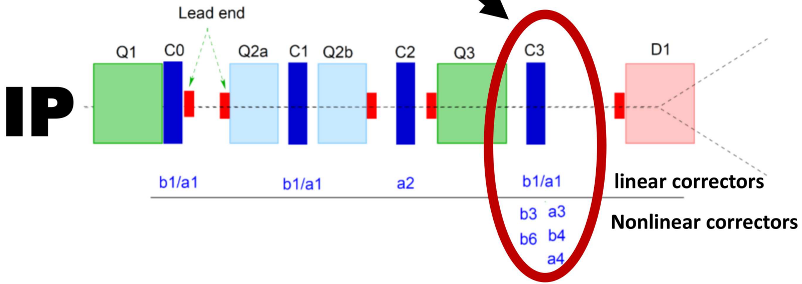
**With particular thanks to
M. Giovannozzi, X. Buffat, N. Karastathis,
R. Tomas and the
LHC Optics Measurement and Correction Team**

LHC commissioning has traditionally focused on linear optics

Reduction in β^* means nonlinear errors in experimental IRs can also significantly perturb the beam

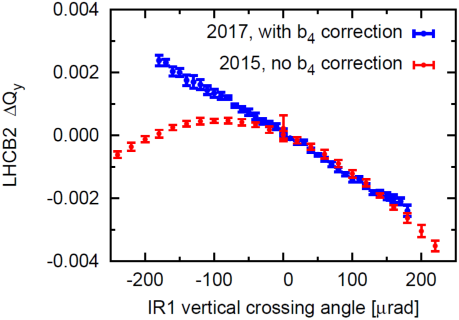


Dedicated nonlinear correctors left and right of the experimental IRs (similar to HL-LHC)



Before 2017 these nonlinear correctors were never used

➢ **Since 2017 we have incorporated beam-based correction of nonlinear optics into the LHC commissioning strategy**



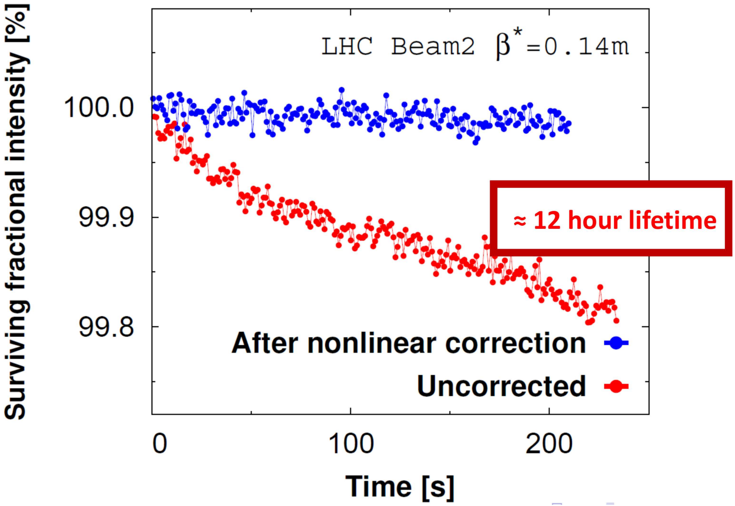
- **Measure a variety of beam-based observables for nonlinear optics**
- **Determine normal/skew sextupole and normal/skew octupole corrections in low-β* IR**
- **Led to operational improvements in the LHC**

Important experience for HL-LHC: we will squeeze to even lower β* and similar correction scheme is planned

What did we learn relevant to HL-LHC?

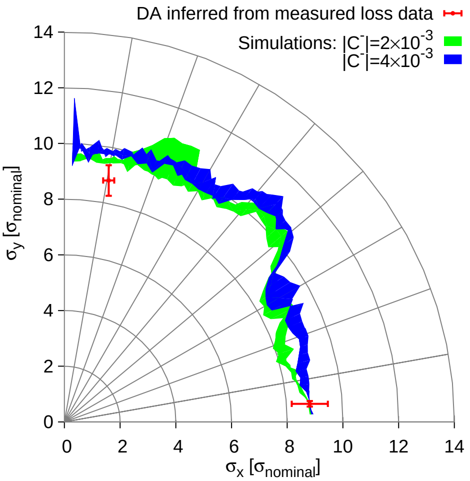
Concern over reduction of lifetime & dynamic aperture from nonlinear errors in low-β IRs should be taken seriously

Observed pronounced effect of IR-nonlinear corrections on lifetime of non-colliding pilot during tests of $\beta^* = 0.14\,\mathrm{m}$ optics



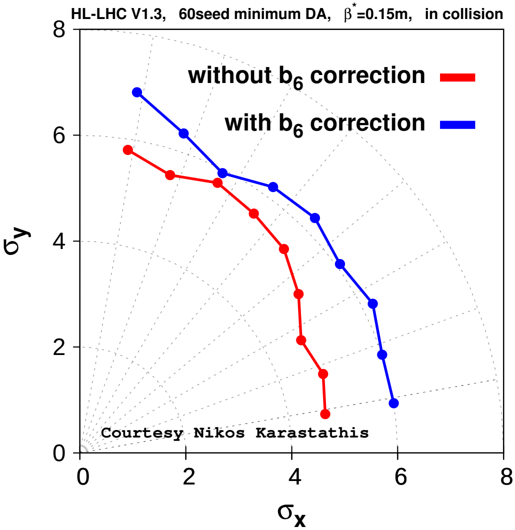
Multiple studies demonstrate good agreement between simulated and measured dynamic aperture

