Non-linear modelling and machine set-up.

Ewen Maclean, on behalf of the LHC OMC team.

June 19, 2013

Many thanks to the members of the OMC team, the ABP and OP groups, and to all others who have contributed to the studies presented here.

OMC review: Outline

MSS

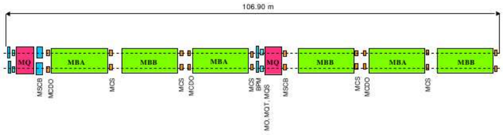
Skew sextupoles

- **MSS: Arc Skew sextupoles**
- for correction chromatic coupling (a_3 in arc dipoles)
- MSS have not been used in operation so far
- First commissioning was performed with Beam as an MD in 2012
- Should be implemented post-LS1
- See talk by Y.I.Levinson

MCS

Skew sextupoles

- **MCS: sextupolar spool pieces**
- Intended for correction of b_3 in arc dipoles
- Mounted on ends of arc dipoles



MQT: trim quadrupole

MQS: skew trim quadrupole

MO: lattice octupole

MSCB: sextupole (skew sextupole) + orbit corrector

MCS: spool piece sextupole

MCDO: spool piece octupole + decapole

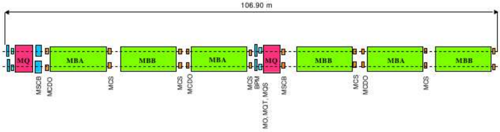
- Used since start of commissioning
- Have never been checked
- Optimize via feed-down to tune under influence of closed orbit bumps (M. Hayes, 'TOLERANCES OF THE SPOOL PIECE CORRECTION SYSTEM FOR THE LHC', LHC Project Report 590)
- Beam based check of MCS should be included in commissioning post-LS1

MCDO

Spool pieces

- **MCO & MCD: octupole and decapole spool pieces**
- Intended for correction of b_4 and b_5 errors in arcs

- MCO are nested within the MCD → 'MCDO'
- MCDO are mounted on ends of every second dipole (MB.A)



MQT: trim quadrupole

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MCS: spool piece sextupole

MCDO: spool piece octupole + decapole

- Split into families by arc (8 MCO families/beam, 8 MCD families/beam)
- As MCO are nested within MCD, MCO are not pre-cycled

MCDO status

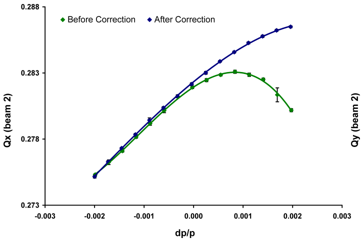
- **In 2011 two MCO families in Beam 2 were broken:**
- Beam 2: Arc78, Arc81

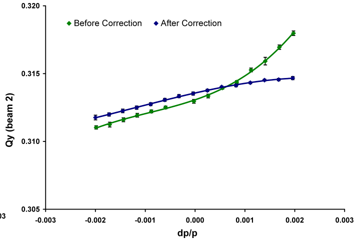
- **In 2012 three families of Beam 2 were off + one family off in Beam 1:**
- Beam 2: Arc12, Arc78, Arc81
- Beam 1: Arc12

- In 2011 studies were made of non-linear chromaticities at injection (nominal spool piece settings and zero Landau octupoles)
- $Q''_x \sim -1800,\ Q'''_x \sim -2 \times 10^6$
- $Q''_y \sim \ +800,\ Q'''_y \sim +0.8 \times 10^6$

Q'' and Q''' measurement and correction

- In 2011 tested beam-based correction of injection non-linearities via correction of the non-linear chromaticity
- Global trims applied to MCO and MCD to correct Q'' and Q'''
- **Q'' correction:** MCO to zero field settings, then $+6.41\,\mathrm{A}$ trim to all MCO
- **Q''' correction:** -25% MCD powering for all families ($+35\,\mathrm{A}$)





	$Q''_x\,[10^3]$	$Q''_y\,[10^3]$	$Q'''_x\,[10^6]$	$Q'''_y\,[10^6]$
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)

