Amplitude Detuning from misaligned Triplets and IR multipolar Correctors

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Outline

- Setup
  - Motivation
  - Misaligning Correctors
  - Misaligning Triplets
  - Simulation and Measurement details
- Results
  - Corrector Misalignments
  - Triplet Misalignments
  - Conclusion

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Motivation

With the advent of the HL-LHC, new triplets with larger aperture and new corrector packages[1], for corrections of high-order non-linear magnetic field errors, will be installed in the low β Interaction Points (IP1 & IP5), which will require precise orbit control.

The goal of this study is, to investigate the influence of the expected remaining orbit deviations[2] in the triplets and the associated non-linear corrector packages on Amplitude Detuning.

A preliminary study showed large detuning, which turned out to be a bug, but triggered this more extensive study.

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[1] O. Brüning et al - *LHC Report 504: Dynamic aperture studies for the LHC separation dipoles*, 2004. https://cds.cern.ch/record/742967

[2] D. Gamba et al - *IP ORBIT CORRECTION UPDATE FOR HL-LHC*, IPAC, 2018. http://cds.cern.ch/record/2648556

Misaligning Correctors

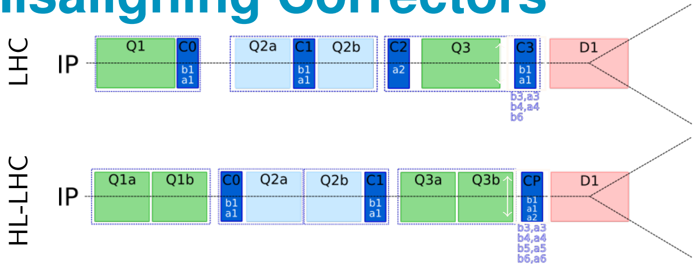
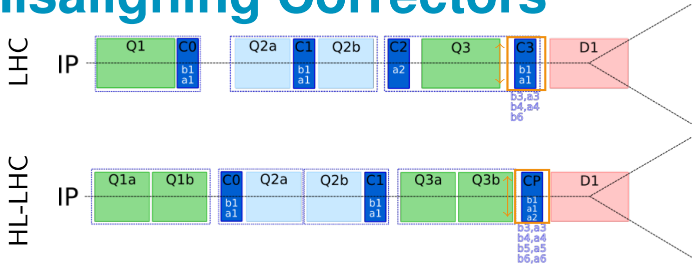


Figure: Schematic representation of half of the IR region in the accelerator.

- setup LHC/HL-LHC Sequence
- 60 WISE error realizations: octupole, (skew-)decapole and (skew-)dodecapole to MQX and MBX
- calculate triplet corrections for the MCX
- 50 misalignment realizations for **MCX**, **uniformly distributed** $\in [-1\,\text{mm}, 1\,\text{mm}]$

⇒ check Amplitude Detuning

Misaligning Correctors



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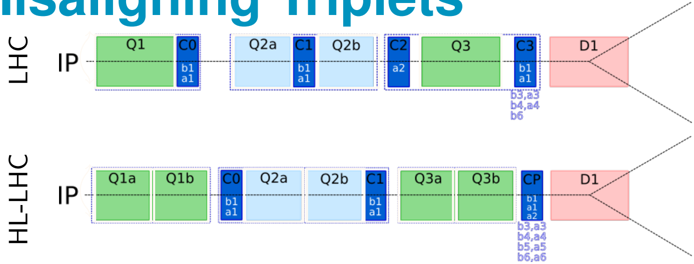
Misaligning Triplets



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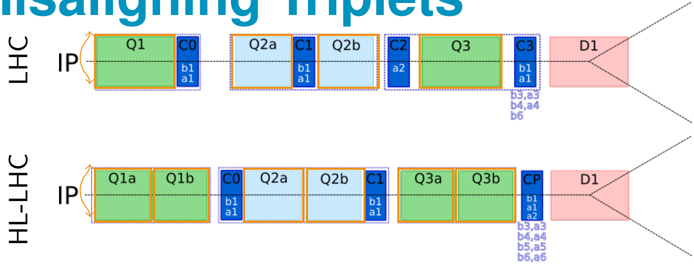
- setup LHC/HL-LHC Sequence
- 60 WISE error realizations: octupole, (skew-)decapole and (skew-)dodecapole MQX and MBX
- calculate triplet corrections for the MCX
- 50 misalignment realizations for **Q1-Q3**, **truncated-gaussian distributed** $\sigma = 0.4\,\text{mm}$ (0.8 mm Q3), cut at $2.5\,\sigma$

