Measurement of nonlinear errors in experimental insertions

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Many thanks to the Optics Measurement and Corrections team and M. Giovannozzi

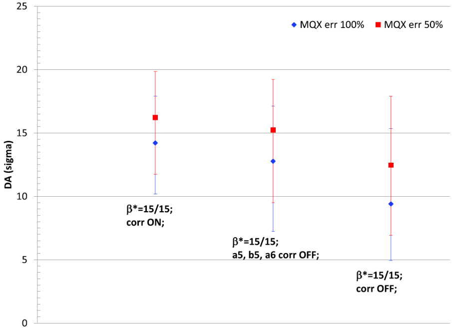
CERN

NL-errors in experimental IRs significantly impact dynamic aperture

- 3-4 σ effect @ 40 cm
- $\sim 5\,\sigma$ effect for HL-LHC
- Dedicated correctors provided in IRs:

  a_3, b_3, a_4, b_4, b_6 in LHC

  $+\ a_5$, b_5, a_6 in HL-LHC



M.Giovannozzi et. al. CERN-ACC-2013-0168

Optimal corrections calculated locally from magnetic model:

- Minimization of selected RDTs over IR

  O.Bruning, S.Fartoukh, M.Giovannozzi, T.Risselada. LHC Project Note 349

- Minimization of transfer map coefficients left and right of IP

  R.Tomás, M.Giovannozzi, R.de Maria. PRSTAB,12,011002(2009)

Requires an accurate magnetic model!

Existing method for beam-based study uses feed-down to $Q_{X,Y}$ & $|C^-|$

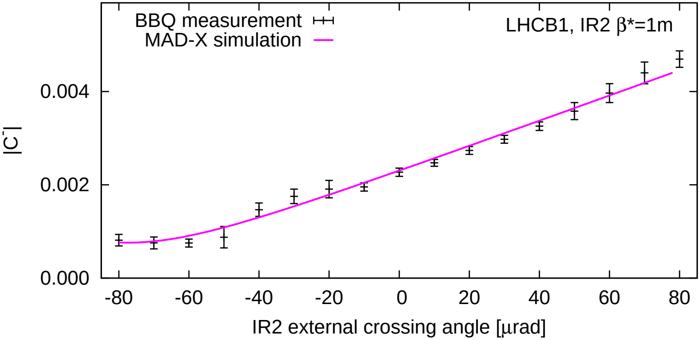
First measurement and correction of nonlinear errors in the experimental insertions of the CERN Large Hadron Collider
E.H.Maclean, R.Tomás, M.Giovannozzi, THB.Persson. Accepted PRSTAB

- Closed orbit bumps through IR varied
- BBQ measurements compared to MAD predictions

Feed-down order	1^{st} order		2^{nd} order		3^{rd} order		4^{th} order	
Multipole	$\mathbf{b}_3$	$\mathbf{a}_3$	$\mathbf{b}_4$	$\mathbf{a}_4$	$\mathbf{b}_5$	$\mathbf{a}_5$	$\mathbf{b}_6$	...
Horizontal displacement	ΔQ	ΔC	ΔQ	ΔC	ΔQ	ΔC	ΔQ	...
Vertical displacement	ΔC	ΔQ	ΔQ	ΔC	ΔC	ΔQ	ΔQ	...

- This method has been used in MD during Run 1 & 2015 MD2

- **Validated several aspects of the magnetic model in 2012:**



- b_3 **components in IR2 at** $3.5\,\mathrm{TeV}$ **in 2011**

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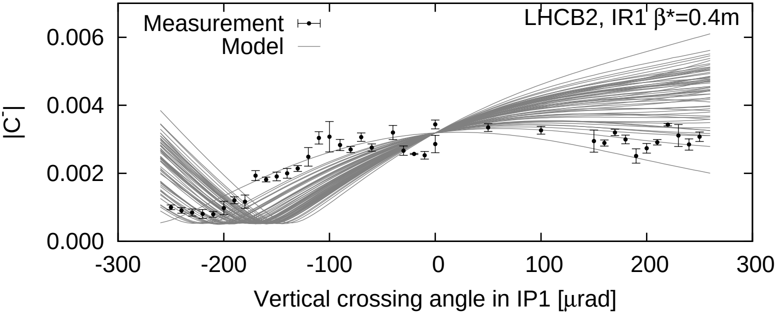
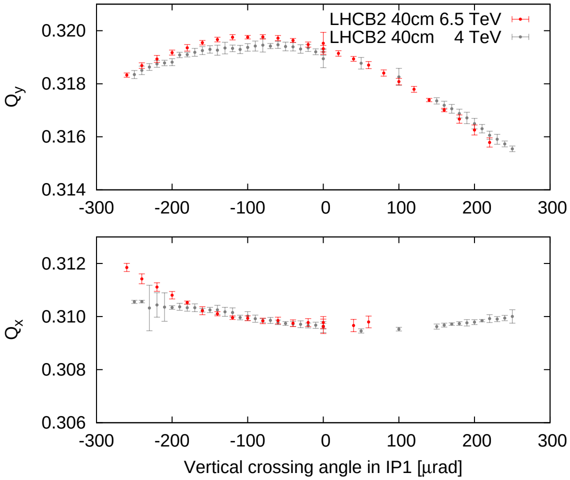