- Q'' and Q''' corrections also reduced amplitude detuning and decoherence

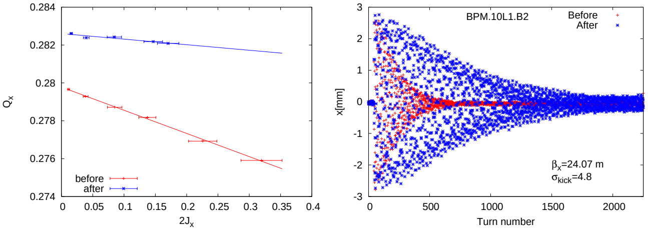


Figure: Decoherence and detuning before/after Q'' and Q''' correction

Comparison with simulation

- **There are very substantial deficits in the simulated non-linear chromaticites compared with measurements**
- Between 75 and 100% of measured Q'' is missing from the model
- Between 50 and 85% of measured Q''' is missing from the model
- (simulations done with MAD-X / PTC including best available knowledge of magnetic and alignment errors)

	$\Delta Q_x''[10^3]$	$\Delta Q_y''[10^3]$	$\Delta Q_x'''[10^6]$	$\Delta Q_y'''[10^6]$
meas-mod	-1.8 ± 0.1	0.6 ± 0.1	-1.0 ± 0.1	0.70 ± 0.1

- $\Delta Q''$ & $\Delta Q'''$ on correction with MCDO agreed very well with simulations

Horizontal	$\mathbf{\Delta Q''}[10^3]$	$\mathbf{\Delta Q'''}[10^6]$
Measured	1.4 (0.03)	1.5 (0.08)
Modelled	1.3	1.6

Vertical	$\mathbf{\Delta Q''}[10^3]$	$\mathbf{\Delta Q'''}[10^6]$
Measured	−0.93 (0.04)	−0.97 (0.1)
Modelled	−0.90	−0.91

Comparison with simulation

- Systematic horizontal misalignment ($\bar{\delta}_x$) of MCD w.r.t. the b_5 errors may generate Q''
- but $\Delta Q''$ on correction of NL-chroma with MCDO agreed well with model

- From difference between modelled and measured $\Delta Q''$ on correction with MCDO, the allowed systematic misalignment is: $-0.12\,\mathrm{mm} \le \bar{\delta}_x \le +0.05\,\mathrm{mm}$ (based on $\pm 2\sigma_{fit}$)
- Too small to explain all missing Q''
- $\bar{\delta}_x = -0.1\,\mathrm{mm} \rightarrow Q''_x = -360,\ Q''_y = 280$
- Best fit: $\bar{\delta}_x = -0.055\,\mathrm{mm} \rightarrow Q''_x = -200,\ Q''_y = 150$

- Potentially a small but non-negligible contribution
- No clear evidence such a misalignment exists

Comparison with simulation

- At injection MCO have extremely large hysteresis errors w.r.t. the linear model implemented in LSA
- E. Todesco provided an estimate of the real field in the MCO
- These errors have been incorporated in the model

	$\Delta Q_x''[10^3]$	$\Delta Q_y''[10^3]$	$\Delta Q_x'''[10^6]$	$\Delta Q_y'''[10^6]$
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

- MCO hysteresis accounts for large proportion of missing Q'' (especially in y plane)

- Still significant missing Q'' in model ~ -1100 units in x, & ~ 100 units in y
- MCO field is small at injection, estimate of hysteresis may become imprecise at small fields

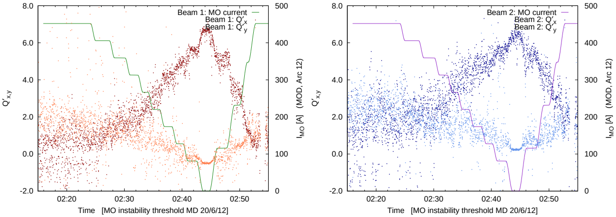
Landau octupoles

Landau octupoles

- **MO: Landau octupoles**
- provide Landau damping for stabilization of the beams
- As-designed 84 focusing (MOF) and 84 defocusing (MOD)
- Two Beam 1 MOD and two Beam 2 MOF were lost in Arc34
- All MO are located next to a BPM