⇒ check Amplitude Detuning

Misaligning Triplets



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- setup LHC/HL-LHC Sequence
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⇒ check Amplitude Detuning

Setup

	Simulation		Measurements[1]
	LHC	HL-LHC (v1.3)	LHC
Energy	6.5 TeV	7.0 TeV	6.5 TeV
β^*	30 cm round optics		
Orbit	flat orbit		
Q_x, Q_y	0.31, 0.32		
MO Power	off (see later)		off
b_4 corrected	yes		

[1] in MD3311 `http://cds.cern.ch/record/2692810`

Calculate Detuning

Feeddown:

$$K_5 \rightarrow K_4 = dx \cdot K_5$$

$$K_5S \rightarrow K_4 = -dy \cdot K_5S$$

$$K_6 \rightarrow K_4 = \frac{1}{2}\left(dx^2 - dy^2\right) \cdot K_6$$

$$K_6S \rightarrow K_4 = -dx \cdot dy \cdot K_6S$$

Detuning:

$$\frac{\partial Q_x}{\partial 2J_x} = \frac{K_4}{32\pi}\beta_x^2$$

$$\frac{\partial Q_x}{\partial 2J_y} = -\frac{K_4}{16\pi}\beta_x\beta_y$$

$$\frac{\partial Q_y}{\partial 2J_y} = \frac{K_4}{32\pi}\beta_y^2$$

$K_n(S)$: Integrated (skew) magnetic field strength, with $n = 4 \Rightarrow$ octupole etc.
dx, dy: Beam offset from element center
$J_{x,y}$: Action

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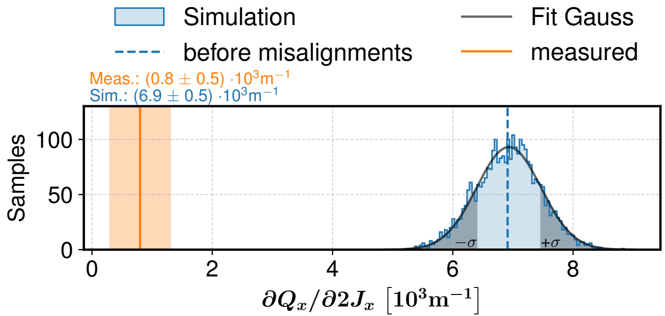
Subsection 1

Corrector Misalignments

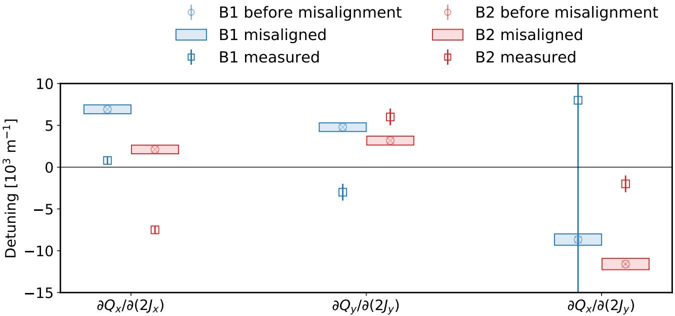
Misalign LHC Correctors



- Shown: result for Beam 1 direct horizontal term
- Simulation "offset" from zero due to amplitude detuning from arc-sextupoles
- Gaussian detuning distribution (from uniform misalignments)

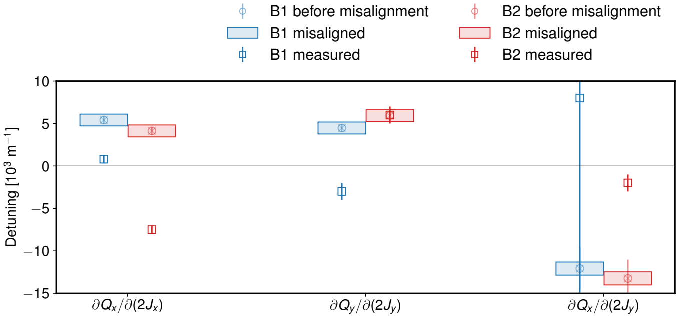
⇒ compare for both beams and all detuning components