- b_3 **&** a_4 **components in IR1 at** $4\,\mathrm{TeV}$ **in 2012**

- 2 crossing angle scans performed in 2015, $\approx 1\,\mathrm{hour}$ total beam time

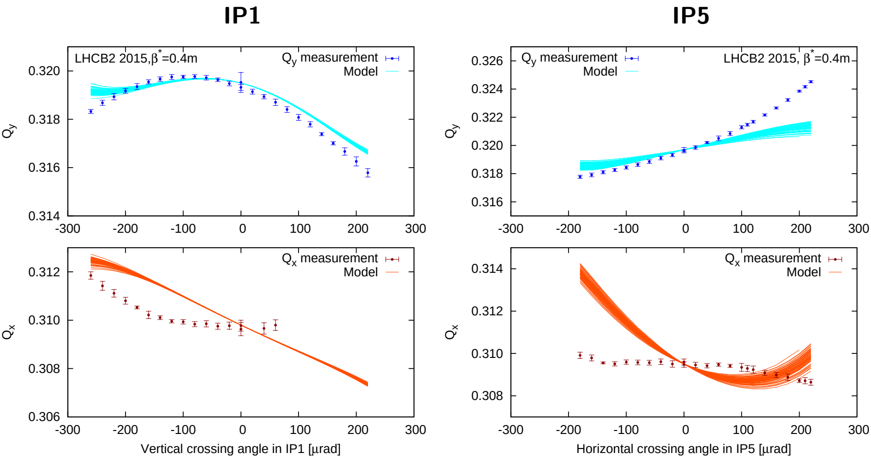
  Measurements performed by E.H.Maclean, R. Tomás and P. Skowronski

- IP1-V, IP5-H, but no useful coupling data from BBQ



- Show comparable errors with $4\,\mathrm{TeV}$ measurements

- **Feed-down scans in IR1 & IR5 show large discrepancies in 2012 & 2015**
- **IR1:** a_3 + higher orders (b_4? a_5? b_6?)
- **IR5:** $b_3 + b_4$ + higher orders (b_5? b_6?)
- Feed-down to $|C^-|$ never measured for IR5



- **Cannot rely only on magnetic measurements for NL corrections**

- Many observed discrepancies give smaller feed-down than predictions, **but...**

  $\rightarrow$ Doesn't imply smaller errors $\rightarrow$ could be cancellations

  $\rightarrow$ minimizing feed-down doesn't necessarily correct RDTs or DA

- **Require beam-based methods to understand errors**

  $\rightarrow$ large number of possible combinations of sources

  $\rightarrow$ difficult to measure high order multipoles

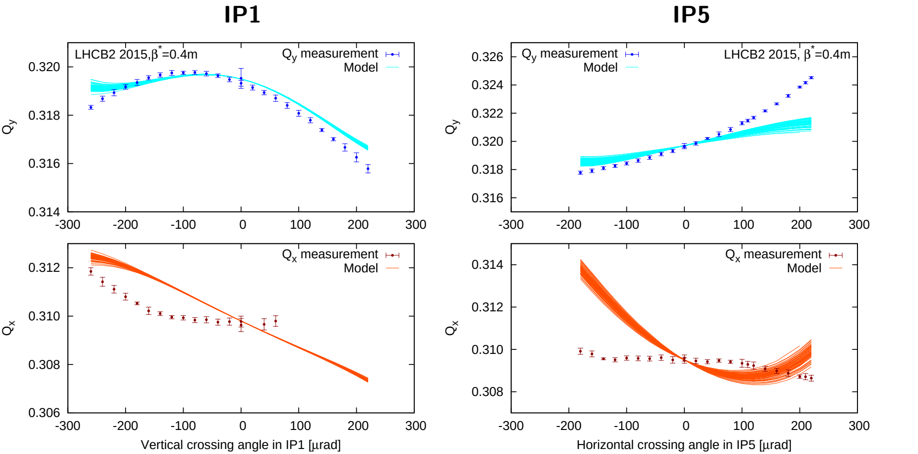
- **Basic 'feed-down with BBQ' type measurements faces a number of limitations in determining the sources**

  $\rightarrow$ AC-dipole measurements improve reliability of $Q_{x,y}$ & $|C^-|$ measurements, may give local information