Landau octupoles: Q' and $|C^-|$ dependence on MO powering

- In 2012 Q' shifts correlated with MO powering were observed

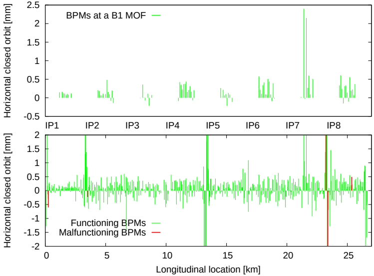


- WISE data shows systematic misalginment of the MO
- Feed-down from MO alignment explains 15-50% of observed $\Delta Q'$

	Beam 1		Beam 2	
	model	measured	model	measured
$\Delta Q'_x$	0.96	6.3±0.8	1.36	4.7±0.7
$\Delta Q'_y$	−0.53	−2.3±0.4	−1.12	−2.2±0.6

Landau octupoles: Q' and $|C^-|$ dependence on MO powering

- Feed-down due to closed orbit (CO) is another possible source



- $dp/p \sim 0.05 \times 10^{-3}$
- Similar orbits for MOF / MOD
- Similar orbits for both beams

- Observe substantial systematic CO in the MOF and MOD
- Observe minority of MO with dramatic excursions
- **BPM.29R7.B1→2.40mm!**
- **BPM.33R7.B1→2.15mm!**
- These 2 MO explain $\sim 30\%$ of the Beam 1 $\Delta Q'_x$
- Results from broken orbit corrector

Landau octupoles: Q' and $|C^-|$ dependence on MO powering

- Systematic CO + MO alignment explains majority of observed $\Delta Q'$

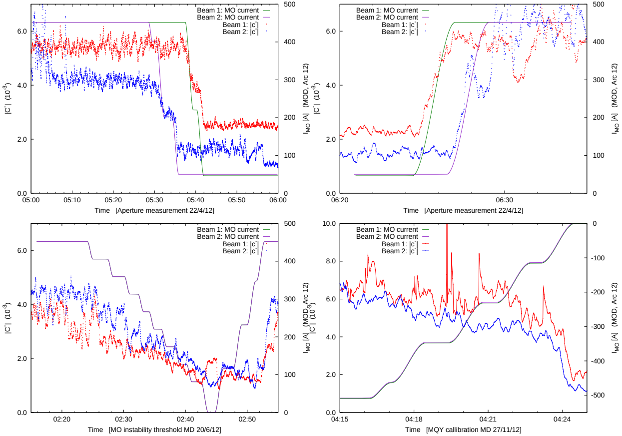
Table: Modelled Q' shifts on depowering the MO in MAD-X, including MO alignment and CO.

		Model	Measurement
B1	$\Delta Q'_x$	5.3	6.3±0.8
B1	$\Delta Q'_y$	-1.5	-2.3±0.4
B2	$\Delta Q'_x$	4.1	4.7±0.7
B2	$\Delta Q'_y$	-1.6	-2.2±0.6

- Magnetic errors in MO have a small effect: $\delta(\Delta Q') \leq 0.2$

Landau octupoles: Q' and $|C^-|$ dependence on MO powering

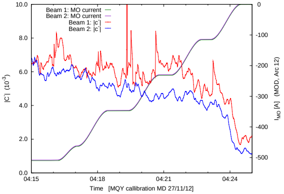
- Shifts in $|C^-|$ on changes in MO powering were also observed by BBQ

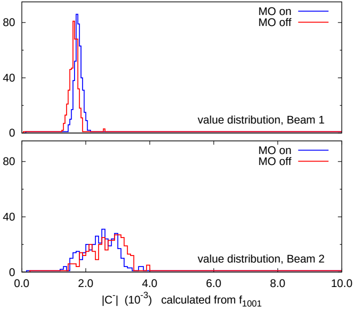


- $\Delta|C^-|_{BBQ}$ is independent of MO polarity
- Alignment + CO + magnetic errors do not explain $\Delta|C^-|_{BBQ}$

