The 7th Evian Workshop: Nonlinear optics commissioning in the LHC

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and the **O**ptics **M**easurement and **C**orrection (**OMC**) Team

(From talk by Mike Lamont, circa. 2011)

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Talk on behalf of the OMC "Owls"

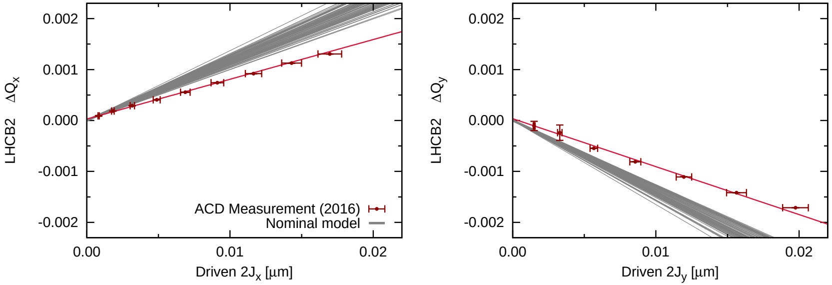
Particular thanks also go to X.Buffat, M. Giovannozzi, S. Fartoukh and R. De Maria

Why nonlinear optics commissioning???

→ impact of NL-error in experimental insertions increases for small β^*

Normal octupole (b_4)

- Normal octupole causes tune spread with particle amplitude
- Landau octupole (MO) intentionally introduce b_4 for damping of instabilities



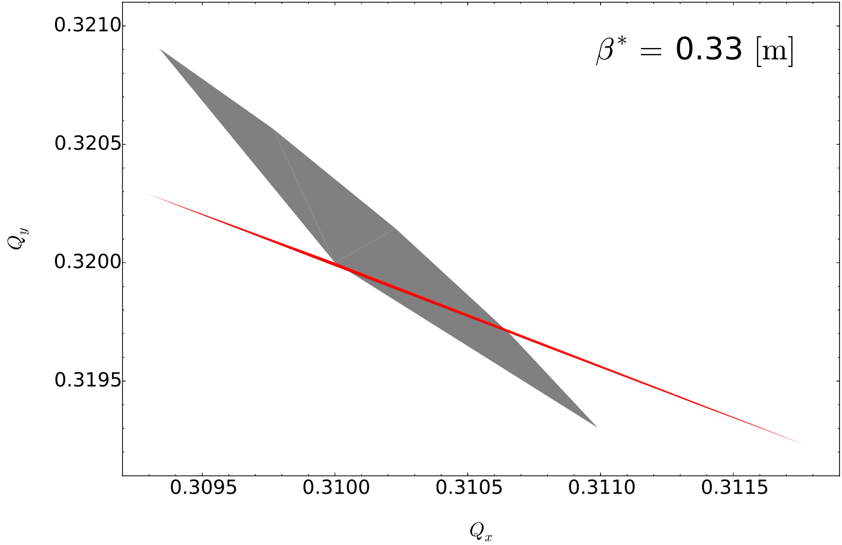
- **Measured Q-spread from IR-b_4 at 40cm $\sim \frac{1}{3}$ of that generated by MO (2016)**

Tune spread generated in experimental insertions is not a small effect!

- Since 2012 observe online BBQ $|C^-|$ cannot be trusted with strong MO
  $\rightarrow$ low-β optics is in equivalent situation even without MO
  $\rightarrow$ **Online $|C^-|$ should be ignored for $\beta^* < 80\,\mathrm{cm}$.**
- IR tune-spread may enhance or correct detuning introduced by MO
  $\rightarrow$ potential impact on Landau damping of instabilities

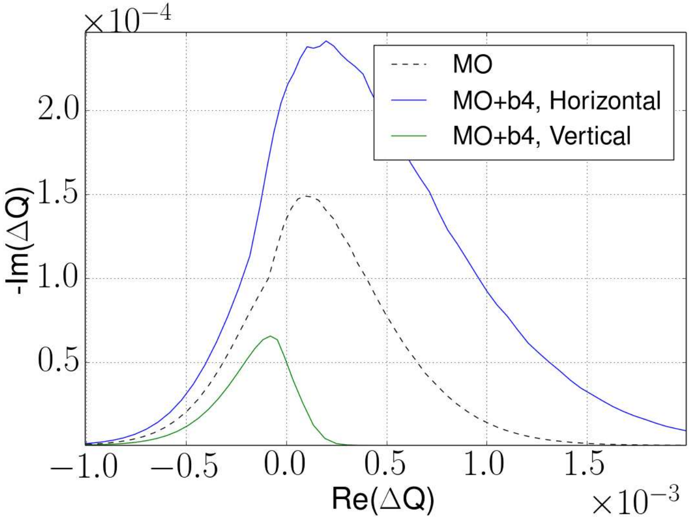
Contribution of experimental insertions depends on β^*
$\rightarrow$ **Tune footprint varies significantly during the squeeze!**
$\rightarrow$ See companion slide.