Misalign LHC Correctors



- amplitude detuning spread from misalignments is small compared to expected detuning without misaligments
- also smaller or of similar order as measured amplitude detuning
- contribution only from feeddown from b_6 as, this is the only corrector

Misalign HL-LHC Correctors

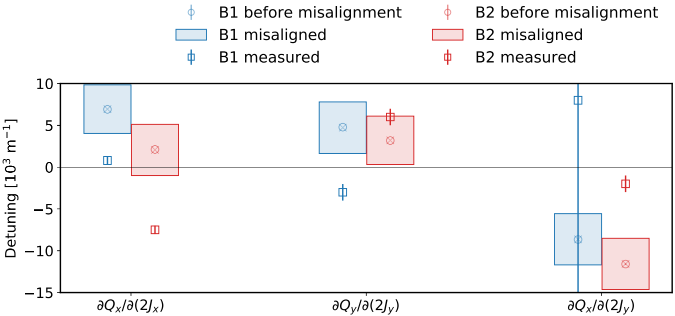


- amplitude detuning spread from misalignments is small compared to expected detuning without misalignments
- also smaller or of similar order as measured amplitude detuning
- contribution from feeddown from b_5, a_5, b_6, and a_6 (see appendix)

Subsection 2

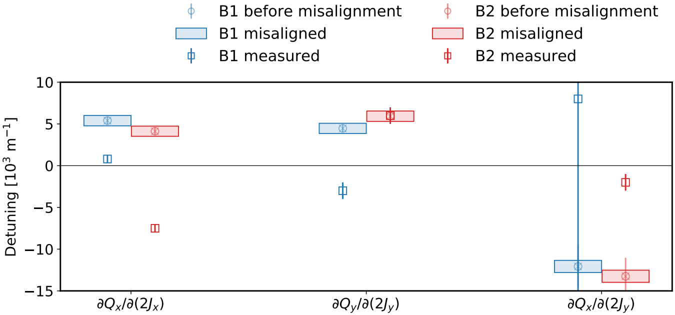
Triplet Misalignments

Misalign LHC Triplets



- amplitude detuning spread from misalignments is of equal order compared to expected detuning without misalignments, but not problematic
- large spread compared to HL-LHC; reasons under investigation (possibly: cancellation due to shorter magnets / independent misalignments, differences in error-tables)

Misalign HL-LHC Triplets

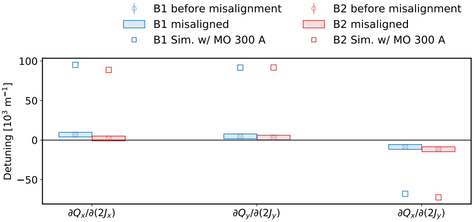


- amplitude detuning spread from misalignments is small compared to expected detuning without misalignments
- also spread smaller or of similar order as measured amplitude detuning

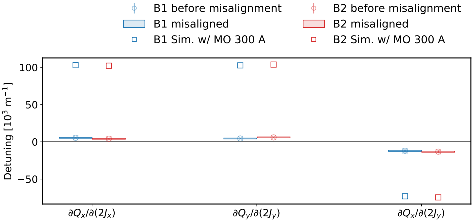
Misalign Triplets

… and compare to powered MO's

LHC



HL-LHC



- MO powering of 300 A causes amplitude detuning to increase from $\sim 5 \cdot 10^3 \mathrm{m}^{-1}$ up to $\sim 100 \cdot 10^3 \mathrm{m}^{-1}$ in the direct terms.

Conclusion

- Expected amplitude detuning spread is larger from investigated triplet misalignment than from corrector misalignments in the **LHC**.
- Expected amplitude detuning spread is marginally larger from investigated corrector misalignments than from triplet misalignments in the **HL-LHC**.
- The investigated misalignments, with spreads of $\pm$ 1 mm in the MCX and $\pm$ 0.4 mm(0.8 mm) in the MQX do not cause problematic amplitude detuning in either machine.
- Amplitude detuning is negligible when comparing to expected detuning from MO powering.
- Expected detuning from triplet-misalignments is smaller for **HL-LHC** than for **LHC** for the same $\beta^* = 30\,\text{cm}$.