Landau octupoles: Q' and $|C^-|$ dependence on MO powering

- On two occasions had AC-dipole measurements with/without MO powered
- Via spectral analysis of turn-by-turn betatron oscillation data find coupling RDTs (f_{1001}, f_{1010})
- Shifts in RDTs are negligible compared with BBQ shift

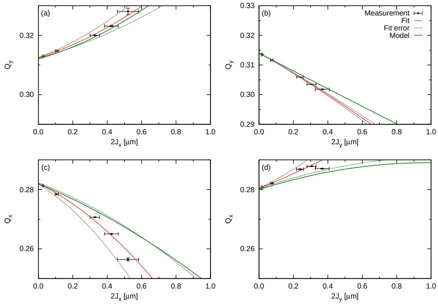




- RDT method well verified during commissioning
- with MO off RDT and BBQ agree well
- Trust RDT over BBQ, $\Delta|C^-|$ was not a real change in coupling

Landau octupoles: amplitude detuning at injection

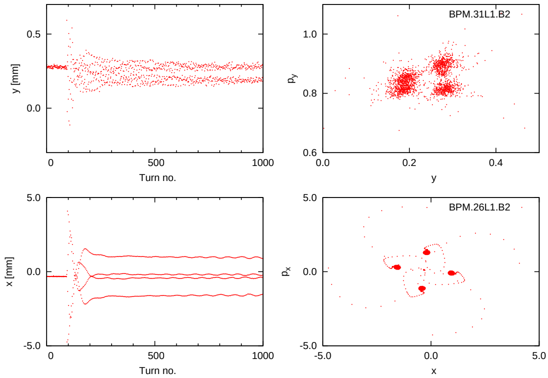
- **Measurements of amplitude detuning in June 2012 (nominal settings)**
- Observe substantial detuning, dominated by MO
- Simulated detuning agrees quite well with observations (better in H-plane)
- $|C^-|$ determines uncertainty on simulated detuning



- Missing b_4 (determined by matching first order detunings to measurement) generates $\delta(Q''_x) = -1100$, $\delta(Q''_y) = +400$
- This agrees well with Q'' deficit in 2011 measurements with zero MO

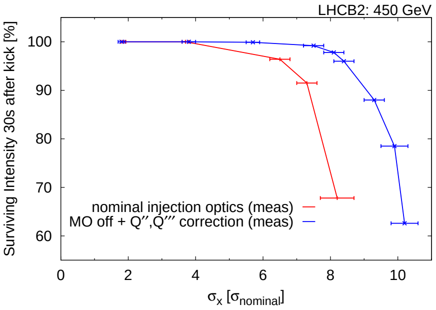
Landau octupoles: amplitude detuning at injection

- Largest horizontal kicks drove $Q_{x,y}$ to 4$^{\text{th}}$ & 3$^{\text{rd}}$ order resonances



Landau octupoles: dynamic aperture measurement and modelling

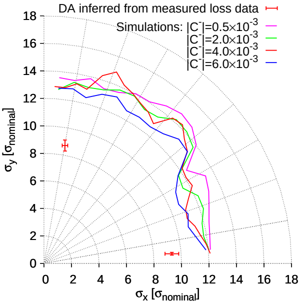
- **Dynamic aperture may be determined from losses on kicking the beam**
- Powering MO to zero, and correcting NL-chromaticities increased the DA



- With nominal settings, loss data suggests $DA \sim 9.3 \pm 0.5\sigma_{nominal}$
- After correction, data shows losses occurring at $\sim 11.2 \pm 0.4\sigma_{nominal}$ (consistent with a DA outside of the collimator aperture at $12\sigma_{nominal}$)