- **observe agreement at level of ≈ 10 % using different techniques & over different machine configurations,** e.g. injection in 2012:



Multiple simulation studies indicate non-correction of nonlinear errors in low-β IRs is a problem for dynamic aperture

- **LHC experience motivates a target DA $\geq 6\,\sigma$ in HL-LHC**

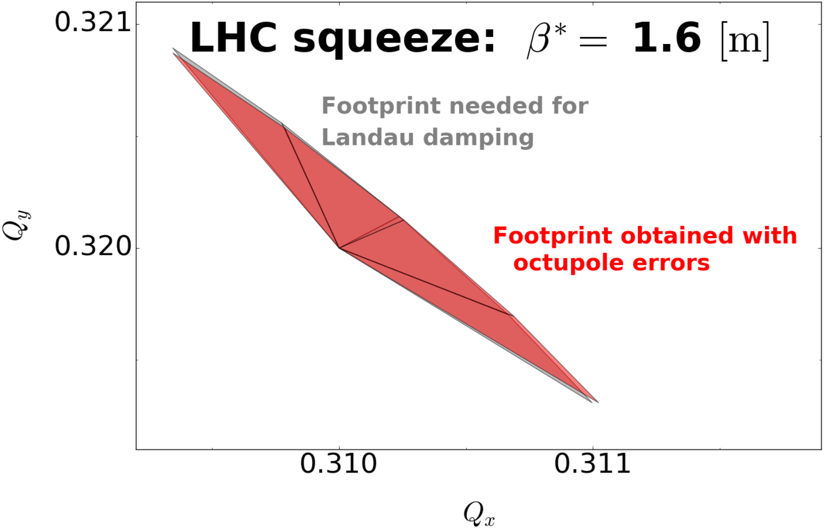


Even dodecapole errors must be corrected if HL-LHC is to reach its desired performance

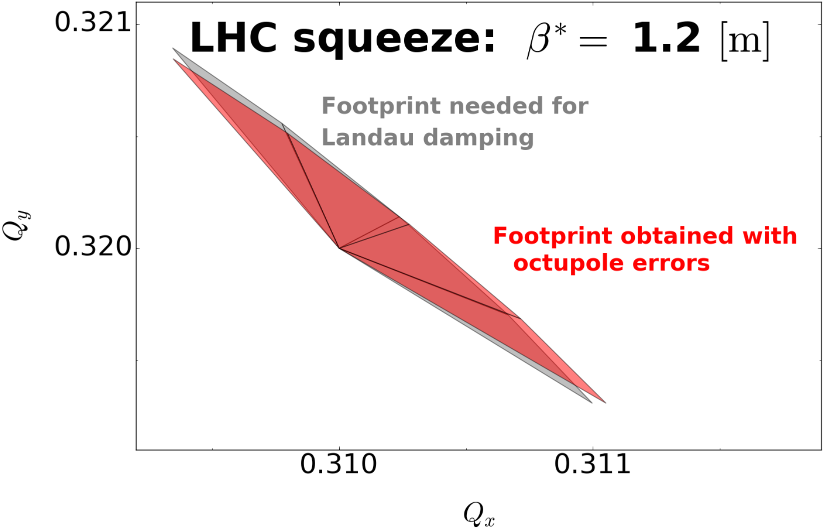
Strong nonlinear errors in the IRs are detrimental to much more than just dynamic aperture

- **Also detrimental to instabilities**

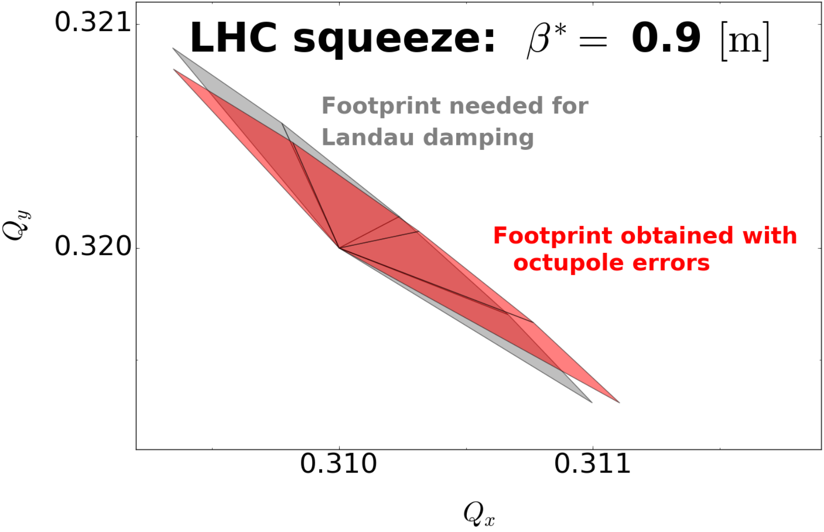
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze



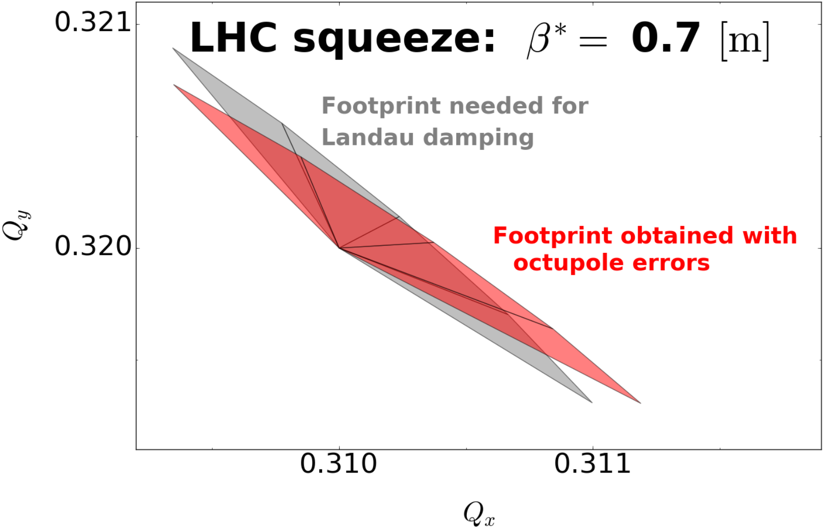
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze



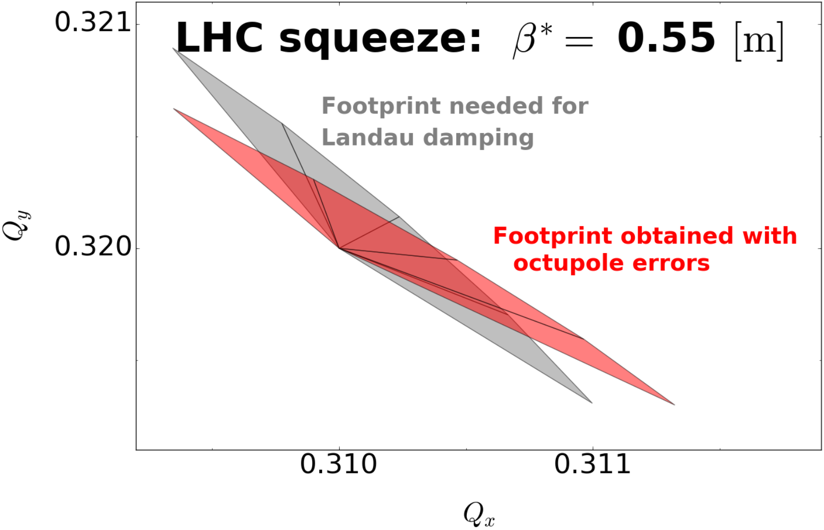
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze



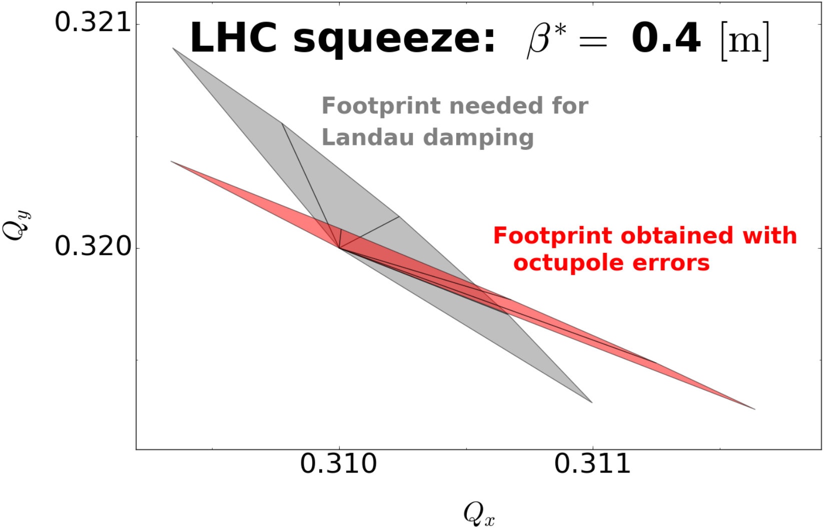
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze



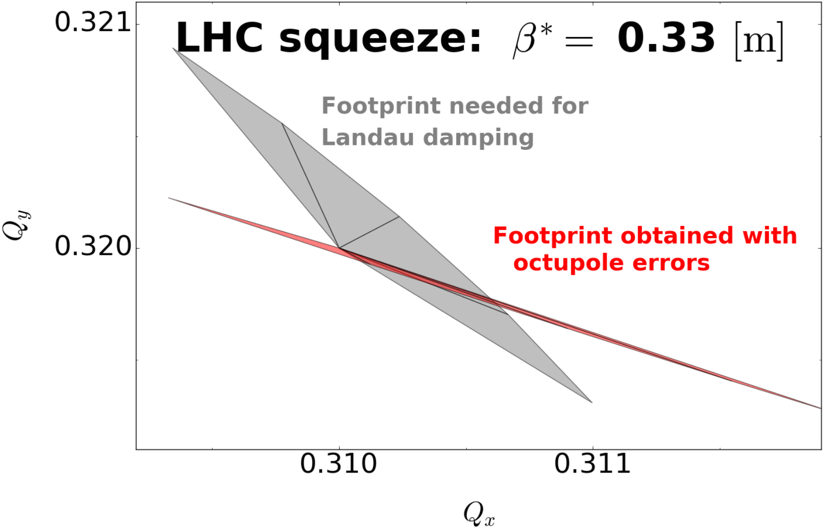
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze



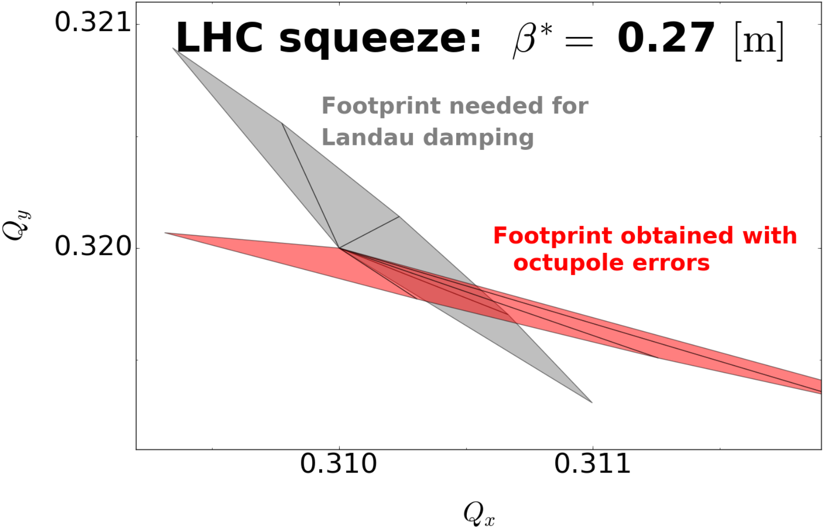
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze



Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze



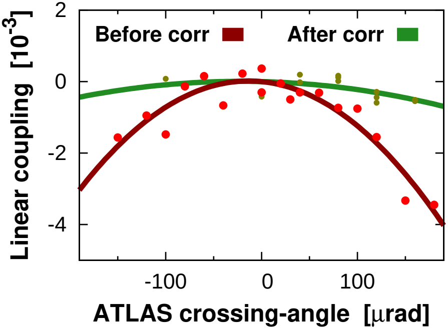
Octupole errors in IRs cause dramatic distortion of tune footprint during the squeeze

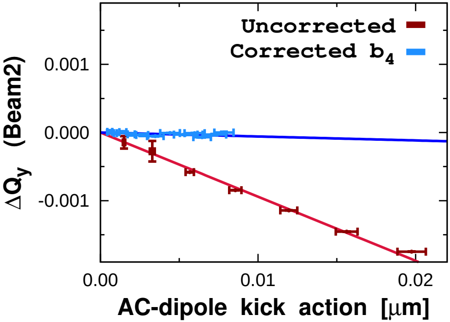


Tune footprint distortion can be detrimental to Landau damping

→ Not just normal octupole errors! Landau damping is also critically dependent on transverse coupling

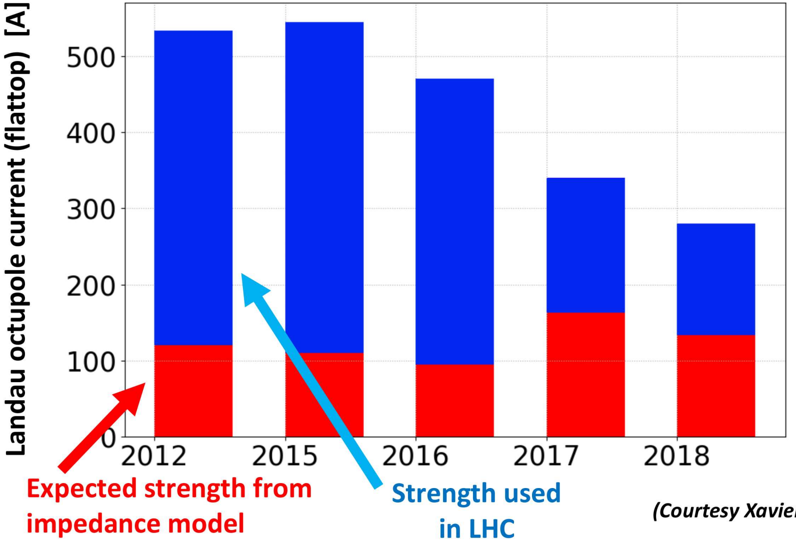
→ Skew octupole & normal/skew sextupole can distort footprint too!





