Nonlinear puzzles of the LHC

E.H. Maclean (University of Manchester),
on behalf of the CERN OMC team and collaborators

Several beam-based nonlinear dynamics studies during Run 1:

- 2 MDs dedicated to study of non-linear optics at injection (July 2011, June 2012)
- 1 General OMC MD, studied variety of aspects throughout cycle (November 2012)
- Various studies performed parasitically throughout the run

General conclusion:

LHC nonlinear dynamics not particularly well understood...

...but not a critical limitation in Run 1

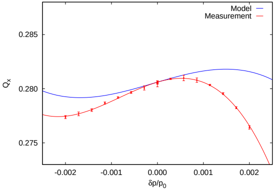
Talk will summarize measurements done + main discrepancies:

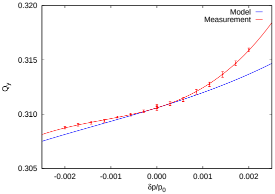
- Nonlinear dynamics @ injection
- Nonlinear dynamics @ top energy
- What are the main missing measurements?

Nonlinear dynamics at injection

First studies of NL-dynamics: nonlinear chromaticity @ injection

- Measurements performed with Landau octupoles depowered (July 2011)
  (nominal state of machine with errors + corrections, but no extra nonlinearity added)





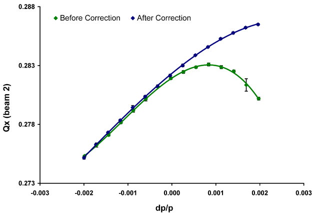
- Large second (Q'') and third (Q''') order chromaticities observed
- Order of magnitude greater than expected from model

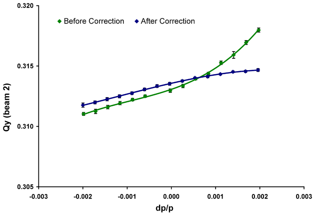
	$\Delta Q_x''$ $[10^3]$	$\Delta Q_y''$ $[10^3]$	$\Delta Q_x'''$ $[10^6]$	$\Delta Q_y'''$ $[10^6]$
measured − modelled	-1.7 ± 0.1	0.7 ± 0.1	-1.2 ± 0.1	0.6 ± 0.1
$\frac{\textit{measured} - \textit{modelled}}{\textit{measured}}$	$\sim$ 94%	$\sim$ 70%	$\sim$ 55%	$\sim$ 86%

From July 2011 to November 2012 discrepancy stable

Beam-based correction of Q'' & Q''' demonstrated (July 2011)

- Used global trims of octupolar & decapolar correctors in arcs

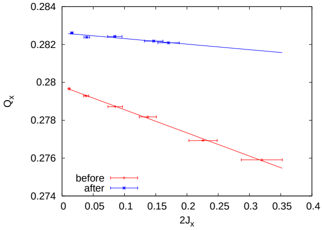


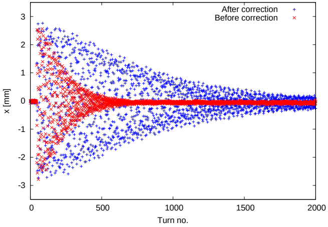


	$Q''_x\,[10^3]$	$Q''_y\,[10^3]$	$Q'''_x\,[10^6]$	$Q'''_y\,[10^6]$
Before	-2.1 (0.02)	0.74(0.03)	-1.9 (0.06)	0.8 (0.09)
After	-0.72(0.02)	-0.19(0.02)	-0.37(0.05)	-0.15(0.04)

- Corrections fairly effective at reducing $|Q''|$ and $|Q'''|$, but some residuals remain
- Q''' correction $\sim$ 25 % reduction in decapole corrector powering

Correction of the NL-chromaticity also reduced amplitude detuning and decoherence





Two possible sources of Q'' discrepancy considered:

- Feed-down from decapoles in arcs
- Hysteresis errors in octupolar correctors

Intro
Injection
Top energy
Missing Measurements
Conclusions

Shifts in Q'' & Q''' upon correction agreed well with model

	$\Delta Q_x''$ [10^3]	$\Delta Q_y''$ [10^3]	$\Delta Q_x'''$ [10^6]	$\Delta Q_y'''$ [10^6]
Measured	1.4 ± 0.03	-0.93 ± 0.04	1.5 ± 0.08	-0.97 ± 0.1
Modelled	1.3	-0.90	1.6	-0.91

- Limits contribution of feed-down from decapole correctors
- $\Delta Q'' \sim 200 \pm 150 \rightarrow$ **can make only a small contribution**

Octupole correctors in arcs have large hysteresis errors

- estimates of real octupole field included in simulation

	$\Delta Q_x''[10^3]$	$\Delta Q_y''[10^3]$	$\Delta Q_x'''[10^6]$	$\Delta Q_y'''[10^6]$
meas-mod	-1.8 ± 0.1	0.6 ± 0.1	-1.0 ± 0.1	0.70 ± 0.1
$(mod\ with\ hyst) - mod$	-0.5	0.34	$+0.006$	-0.003

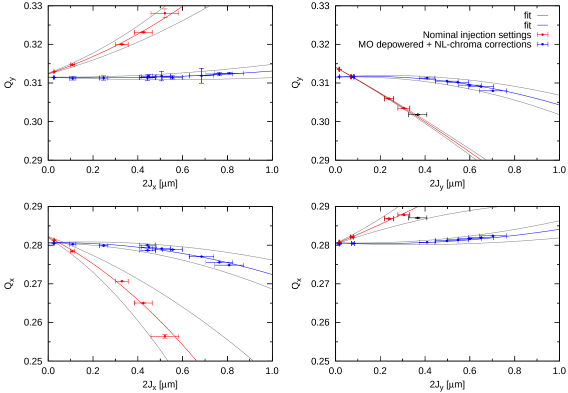
- Octupole corrector hysteresis can explain $\sim 60\,\%$ of Q_y'' and $\sim 30\,\%$ of Q_x'' discrepancies

Significant discrepancy in Q_x'' still unexplained

Large Q''' discrepancy unexplained

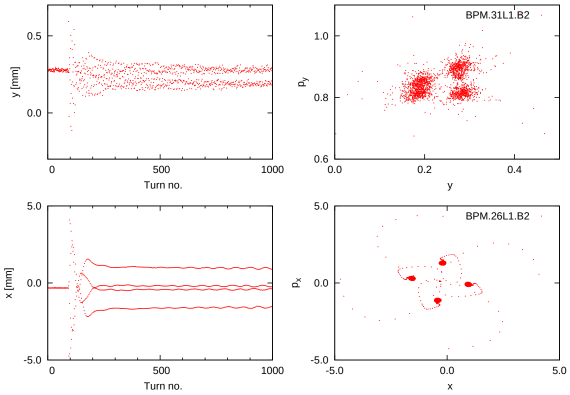
Nominal inj' optics include strongly powered Landau octupoles

- Q'' measurements show expected Landau octupole response
- Q'' & first order detuning dominated by Landau octupoles
- But discrepancy still non-negligible for nominal optics ($\sim \frac{1}{6}$ of measured value)
- Detuning measurements performed to large amplitude in 2012:



Observed large 1st & 2nd order detuning with amplitude

Simultaneous detuning onto 3rd & 4th order resonances with J_x

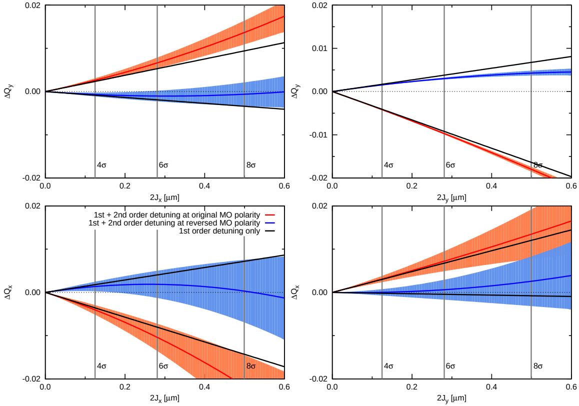


- **2nd order detuning qualitatively consistent between model & measurement**

	[unit]	Meas'	± err	Model	± err
$\frac{\partial^2 Q_x}{\partial \epsilon_x^2}$	$[10^9 \text{m}^{-2}]$	-60	30	-14	4
$\frac{\partial^2 Q_y}{\partial \epsilon_x^2}$		34	10	18	9
$\frac{\partial^2 Q_x}{\partial \epsilon_y^2}$		11	34	-10	10
$\frac{\partial^2 Q_y}{\partial \epsilon_y^2}$		-13	3	-2	5