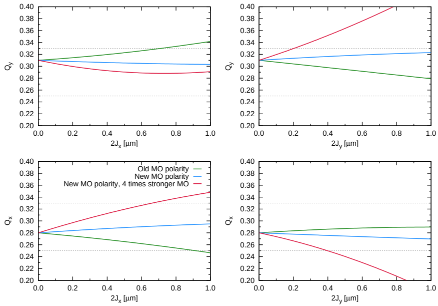
Landau octupoles: dynamic aperture measurement and modelling

- Coupling amplitude/phase give non-negligible uncertainty in DA simulation
- Agreement between model and measurement is better than the factor 2 margin of safety previously specified
- Vertical model is significantly worse than horizontal (complicated by non-linear coupling)



- Model DA_x is $2.7 \pm 0.7\sigma_{nominal}$ larger than inferred from measured loss data
- Due to missing b_4, modelled Q_y reaches third order resonance $\sim 2.7\sigma_{nominal}$ later than was measured

- **In second half of 2012 the MO polarity was reversed**
- All non-linear studies at injection performed with old MO polarity
- Model agrees fairly well with MO powered, can extrapolate to new settings



- **MO being used to do job of MCO**
- **2012 polarity flip = polarity flip + reduction in** $|detuning|$ **&** $|Q''|$
- Old polarity: unnecessarily strong MO at injection
- Significantly increasing MO powering will result in hitting 3rd order resonance at lower amplitudes

Non-linear errors in the experimental insertions

Non-linear errors in the experimental insertions

- Low-β insertions require large β in the triplets and separation dipoles.
- Non-linear errors in the IRs can have significant impact
- **MCX:** dedicated correctors both sides of the IP.

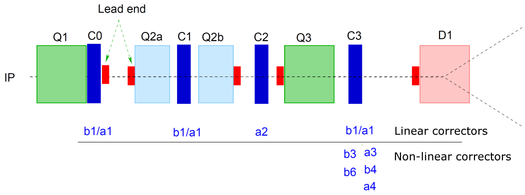


Figure: Schematic of the IR corrector layout.

- NL correctors in IRs not been used in operation so far
- several correctors are unlikely to be available post-LS1:
  - MCOSX3.L1 (a_4)
  - MCOSX3.L2 (a_4), MCOX3.L2 (b_4), MCSSX3.L2 (a_3)
- All other correctors should be available

Non-linear errors in the experimental insertions

- Ideally correct by minimization of dominant RDTs
- Also possible simply to correct errors locally on either side
- Require accurate magnetic model of NL-errors in IR:
  - Aim to verify magnetic model with beam-based measurements
  - Need to verify corrections with beam-based measurements

Table: Feed-down to tune (ΔQ) and coupling (ΔC) from NL-multipoles

Feed-down order	1st order		2nd order		3rd order		4th 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	...

- Can identify NL-errors, and check corrections, via feed-down to tune and coupling with varying closed orbit (CO) bumps through IR

Non-linear errors in IR2

- **During 2011 several studies of IR2 were made:**
- eg: Test of the reversal of IR2 external crossing angle (end of fill)

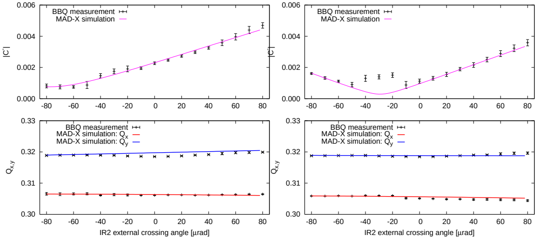


Figure: Modelled and measured tunes and couplings, versus external crossing angle (vertical).