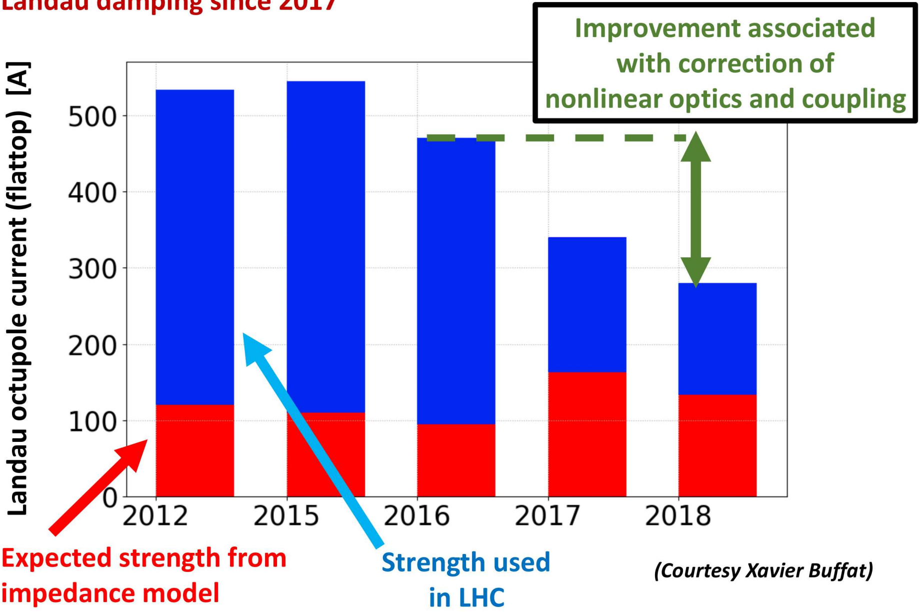
We have demonstrated in LHC that we can measure and correct nonlinear errors up to octupole order with beam

Significant reduction in Landau octupole strength required to maintain Landau damping since 2017

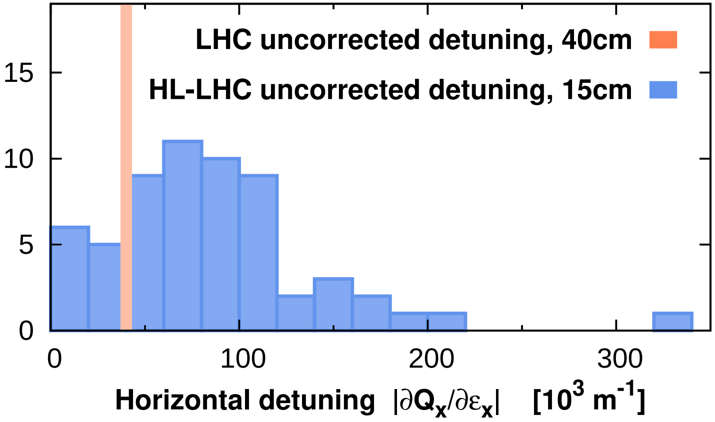


(Courtesy Xavier Buffat)

Significant reduction in Landau octupole strength required to maintain Landau damping since 2017



Any non-correction of the nonlinear optics will eat into the margins available for Landau damping in HL-LHC



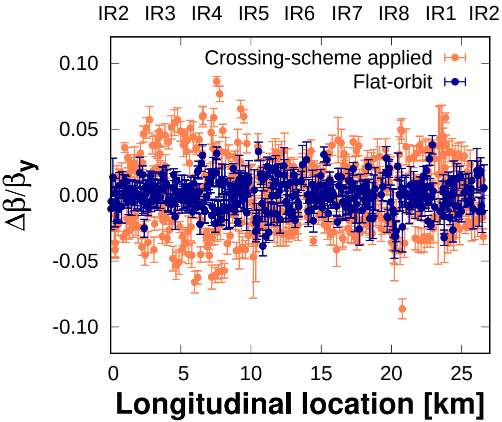
- implications for non-colliding bunches at end-of-squeeze
- implications for required tele-index during squeeze

Strong nonlinear errors in the IRs are detrimental to much more than just dynamic aperture

- **Detrimental to linear optics**
- **Detrimental to our ability to measure linear optics**

Before 2017 all optics commissioning of LHC was performed at flat-orbit

$\rightarrow$ **nonlinear errors generate β-beating when crossing-scheme applied**



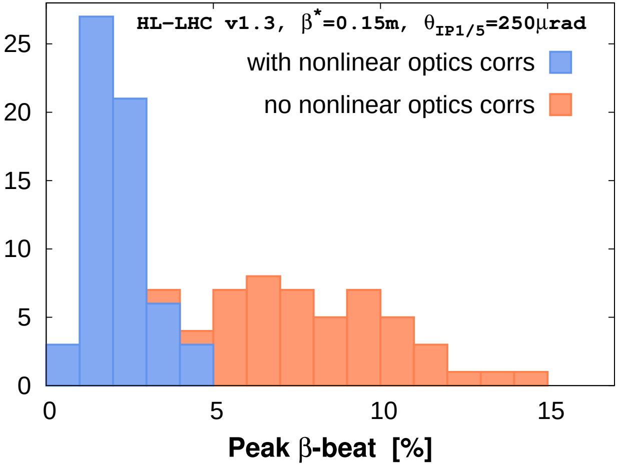
2.5 % luminosity imbalance from uncorrected nonlinear errors in LHC at $\beta^* = 0.4\,\mathrm{m}$