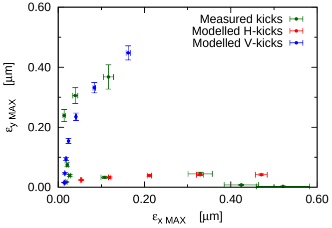
- **model underestimates the second order detuning...**

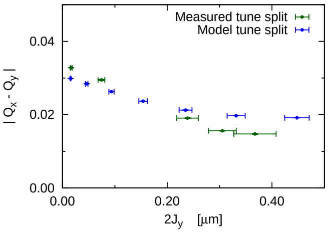
Unexplained Q'' & $\frac{\partial Q}{\partial \epsilon}$ discrepancy of bare machine + unexplained second order detuning have potential to give very different behaviour for different polarity of Landau octupoles



Large amplitude vertical kicks at nominal optics observed to couple into horizontal plane

- large vertical kicks at nominal injection optics show significant coupling into horizontal plane (left)
- Tune split decreases with vertical kick amplitude, appears to saturate at $\Delta Q \sim 0.0015$ (right)



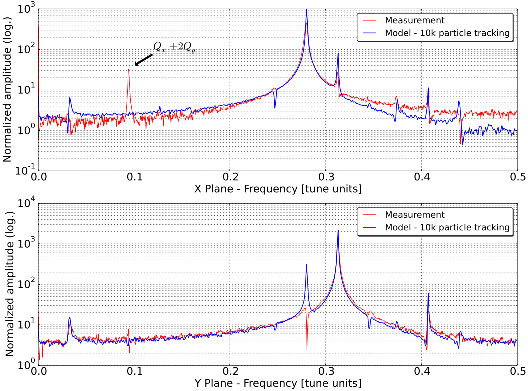


- Qualitatively reproduced in the model
- Tune split significantly larger than ΔQ_{min} from linear coupling: $|C^-| \sim 0.003$

Unexpected influence of nonlinear coupling on the beam dynamics

Unexpected octupolar resonance line observed (Studies by Felix Carlier, CERN)

- Large amplitude diagonal kicks after NL-dynamics corrections show large octupole spectral lines
- $\pm(Q_x + 2Q_y) \sim \mp 0.1$ corresponding to f_{1102} & f_{2020}



- **Spectral line doesn't appear in model**

  (Non-linear model with matching of detuning with amplitude & NL-chromaticity)

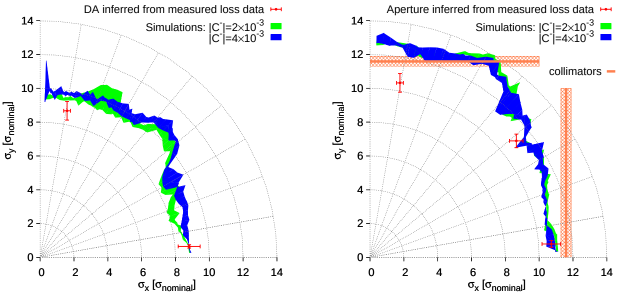
Several possible sources have been excluded:

- **Geometrical BPM nonlinearity:**
  $\longrightarrow$ Varying terms in BPM nonlinearity could not compensate resonance without significantly distorting spectrum
  $\longrightarrow$ Revised corrections for Run 2 did not eliminate spectral line
- **'Surviving line':**
  $\longrightarrow$ Certain actions & detuning with amplitude may give small decoherence of specific frequencies
  $\longrightarrow$ Measured amplitude detuning + measured kick actions rule out $\pm(Q_x + 2Q_y)$ as surviving line
- b_4 **errors in arcs & octupole corrector settings:**
  $\longrightarrow$ response matrix of octupole RDT to octupole correctors could not reproduce observed spectrum
  $\longrightarrow$ Strongly indicates b_4 errors in arc dipoles or corrector settings are not the source