  $\rightarrow$ combination with additional observables

Combining amplitude detuning and feed-down

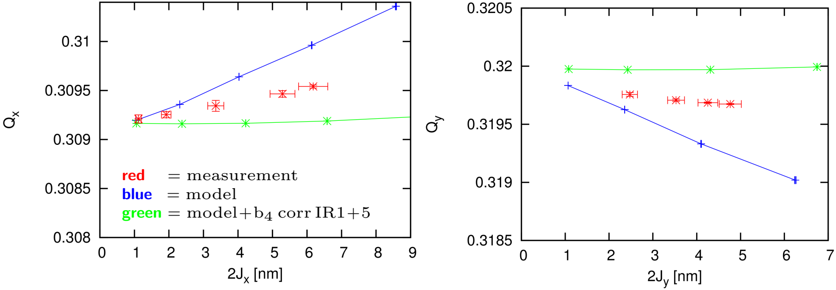
- IR5: shows small octupole feed-down wrt model (quadratic change of tune with X'ing angle)
- IR1: quadratic variation of Q_y with X'ing angle agrees with model
- IR1: feed-down to Q_x indicates some combination of b_4, a_5, or b_6



Combining amplitude detuning and feed-down

- Detuning dominated by IR1&5, expect ∼equal contributions
- Don't expect cancelling sources of b_4 feed-down to also cancel amp-det'
- Method for amplitude detuning via AC-dipole developed in Run 1

  S.White, R.Tomás, E.H.Maclean. PRSTAB,16,071002(2013)
- Amplitude detuning was measured @ 6.5 TeV in 40 cm commissioning MD

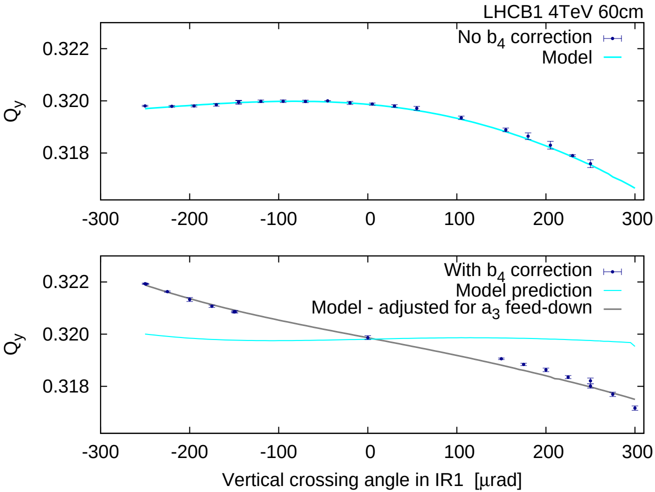


Amplitude detuning measurements by A.Langner, comparison to simulation by S.Monig

- **Fairly confident of ∼ nominal b_4 errors in IR1, with ∼ 0 in IR5**

Knowing errors still doesn't guarantee ability to correct...

- IR1 b_4 correction @ $4\,\mathrm{TeV}$, $60\,\mathrm{cm}$ worked for LHCB2
- **but generated large feed-down to** a_3 in LHCB1 only
- **can't be compensated with common local correctors**



What about b_6?

- **Feed-down + 2nd order detuning**

  $\longrightarrow$ small tune shifts

- **Long term DA** M.Giovannozzi PRSTAB,15,024001(2012)

  $\longrightarrow$ Beams blown up with ADT, DA studied for various b_6 corrector settings
  $\longrightarrow$ but what is being corrected? (Single IP squeeze?)

- **AC-dipole: RDTs & short term dynamic aperture**

  $\longrightarrow$ Difficult lines to observe (use working point to enhance resonances)

  $\longrightarrow$ DA measurement with AC-dipole is a very new topic

  S.Monig et. al. *Short term dynamic aperture with AC dipoles*. CERN-ACC-NOTE-2015-0027

- **Lifetime optimization in collision**

  $\longrightarrow$ Used at RHIC (4 % Lumi increase from $b_5 + b_6$) W.Fischer, IPAC'10,THPE099

  $\longrightarrow$ MD proposal by Y.Papaphilippou (https://md-coord.web.cern.ch/app/#/md_requests/449)

  $\longrightarrow$ What is being corrected?? Magnet errors? Beam-beam? MO? Lower-orders? Which IR?

None of these are quick or straightforward methods.

Conclusions

- Require beam-based method to complement magnetic measurements
- **If we can get data** feed-down studies provide data on status of nonlinear errors in experimental insertions
- Think we understand b_3 in IR2 & $b_3+a_4+b_4$ in IR1 & b_4 in IR5
- Clear discrepancies in a_3 IR1 & b_3 IR5, hints for higher orders
- a_3,a_4,a_5 in IR5 never successfully measured
- Benefits to combining feed-down studies with additional observables
- Exploring ways to overcome limitations of feed-down methods

Some reasons for optimism, but a lot of challenges.

Looking forwards to commissioning next year!