- **Sextupole correction improved optics stability vs crossing-scheme**
- **Additional iteration of linear optics to correct residual β-beating**

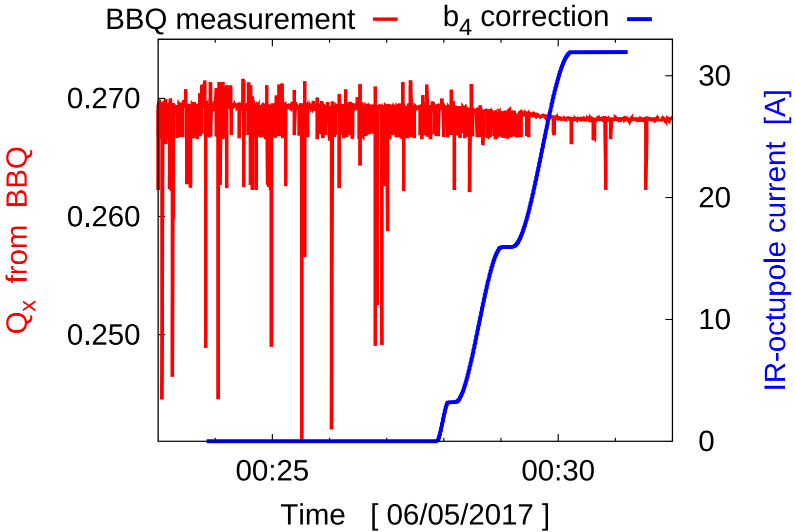
Nonlinear optics correction + linear iterations corrected β-beating to same level obtained at flat-orbit

Potential for much larger β-beating at end-of-squeeze in HL-LHC

- **in worst case β-beating from nonlinear errors gives substantial lumi-imbalance and impinges significantly on machine protection limits**
- **expect similar commissioning procedure to LHC will be mandatory**



Key instrumentation & tools we use to measure linear optics are deteriorated by strong nonlinear errors



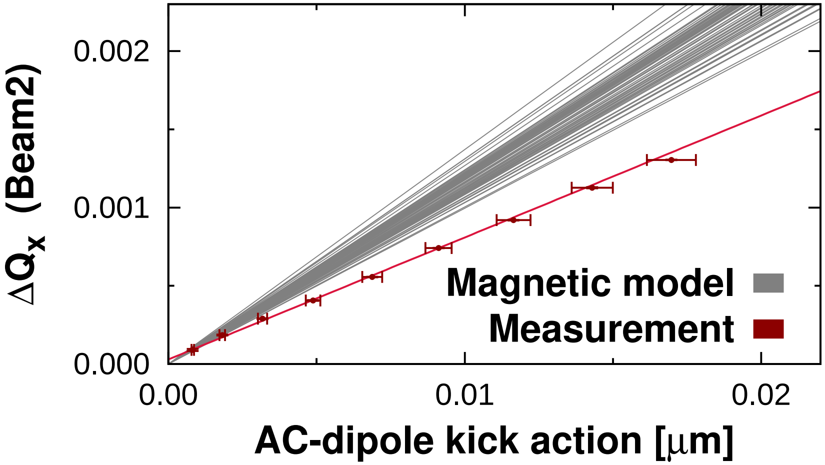
At low-β^* the success of linear optics commissioning is contingent on the correction of nonlinear errors in the IRs

- **Commissioning of the linear and nonlinear optics cannot be considered independently**
- **A combined approach is necessary**

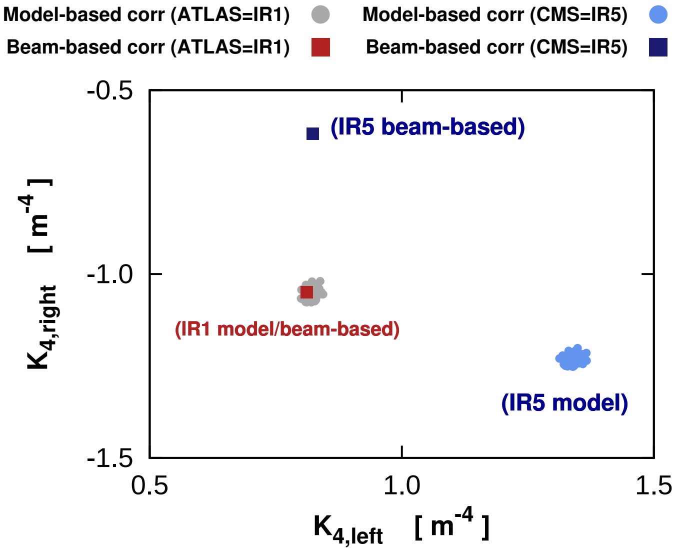
A first iteration of the nonlinear corrections needs to be available from DAY 1 of low-β commissioning

Beam-based corrections determined in LHC were not consistent with the magnetic measurements