By 33cm tune spread bears little relation to intended footprint



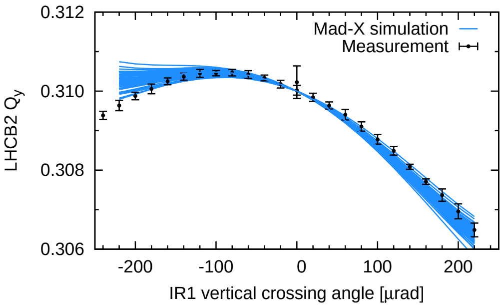
Stability diagram at $\beta^* = 33\,\mathrm{cm}$ with & without IR b_4 errors

Simulations and plot by Xavier Buffat (CERN)



Can we correct?

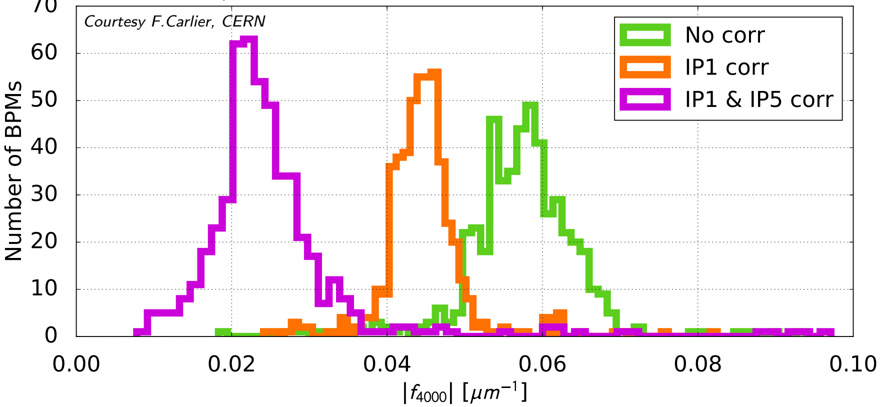
- Dedicated correctors left & right of IP allow local compensation
- Discrepancy of beam-based measurements with magnetic model
  → can't calculate correction directly from magnetic measurements
- **Want local correction per-IP**
  → challenge is separating contribution from IR1 & IR5



- 2^{nd} order feed-down to $Q_{x,y}$ in IR1 agrees with magnetic model
- 2^{nd} order FD did not agree in IR5
  → significantly smaller
- **Apply nominal IR1 correction, then minimize residual in IR5**

- **Successful correction of b_4 achieved at 40cm**
- **Validated by direct measurement of b_4 Resonance Driving Terms (RDT)**

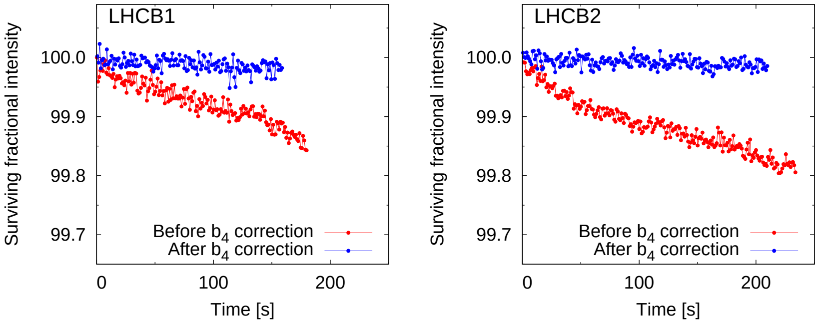
Histogram of f_{4000}, driving $4Q_x$ resonance, measured in LHC BPMs before and after local correction of b_4 in IR1 & 5.



Local corrections are independent of β^*

- IR1 correction at $40\,\mathrm{cm}$ validated at $4\,\mathrm{TeV}$, $60\,\mathrm{cm}$ in 2012
  Phys. Rev. ST Accel. Beams 18, 121002 (2015), E.H. Maclean, R. Tomás, M. Giovannozzi, T.H.B. Persson.