- Excellent agreement between MAD-X model and magnetic measurements
- Some jumps in data caused by powering/depowering the chirp
- NL-errors in IR2 dominated by b_3 in D1 separation dipoles

- IR2 model also agrees well for higher orders

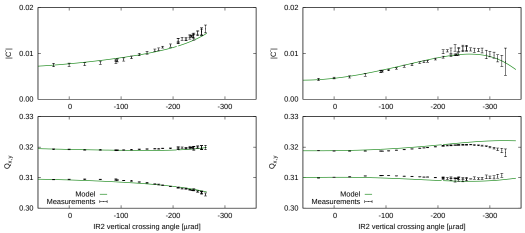


Figure: Modelled and measured Q and C^-, versus the total crossing angle (vertical) at IP2 during vertical aperture measurements. Beam 1 (left) & Beam 2 (right)

- Possibly slight discrepancy at largest excursions
- need further studies, multipole-by-multipole correction, to say more
- Errors in IR2 are very well understood
  $\rightarrow$ local correction possible right of IP2 for multipoles with broken MCX

Non-linear errors in IR1

- **In 2012 dedicated studies of NL errors in IR1 were performed**
- Measurements on Beam 2 during $\beta^* = 40\,\mathrm{cm}$ MD agree well with model
- First attempts to correct the IR1 a_3, b_3, and b_4 errors performed at $60\,\mathrm{cm}$
- $|C^-|$ data obtained from BBQ was unusable
  $\rightarrow$ do not know if b_3 correction worked

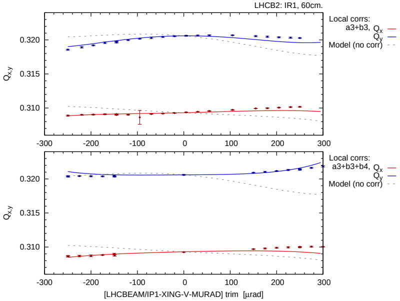


Figure: Modelled and measured Beam 2 tune variation with IP1 crossing angle (vertical), with sextupolar and sextupolar+octupolar corrections applied.

- In Beam 2 a_3 and b_4 corrections were successful

Non-linear errors in IR1

- In Beam 1 some a_3 discrepancy
- On b_4 correction, significant a_3 generated

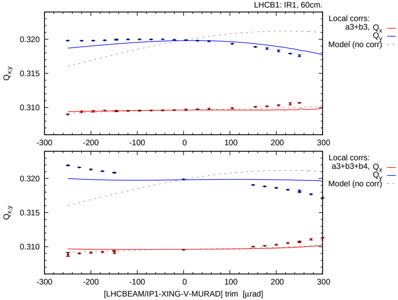


Figure: Modelled and measured Beam 1 tune variation with IP1 crossing angle (vertical), with sextupolar and sextupolar+octupolar corrections applied.

- sources are uncertain, however:
- a_3 discrepancy $\sim$ 25% kcssx.l1
- a_3 generated by b_4 correction can be explained by $\sim$ 2.5 mm misalignment of MCOX.L1

Non-linear errors in IR5

- **Also performed dedicated measurements in IR5 at** $60\,\mathrm{cm}$
- No corrections applied
- Coupling data was not usable
- Observe a large discrepancy between model and measurement

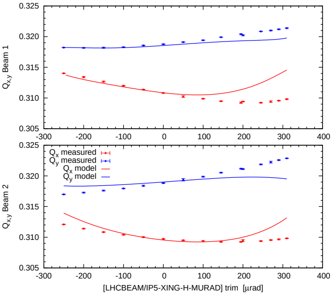


Figure: Modelled and measured tune variation with IP5 crossing angle (horizontal), with no corrections applied.

- Not explained by orbit leakage into arcs
- Needs to be understood before corrections can be implemented

Conclusions

MSS & MCS:

- **MSS:** Not used in operation yet, but commissioned with beam in 2012 MD
- **MCS:** Used in operation, but never checked with beam
- Would like to include in commissioning post-LS1

MO, MCO & MCD:

- Studied at injection
- Still some missing b_4 in model, but fairly well understood (especially when MO on)
- Several missing MCO families, MCO have substantial hysteresis errors
- Old MO polarity: MO were unnecessarily strong
- New MO polarity: MO doing the job of the MCO

- Suggest a beam-based non-linear chromaticity correction of bare machine with MCDO
- Should simplify operation with MO