Observe significant discrepancies for several beam-based observables between predictions of magnetic model and LHC measurements



Corrections determined from magnetic model did not agree with those needed to optimize LHC observables → reason is under investigation



All our experience in LHC suggests high-order corrections can be critical to successful commissioning and operation of HL-LHC

- **Any rapid ramp up in performance will be contingent on having good nonlinear corrections in place early**

Baseline strategy for HL-LHC optics commissioning is all IR-nonlinear correctors powered according to magnetic measurements on DAY 1

- **We will be using and relying on the magnetic measurements from the start of commissioning**
- **It is critical we have good measurements of even the very high-order errors and good understanding of the associated uncertainties**
- **Quality assurance of the measurements and database will be essential**

We also care about alignment errors of nonlinear correctors in the experimental insertions

Misalignments of nonlinear correctors in low-β^* IRs can significantly complicate optics commissioning

- **During dedicated tests in LHC observed normal octupole correction introducing extra skew sextupole error $\approx 2\times$ larger than the bare a_3**
- **During 2017/18 LHC commissioning observed that skew octupole corrector powering changed required skew sextupole correction by 30 %**
- **Both cases compatible with $1\,\mathrm{mm}$ level corrector misalignments**

Even high-order corrector alignment is a non-negligible concern for HL-LHC

$\rightarrow$ need good measurement of corrector alignments to plan commissioning strategy

Conclusions

- **Correction of nonlinear optics errors at low-β^* will be essential for successful operation of the HL-LHC**

  $\rightarrow$ clear indications the nonlinear errors are relevant for lifetime (as expected)

  $\rightarrow$ nonlinear errors are relevant to Landau damping and linear optics

- **Demonstrated ability to measure & correct IR-errors to octupole order**

- **Success of the linear commissioning is contingent on the quality of nonlinear corrections**

  $\rightarrow$ can't consider linear and nonlinear optics commissioning independently

- **Rapid progression of HL-LHC performance will rely on nonlinear corrections calculated from the magnetic measurements**

  $\rightarrow$ Need accurate measurements of even very high-order errors

  $\rightarrow$ Quality assurance of the measurements & database will be key

- **High-order corrector alignment in the IRs can't be neglected**

  $\rightarrow$ rely on good measurements to plan commissioning strategy

A detailed review of the changes to LHC optics commissioning strategy since 2017 is available in PRAB:

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 061004 (2019)

Editors' Suggestion

New approach to LHC optics commissioning for the nonlinear era

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In 2017, optics commissioning strategy for low-β^* operation of the CERN Large Hadron Collider (LHC) underwent a major revision. This was prompted by a need to extend the scope of beam-based commissioning at high energy, beyond the exclusively linear realm considered previously, and into the nonlinear regime. It also stemmed from a recognition that, due to operation with crossing angles in the experimental insertions, the linear and nonlinear optics quality were intrinsically linked through potentially significant feed-down at these locations. Following the usual linear optics commissioning therefore, corrections for (normal and skew) sextupole and (normal and skew) octupole errors in the high-luminosity insertions were implemented. For the first time, the LHC now operates at top energy with beam-based corrections for nonlinear dynamics, and for the effect of the crossing scheme on beta-beating and dispersion. The new commissioning procedure has improved the control of various linear and nonlinear characteristics of the LHC, yielding clear operational benefits.

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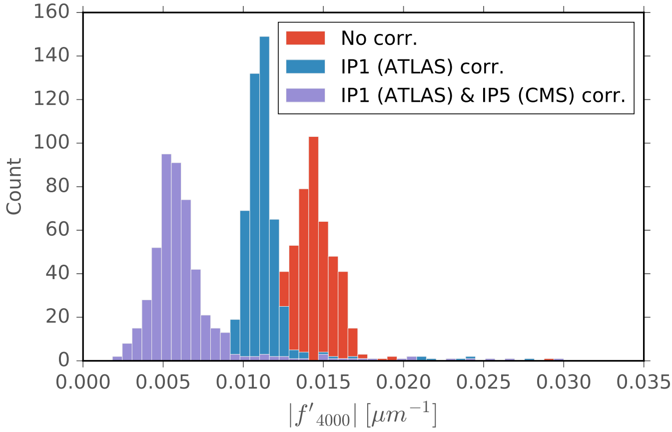
I. INTRODUCTION

Control of linear optics is a key operational concern at

collider [11,12]. In the High-Luminosity LHC (HL-LHC) [13] compensation of nonlinear errors in experimental IRs is expected to be an operational necessity [14–16], with

Reserve

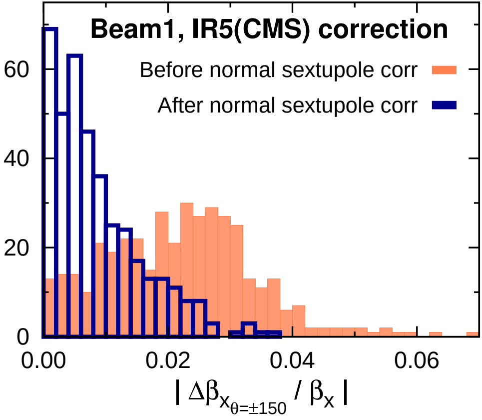
Although not directly used to determine corrections clearly saw reduction in strength of $4Q_x$, $3Q_y$ and $Q_x - Q_y$ resonances