Thank you for your attention!

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Amp. Det. References

Table: Reference Values Summary

	$[10^3\ m^{-1}]$		MD3311	w/ Errors	MO-Powering 0 A	300 A	570 A	0 A **w/o Sextupoles**
Beam 1	$\partial Q_x / \partial 2J_x$	LHC	0.8 ± 0.5	6.9 ± 0.0	6.6	95.2	174.8	0.1
		HL-LHC	–	5.4 ± 0.4	5.3	103.0	191.0	0.2
	$\partial Q_y / \partial 2J_y$	LHC	8 ± 28	4.8 ± 0.0	4.	91.7	170.2	0.1
		HL-LHC	–	4.5 ± 0.4	4.6	102.7	191.0	0.2
	$\partial Q_x / \partial 2J_y$	LHC	-3 ± 1	-8.7 ± 0.1	-7.9	-67.9	-121.8	0.0
		HL-LHC	–	-12 ± 2.5	-12.4	-73.2	-127.9	0.1
Beam 2	$\partial Q_x / \partial 2J_x$	LHC	-7.5 ± 0.5	2.1 ± 0.0	1.9	88.8	166.9	0.1
		HL-LHC	–	4.1 ± 0.4	4.2	102.2	190.4	0.2
	$\partial Q_y / \partial 2J_y$	LHC	-2 ± 1	3.2 ± 0.0	3.0	91.8	171.8	0.1
		HL-LHC	–	5.9 ± 0.4	5.9	103.7	191.8	0.2
	$\partial Q_x / \partial 2J_y$	LHC	6 ± 1	-11.6 ± 0.1	-12.5	-72.4	-126.3	0.0
		HL-LHC	–	-13.3 ± 2.2	-13.7	-74.6	-129.4	0.1

Corrector Misalignment Feedown

Table: Corrector misalignment summary - feeddown from field components to first order amplitude detuning

	$[10^3\ m^{-1}]$		Sum	Decapole	Skew Decapole	Dodecapole	Skew Dodecapole
Beam 1	$\partial Q_x/\partial 2J_x$	LHC	0.00 ± 0.53	–	–	0.00 ± 0.53	–
		HL-LHC	0.01 ± 0.69	0.00 ± 0.43	0.01 ± 0.55	0.00 ± 0.05	0.00 ± 0.02
	$\partial Q_y/\partial 2J_y$	LHC	0.00 ± 0.52	–	–	0.00 ± 0.52	–
		HL-LHC	0.00 ± 0.70	0.00 ± 0.48	0.00 ± 0.52	0.00 ± 0.05	0.00 ± 0.02
	$\partial Q_x/\partial 2J_y$	LHC	0.00 ± 0.68	–	–	0.00 ± 0.68	–
		HL-LHC	-0.01 ± 0.77	0.00 ± 0.51	0.00 ± 0.59	0.00 ± 0.05	0.00 ± 0.02
Beam 2	$\partial Q_x/\partial 2J_x$	LHC	0.00 ± 0.52	–	–	0.00 ± 0.52	–
		HL-LHC	0.00 ± 0.70	0.00 ± 0.48	0.00 ± 0.52	0.00 ± 0.05	0.00 ± 0.02
	$\partial Q_y/\partial 2J_y$	LHC	0.00 ± 0.53	–	–	0.00 ± 0.53	–
		HL-LHC	-0.01 ± 0.69	0.00 ± 0.43	-0.01 ± 0.55	0.00 ± 0.05	0.00 ± 0.02
	$\partial Q_x/\partial 2J_y$	LHC	0.00 ± 0.68	–	–	0.00 ± 0.68	–
		HL-LHC	0.01 ± 0.77	0.00 ± 0.51	0.01 ± 0.59	0.00 ± 0.05	0.00 ± 0.02