$\pm(Q_x + 2Q_y)$ octupole spectral lines are not understood

Kicks for amplitude detuning also used for DA measurement (30 s DA)

Measurements done before (left) & after (right) turning off Landau octupoles & correcting Q'', Q'''

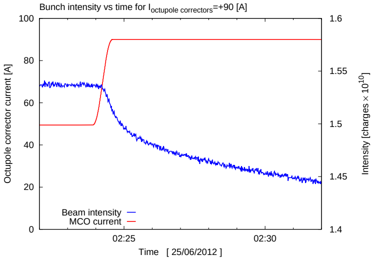


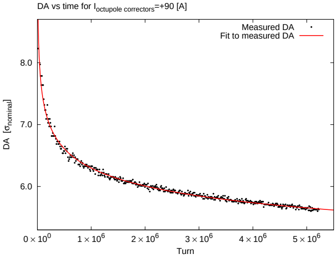
- Minimization of detuning & NL-chromaticity increased DA
- **Nominal optics measurement agrees well with model including known sources**
- Model after correction was matched to measured detuning
  (due to known discrepancies, departure from nominal magnetic cycle)
  → also shows good agreement for diagonal kick (H & V see only collimators)

Agreement much better than factor 2 margin of safety used in design

Alternative DA measurement technique also performed during Run 1

- Bunch blown up to large emittance
- DA varied by trims of Nonlinear circuits
- Longer term DA studied via losses as function of time

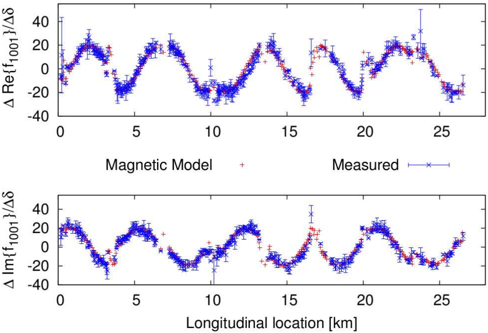




Analysis is ongoing...

Chromatic coupling measured via momentum dependence of linear coupling RDTs

- Measurement & correction demonstrated during General OMC MD (November 2012)



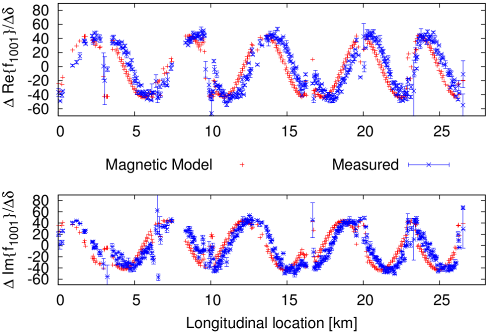
- **Model & measurement show very good agreement**