Correction of β-beating from nonlinear errors in ATLAS/CMS IRs is now an intrinsic part of LHC commissioning strategy

→ nonlinear corrections improve optics stability vs crossing-scheme

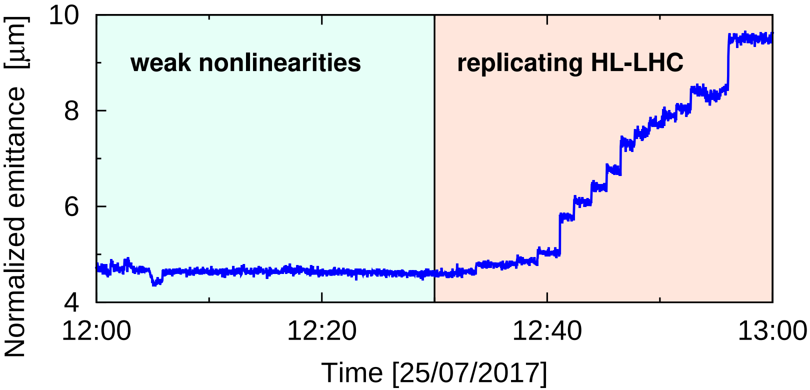
→ additional round of optics commissioning to correct any residual β-beating in operational configuration



lumi-imbalance from optics after correction:

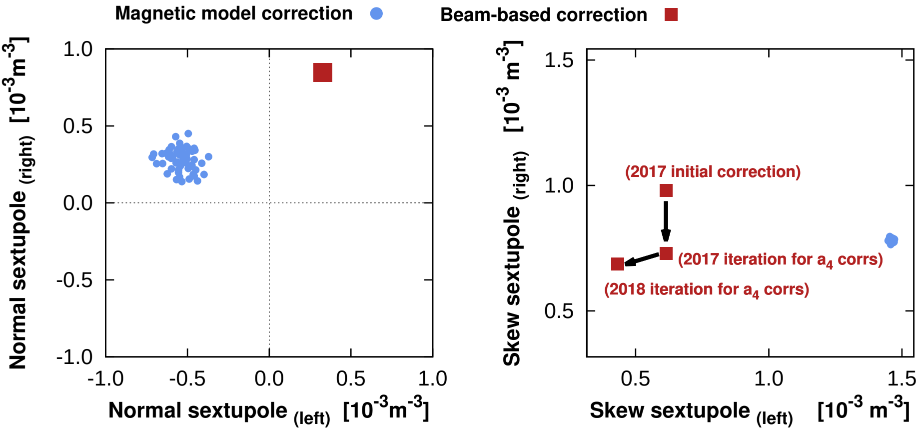
$$\frac{L_{\mathrm{CMS}}}{L_{\mathrm{ATLAS}}} = 1.003 \pm 0.004$$

Linear optics commissioning is dependent on the AC-dipole
→ but strong nonlinear errors deteriorate it's performance!

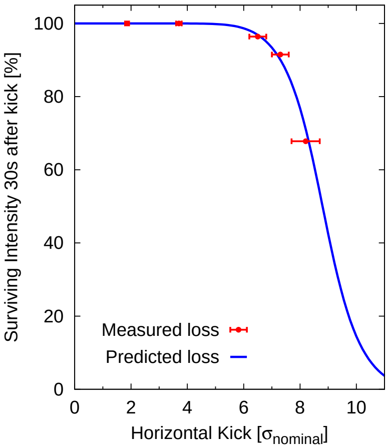


A first iteration of the nonlinear corrections needs to be available from DAY 1 of low-β commissioning

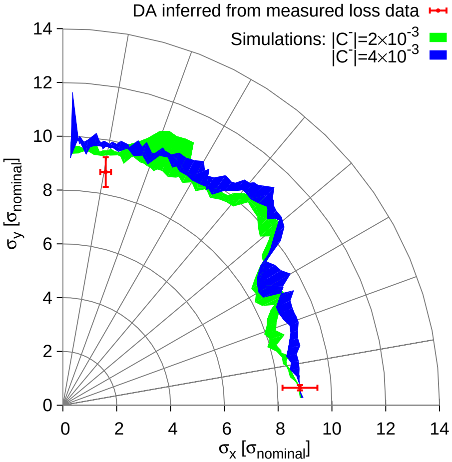
Observed discrepancies with predicted sextupole correction:



- Optimal sextupole correction depended on skew octupole powering
- Indicates 1-mm level misalignment of octupole corrector introducing additional sextupole errors



Surviving Intensity 30s after kick [%]
100
80
60
40
20
0
0
2
4
6
8
10
Horizontal Kick [σnominal]
Measured loss
Predicted loss



DA inferred from measured loss data
Simulations: |C⁻|=2×10⁻³
|C⁻|=4×10⁻³
σy [σnominal]
σx [σnominal]
0
2
4
6
8
10
12
14