Misalign LHC Correctors

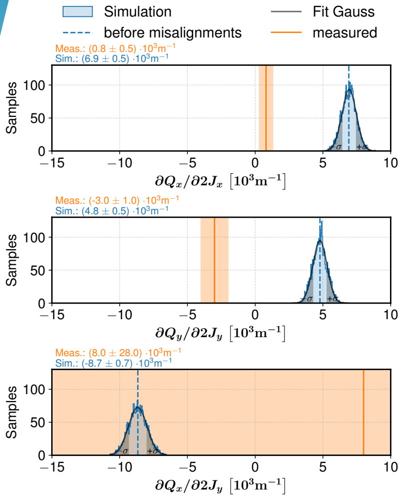

Figure: Beam 1

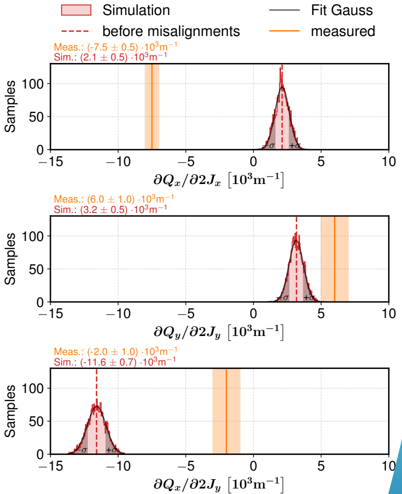

Figure: Beam 2

Misalign LHC Correctors

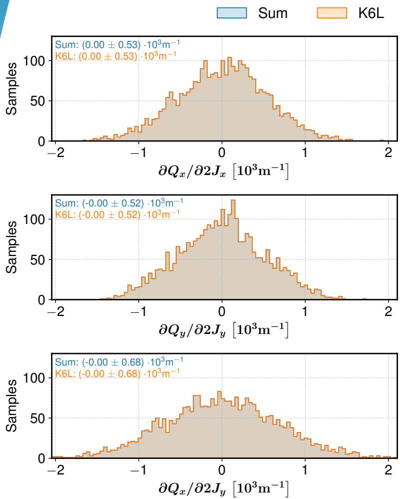

Figure: Beam 1

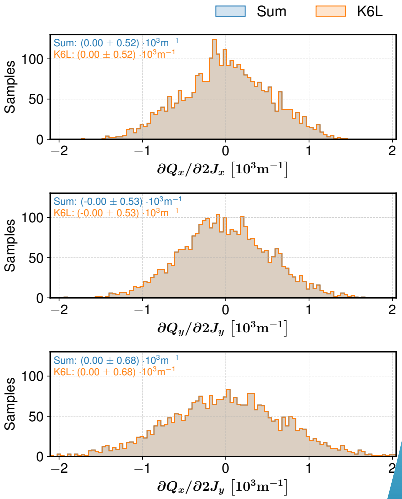

Figure: Beam 2

Misalign HL-LHC Correctors

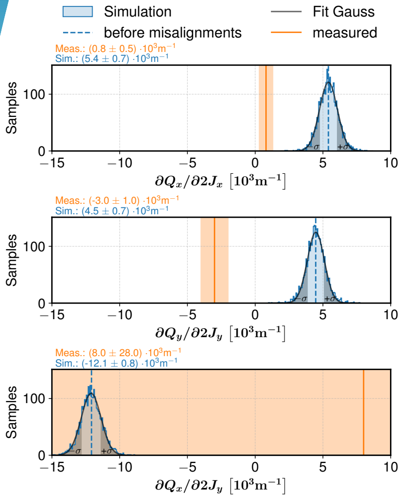

Figure: Beam 1

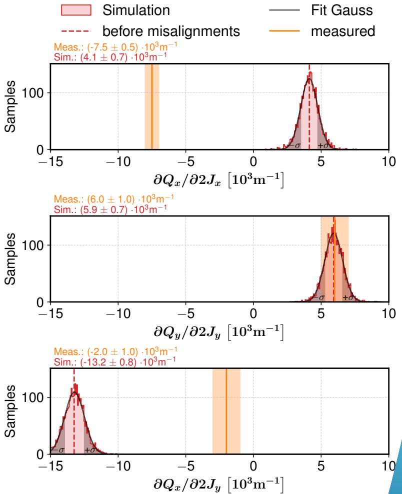

Figure: Beam 2

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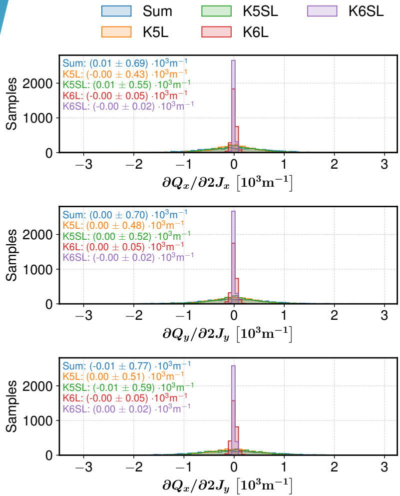