T.H.B. Persson et al. Phys. Rev. ST Accel. Beams 16, 081003

Nonlinear dynamics at top energy

Chromatic coupling also studied at $\beta^* = 0.6\,\mathrm{m}$

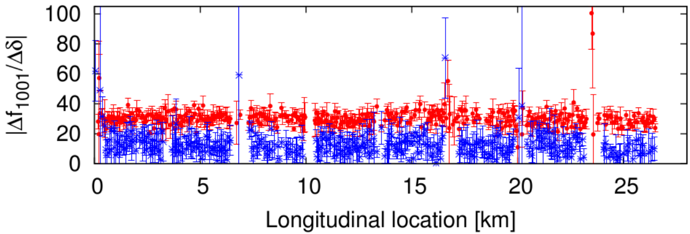
- Again see good agreement with model



- Small phase shift: perhaps due to enhancement of errors in IRs at lower β^*

T.H.B. Persson et al. Phys. Rev. ST Accel. Beams 16, 081003

Correction of chromatic coupling demonstrated at $\beta^* = 0.6\,\mathrm{m}$



will be included for LHC operation in Run 2

T.H.B. Persson et al. Phys. Rev. ST Accel. Beams 16, 081003

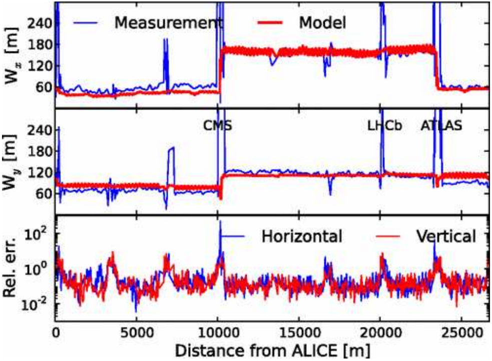
Chromatic twiss functions checked in 2012 commissioning ($\beta^* = 0.6\,\mathrm{m}$)

Characterized by the Montague function (W). δ_p is relative momentum offset.

$$A = \frac{\partial \alpha}{\partial \delta_p} - \alpha\beta$$

$$B = \frac{1}{\beta}\frac{\partial \beta}{\partial \delta_p}$$

$$W = \frac{1}{2}\sqrt{A^2 + B^2}$$



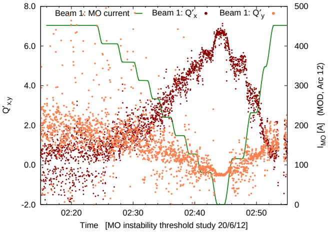
Good agreement of measured Montague function with model

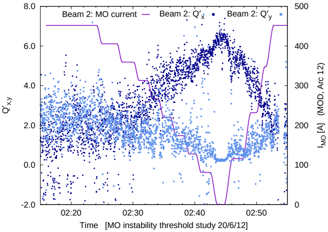
(Large discrepancies in IRs due to poor β measurements)

R. Tomás et al. Phys. Rev. ST Accel. Beams 15, 091001

Large Q' dependence on Landau octupole powering

$\longrightarrow$ Observed at Flattop and Collision optics





- Systematic closed orbit + systematic misalignments of Landau octupoles explain the observed dependence of Q'
- 30 % of Beam 1 Q'_x dependence was result of 1 malfunctioning orbit corrector

Beam 1	Modelled	Measured
Q'_x	5.6	6.3 ± 0.8
Q'_y	-1.5	-2.3 ± 0.4

Beam 2	Modelled	Measured
Q'_x	4.2	4.7 ± 0.7
Q'_y	-1.7	-2.2 ± 0.6

Amplitude detuning at top energy

Amplitude detuning is easily studied at injection optics:

⟶ use kicker magnet to destructively excite multiple fresh injections

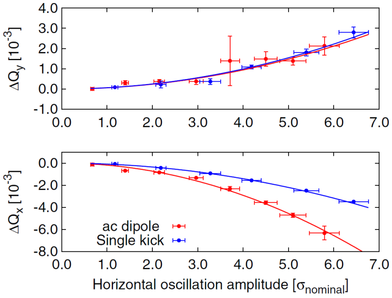
⟶ not possible at top energy as time for ramp-down + inject + ramp-up impractical

Can kick non-destructively with AC-dipole - but alters detuning measurement:

⟶ Direct detuning from n^{th} order multipole measured with AC-dipole is $n/2$ larger that for free oscillations

⟶ Detuning cross terms unaffected

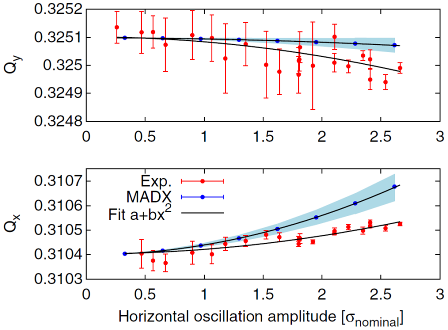
⟶ verified at injection



Provides means to study amplitude detuning throughout LHC cycle

First measurements at $4\,\mathrm{TeV}$ demonstrated application at top energy

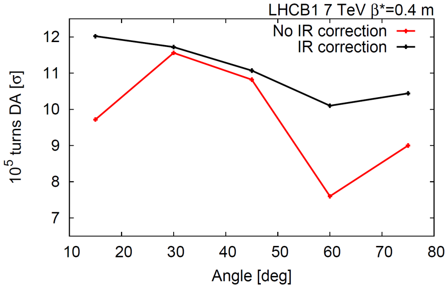
- $\frac{\partial Q_x}{\partial \epsilon_x}$ showed a factor 2.5 discrepancy with model
- Other measurements of low quality & comparison not possible
- Measurements throughout cycle to be performed as part of future commissioning