Conclusions

MCX:

- IR-bumps method has been well verified in 2011/2012
- Strategy for commissioning should be multipole-by-multipole correction based on repeated scans of Crossing angles in the IRs
- Good quality BBQ data for tune and coupling, and well corrected coupling, will be essential

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- Magnetic model of IR2 is well understood
- Likely to suffer from several missing correctors
- Strategy should be local correction with available multipoles on one side if correctors missing, otherwise minimization of RDTs

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- Magnetic model of IR1 is mostly understood
- May require additional corrections for a_3 missing in model
- May need to compensate for a_3 generated by b_4 correction (demonstrates importance of multipole-by-multipole correction)

- Large discrepancies between model and measurement in IR5
- Unclear how to proceed with this IR

Conclusions

Many thanks for your attention

Reserve Slides

MCS

- Poor local correction of MCS can substantially reduce the DA

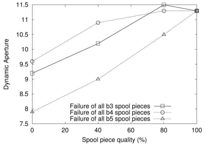

Figure 1: The minimum dynamic aperture (in units of the r.m.s. beam size σ) as a function of b_3,b_4 and b_5 spool piece quality at injection at the LHC. 100% represents full correction and 0% none. For b_3, Q' is always corrected to 2 units using the lattice sextupoles.

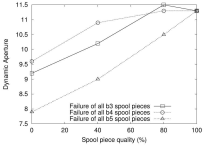

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Table 1: Dynamic apertures of two cases for each spool piece system where a) one arc is underpowered by 20% and is compensated by overpowering another arc also by 20% and b) similarly for 50%. All other arcs are correctly powered. This situation could arise by use of a global correction method. For b_3, Q' is always corrected to 2 units using the lattice sextupoles.

Spool piece	DA after mispowering	
	a) 20%	b) 50%
b_3	11.0±0.5	10.1±0.5
b_4	11.7±0.5	11.5±0.5
b_5	11.0±0.5	10.6±0.5

(from: M. Hayes, 'TOLERANCES OF THE SPOOL PIECE CORRECTION SYSTEM FOR THE LHC', LHC Project Report 590)

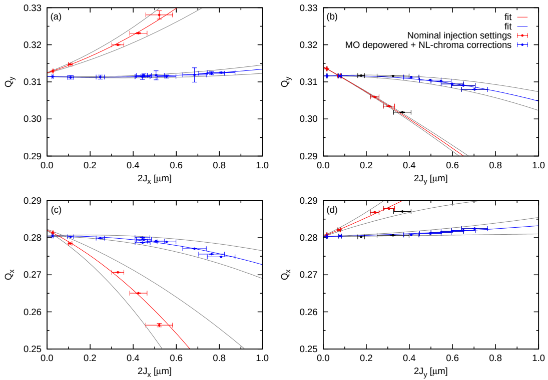
Q' and $|C^-|$ dependence on MO powering

Table: Systematic CO at MOF / MOD during Q' vs I_{MO} measurement

			logged orbit	logged orbit & BPM align'
Beam 1	MOF	$\bar{\delta_x}$[mm]	0.27±0.04	0.25±0.04
		$\bar{\delta_y}$[mm]	-0.029±0.001	0.239±0.001
	MOD	$\bar{\delta_x}$[mm]	0.01±0.02	0.01±0.02
		$\bar{\delta_y}$[mm]	0.016±0.001	0.189±0.001
Beam 2	MOF	$\bar{\delta_x}$[mm]	0.17±0.03	0.17±0.03
		$\bar{\delta_y}$[mm]	-0.032±0.001	0.214±0.001
	MOD	$\bar{\delta_x}$[mm]	0.04±0.02	0.00±0.02
		$\bar{\delta_y}$[mm]	0.024±0.002	0.308±0.002