- Observe improvement in lifetime at $\beta^* = 14\,\mathrm{cm}$ upon applying IR b_4 correction from $40\,\mathrm{cm}$



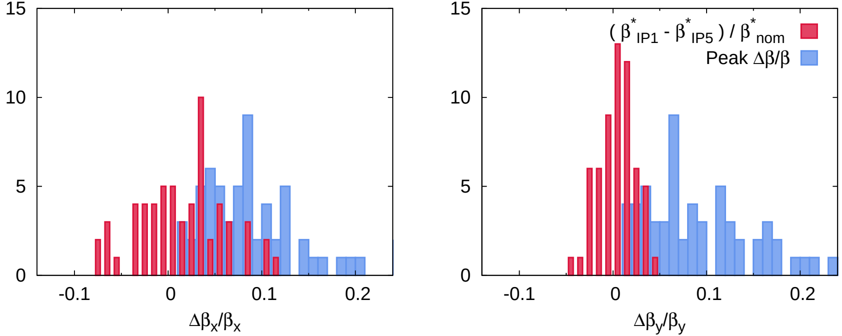
Require $\sim 1/2$ shift for re-validation of b_4 corrections in experimental insertions


HAPPY OPTICS OWLS !!!

IR - sextupole errors

- **IR-nonlinear errors in HL-LHC have a significant impact on the beam dynamics**
- **Feed-down from a_3 & b_3 with crossing scheme applied causes large perturbations to linear optics**

(β-beat in HL-LHC generated **only** *by IR sextupole errors. $\beta^* = 15$ cm, 295 μrad in IR1,5)*



- **Serious risk correction of IR-sextupole errors will be a machine protection issue in HL-LHC, certainly a concern for lumi-balance**


SAD OPTICS OWLS :-(


FOR HL-LHC WANT EXPERIENCE COMMISSIONING b_3 & a_3
ERRORS NOW, WHILE THEY ARE LESS CRITICAL

Effect on linear optics scales by $\sim \frac{4}{3}$ going from 40 cm to 30 cm:

- **β^* imbalance at 40 cm from effective model $\approx$ 1%-1.5 %**
- **β^* imbalance at 30 cm from effective model $\approx$ 1%-2%**
- **From measurement expect peak $\frac{\Delta\beta}{\beta} \approx 4\,\%$ from nonlinear errors**

- **Aim to correct $\frac{\Delta\beta}{\beta}$ & ATLAS/CMS β^*-imbalance from IR-sextupole feed-down in 2017**
- **Not large enough to be a machine protection issue**
  $\rightarrow$ Perform nonlinear optics commissioning in parallel with other tasks, after initial commissioning of linear optics with flat orbit

Correction strategy for IR sextupoles:

- Measure feed-down from nonlinear errors to tune and coupling
  $\rightarrow$ **Requires manual or automatic OFB during orbit scans**
- Where beam- & magnetic- measurements agree, implement & validate nominal corrections
- Where beam- & magnetic- measurements disagree, minimize feed-down to $Q_{x,y}$ of both beams with IR-sextupole correctors
- If unable to find a solution fall back to nominal OMC methods
  $\rightarrow$ **Commissioning with crossing angles is untested at low-β**

Nonlinear optics commissioning requires 2 shifts:

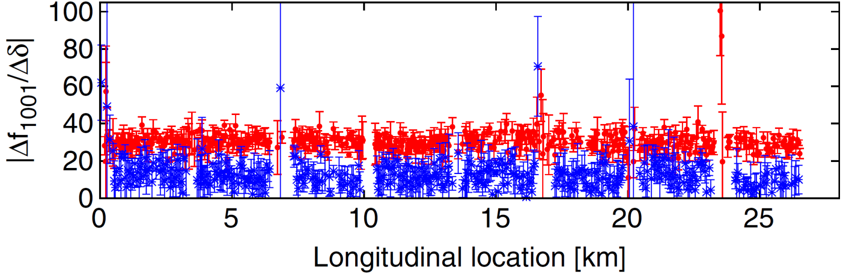
- Combined b_4 validation, and measurement of IR sextupole errors
- Implementation of IR sextupole corrections & final β^* measurement with crossing scheme applied

CHROMATIC COUPLING $\rightarrow$ Change of $|C^-|$ with $\frac{\delta p}{p}$

- Skew sextupole + horizontal dispersion
- Normal sextupole + vertical dispersion
- Measured for free when checking normalized dispersion with AC-dipole

Correction demonstrated at $4\,\mathrm{TeV}$ in 2012

Phys. Rev. ST Accel. Beams 16, 081003 (2013), T.Persson, Y.I.Levinsen, R.Tomás, E.H.Maclean.