Details of theory, verification @ injection & first measurements @ $4\,\mathrm{TeV}$ found in:
S. White et al. Phys. Rev. ST Accel. Beams 16, 071002

Nonlinear errors in experimental insertions:

- At small β^* NL-errors in experimental IRs have significant influence on the dynamics
- Expect correction of IR NL-errors to be significant for DA at $\beta^* = 0.4\,\mathrm{m}$
  (Plot courtesy Rogelio Tomás)



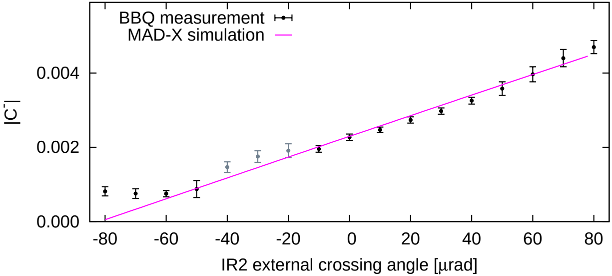
- Correction will be essential for the HL-LHC

Calculation of corrections require accurate magnetic model of IRs

$\longrightarrow$ **Magnetic measurements model will have to be verified & refined via beam-based studies**

NL-errors in IRs studied via feed-down to unconstrained tune and linear coupling, under influence of varying closed orbit bumps through IRs

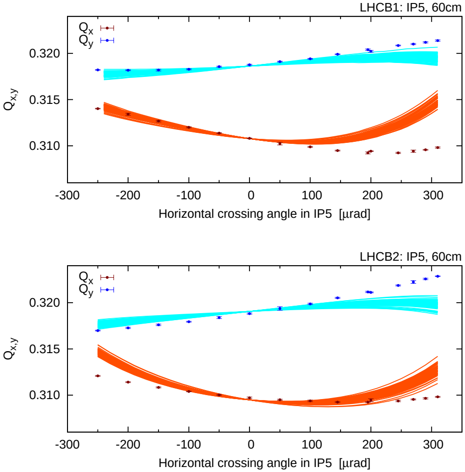
Technique demonstrated for LHC parasitically in IR2
(Spectrometer reversal tests & aperture measurements in 2011)



- Able to measure third & higher order multipoles feeding down to tune and coupling
- **Good agreement between model and measurement in IR2**
- Dominated by b_3 in separation dipoles feeding down to coupling

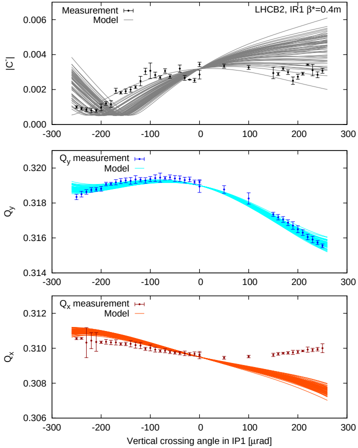
...but find large discrepancies with model in IR5 tunes @ $\beta^* = 0.6\,\mathrm{m}$...