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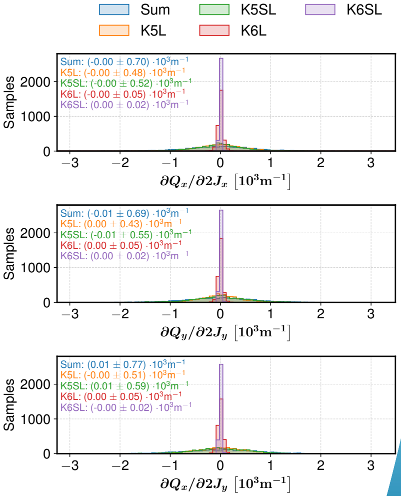


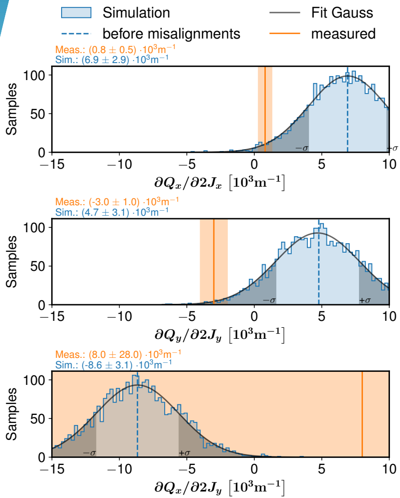
Figure: Beam 2

Triplet Misalignment Feedown

Table: Triplet misalignment summary - feeddown from field components to first order amplitude detuning

	$[10^3\ \mathrm{m}^{-1}]$		Sum	Decapole	Skew Decapole	Dodecapole	Skew Dodecapole
Beam 1	$\partial Q_x/\partial 2J_x$	LHC	0.03 ± 2.90	0.00 ± 2.59	0.03 ± 1.02	0.00 ± 0.68	0.00 ± 0.47
		HL-LHC	-0.01 ± 0.62	0.00 ± 0.42	-0.01 ± 0.44	0.00 ± 0.07	0.00 ± 0.03
	$\partial Q_y/\partial 2J_y$	LHC	-0.05 ± 3.07	-0.03 ± 1.44	-0.03 ± 2.61	0.00 ± 0.74	0.00 ± 0.15
		HL-LHC	0.00 ± 0.61	0.00 ± 0.42	-0.01 ± 0.44	0.00 ± 0.07	0.00 ± 0.02
	$\partial Q_x/\partial 2J_y$	LHC	0.02 ± 3.06	0.03 ± 2.25	0.00 ± 1.78	0.00 ± 1.04	0.00 ± 0.38
		HL-LHC	0.00 ± 0.73	0.00 ± 0.50	0.01 ± 0.51	0.00 ± 0.09	0.00 ± 0.03
Beam 2	$\partial Q_x/\partial 2J_x$	LHC	-0.05 ± 3.07	-0.03 ± 1.44	-0.03 ± 2.60	0.00 ± 0.74	0.00 ± 0.15
		HL-LHC	0.00 ± 0.61	0.00 ± 0.42	-0.01 ± 0.44	0.00 ± 0.07	0.00 ± 0.02
	$\partial Q_y/\partial 2J_y$	LHC	0.03 ± 2.91	0.00 ± 2.59	0.03 ± 1.02	0.00 ± 0.68	0.00 ± 0.47
		HL-LHC	-0.01 ± 0.62	0.00 ± 0.42	-0.01 ± 0.44	0.00 ± 0.07	0.00 ± 0.03
	$\partial Q_x/\partial 2J_y$	LHC	0.02 ± 3.06	0.03 ± 2.25	0.00 ± 1.78	0.00 ± 1.04	0.00 ± 0.38
		HL-LHC	0.00 ± 0.73	0.00 ± 0.50	0.01 ± 0.51	0.00 ± 0.09	0.00 ± 0.03