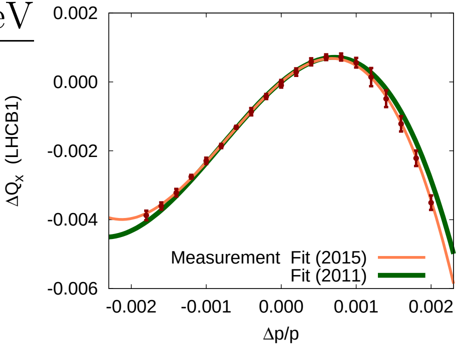


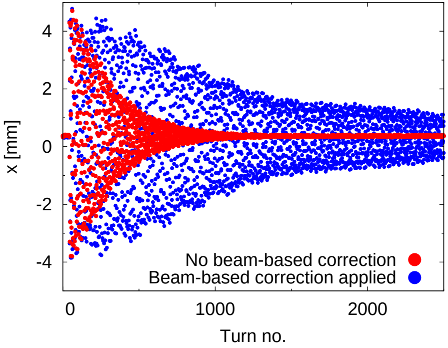
Correction commissioned in 2015, but not applied in operation

- Improved control of coupling with negligible commissioning overhead

Nonlinear optics at $450\,\mathrm{GeV}$

- **Beam-based correction of NL-chroma**
- Order-of-magnitude b_4 error ($Q''_{x,y}$)
- Factor ~ 2 error in b_5 ($Q'''_{x,y}$)
- **Errors stable over 5-year period**



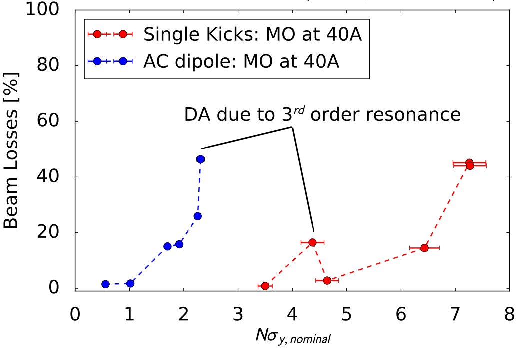


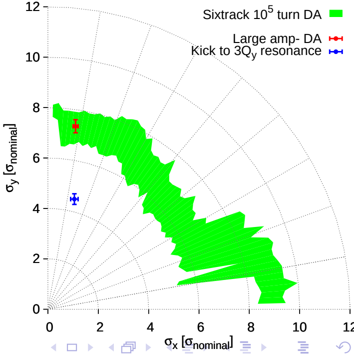
- **Minimizing NL-chroma corrects tune-spread, decoherence & DA**
- Demonstrated in Run I MD
  Phys. Rev. ST Accel. Beams **17**, 081002, E.H.Maclean et.al.
- Used operationally since start of Run II
  CERN-ACC-NOTE-2016-0013, E.H.Maclean et. al.

Dynamic aperture at injection reduced by 40A MO in 2016

- **2012** $\rightarrow$ limited by 3rd order resonance at $\sim 9\,\sigma_{\rm nom}$
- **2016** $\rightarrow$ comparatively small losses on $3Q_y$
  $\rightarrow$ MKA can kick beyond $3Q_y$ with small losses
- **Measured DA:** $\sim 4\,\sigma_{\rm nom}$ (small losses); $\sim 7\,\sigma_{\rm nom}$ (large losses)
- **SIXTRACK DA:** $\sim 7\,\sigma_{\rm nom}$ in vertical; Min $= \sim 5\,\sigma_{\rm nom}$ $(10^5\ {\rm turns})$
- Reduction of DA for driven oscillations validated.

(Courtesy F.Carlier, CERN)





Conclusions

- **Nonlinear errors in IRs are not small effects at low-β!**
- b_4 **has major impact on** Q**-spread through squeeze**

  $\longrightarrow$ Corrections well validated in 2016
- **Correction of IR sextupoles may be major concern for HL-LHC**

  $\longrightarrow$ Need commissioning experience now, while less critical
- **Anticipate** $1\,\% - 2\,\%$ β^* **imbalance from IR-sextupole in LHC**

2 shifts required for commissioning of nonlinear optics


RB.A12 [5890 A] [3.48 TeV]