(No usable coupling data obtained)



...and large discrepancies with model in IR1 Beam 2 @ $\beta^* = 0.4\,\mathrm{m}$

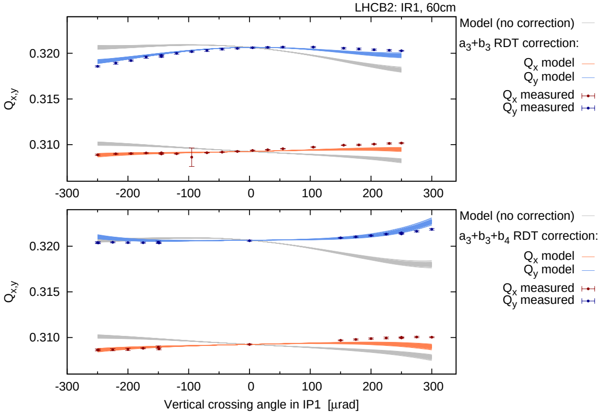
(No Beam 1 data obtained)



Discrepancies need to be understood to calculate corrections

IR1 @ $\beta^* = 0.6\,\mathrm{m}$ showed quite good agreement of tunes

First attempt at correction made for IR1 @ $\beta^* = 0.6\,\mathrm{m}$:



- b_3 correction has no data (no usable coupling data obtained)
- a_3 correction worked well in Beam 1 & Beam 2
- b_4 correction worked well in Beam 2, but in Beam 1 b_4 correction fed-down to a_3

Some partially successful corrections achieved in IR1 @ $0.6\,\mathrm{m}$...
...but also some big discrepancies between measurement & model

Several possible sources of discrepancy:

- **Non-closure of closed orbit bumps used for feed-down studies:**
  $\longrightarrow$ Could generate feed-down in the arcs which confuses the IR measurement
  $\longrightarrow$ Orbit data showed increase in RMS closed orbit in arcs of up to $\sim 0.1\,\mathrm{mm}$ as bump varied
  $\longrightarrow$ Matching of the closed orbit oscillation around the ring showed negligible effect

- **Different behaviour of real closed orbit bump compared to model**
  $\longrightarrow$ Orbit data in IRs (after correcting BPM nonlinearity) showed some discrepancies with model
  $\longrightarrow$ Accounting for measured orbit does not explain observed discrepancies

- **Beta-beating in the IR influencing feed-down**
  $\longrightarrow$ Model assumes nominal optics in the IR, but beta-beat is very well corrected
  $\longrightarrow$ But may explain much larger tune discrepancy @ $\beta^* = 0.4\,\mathrm{m}$, as no dedicated correction applied
  $\longrightarrow$ New techniques for linear optics measurement presented in next talk (*A. Langner*)
  $\longrightarrow$ should reduce measurement uncertainties in IR & allow beta-beat to be included in model

- **Difference of real NL-errors with model from magnetic measurements**
  $\longrightarrow$ Challenge will lie in identifying which multipoles are different & localizing error within IR
  $\longrightarrow$ Will require further beam-based studies

Measurement & correction of NL-errors in experimental IRs likely to be one of the more critical issues for LHC NL-dynamics in Run 2

A relatively wide range of phenomena were studied during Run 1, but some key features of the beam dynamics remain to be examined:

- **Required settings of chromaticity sextupoles to achieve nominal Q' known to be different from expectation of magnetic model**
  $\longrightarrow$ Equivalent to 5-10 units depending on point in cycle
  $\longrightarrow$ Q' discrepancy will need to be studied in more detail

- **Natural chromaticity**

- **Local b_3 correction in the arcs**
  $\longrightarrow$ Quality of local b_3 correction in arcs never checked with beam
  $\longrightarrow$ poor local correction could have sizable impact on DA
  (*M. Hayes*, LHC Project Report 590)

- **Chromatic amplitude detuning**
  $\longrightarrow$ Depends on b_5 - could help identify source of Q''' discrepancy

A lot of interesting observations of the NL-dynamics made during LHC Run 1

Some aspects of the beam dynamics have shown a good agreement to our expectations:

- Chromatic coupling
- Chromatic variation of twiss functions
- Q' dependence on Landau octupole powering
- Qualitative reproduction of nonlinear coupling
- Significantly better agreement of DA at nominal injection optics than factor ~ 2 margin of safety used in the design

Discrepancies between measurements and simulation were found in several observables during Run 1:

- First & second & third order chromaticity
- First & second order detuning with amplitude @ inj'
- Amplitude detuning at top energy
- Octupolar spectral lines @ inj'
- **Feed-down from nonlinear errors in experimental insertions**

Challenge in Run 2 will be further application & development of methods to identify the sources of discrepancies & the implementation of corrections