Landau octupoles: amplitude detuning

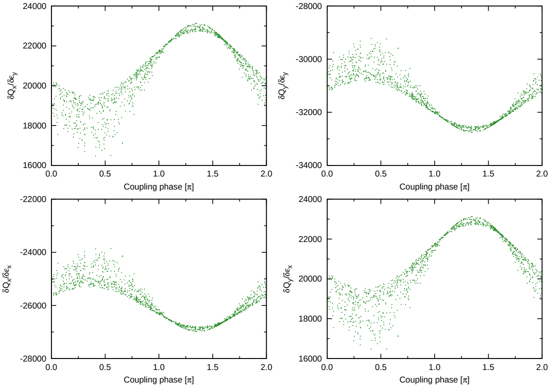
- Measurements of amplitude detuning made in June 2012
- with nominal injection settings (old MO polarity)
- with MO off + corrections to minimize NL-chorma applied



- Observe substantial detuning, dominated by MO

Landau octupoles: amplitude detuning model

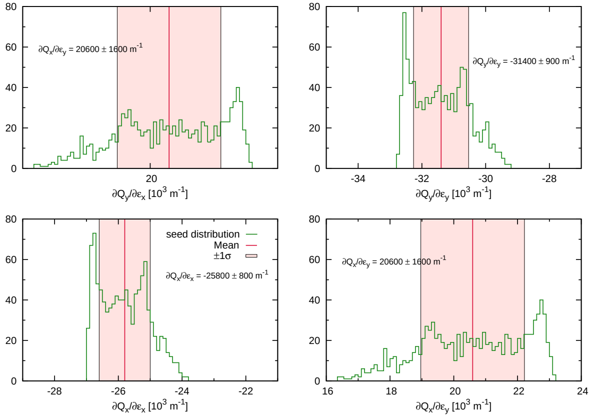
- Linear coupling may affect the detuning
- Considered 1000 seeds
- $|C^-|$ distribution comparable with $|f_{1001}|$ distribution at BPMs
- uniform distribution in coupling phase



Landau octupoles: amplitude detuning model

E.H. Maclean

MSS
MCS
MCDO
NL-chroma simulation
MO
Q' & $|C^-|$
detuning
DA
polarity swap
MCX
Intro
IR2
IR1
IR5
Conclusions
Reserve



- Simulations of correction of the b_3

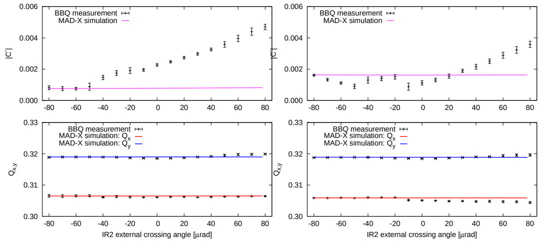


Figure: Simulated variation of Q and $|C^-|$ with corrections applied for b_3

Table: Corrections for b_3 errors in IR2. Corrections were calculated in MAD-X using the FiDel magnetic measurement data, which has been verified in beam-based studies.

Corrector	Strength k $\left[\mathrm{Tm}^{-2}\right]$	Strength $[\%_{max}]$
KCSX.L2	-0.00482	-57.41
KCSX.R2	0.00085	10.15

Non-linear errors in IR1

- In Beam 1 some a_3 discrepancy
- On b_4 correction, significant a_3 generated

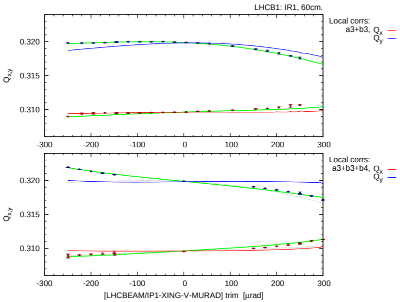


Figure: Modelled and measured Beam 1 tune variation with IP1 crossing angle (vertical), with sextupolar and sextupolar+octupolar corrections applied.

- sources are uncertain, however:
- a_3 discrepancy $\sim$ 25% kcssx.l1
- a_3 generated by b_4 correction can be explained by $\sim 2.5\,\mathrm{mm}$ misalignment of MCOX.L1