Misalign LHC Triplets



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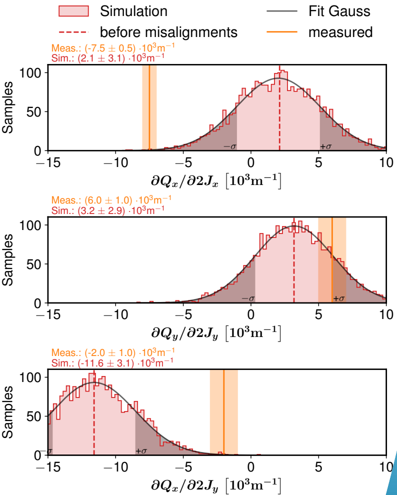


Figure: Beam 2

Misalign LHC Triplets

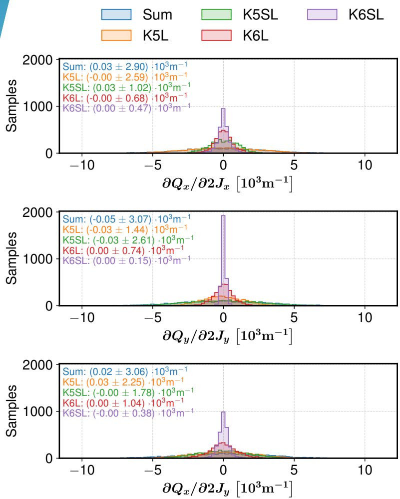


Figure: Beam 1

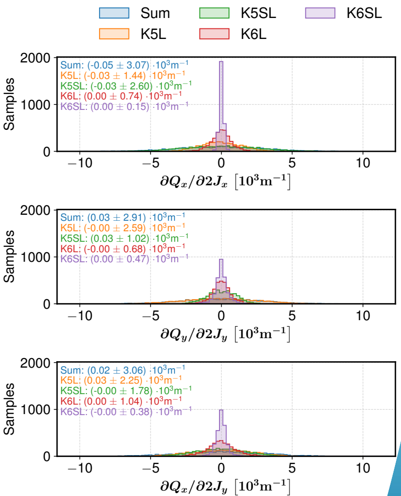


Figure: Beam 2

Misalign HL-LHC Triplets

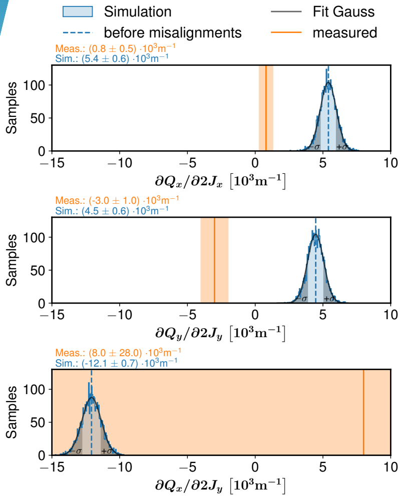


Figure: Beam 1

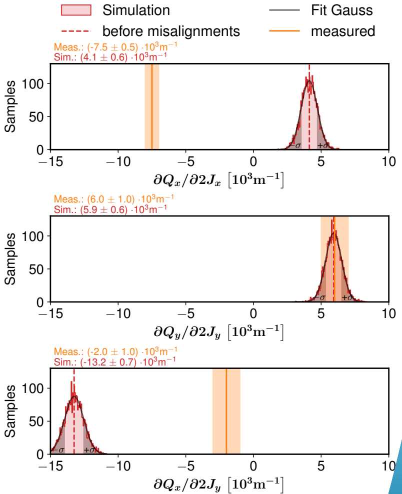
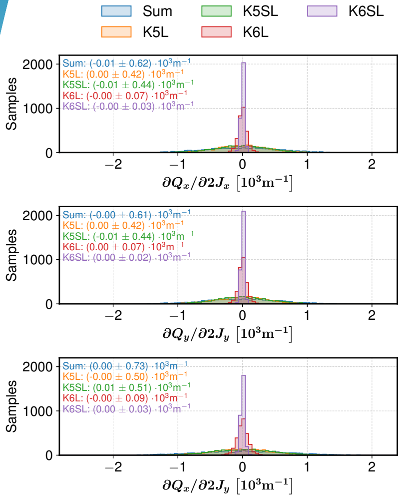


Figure: Beam 2

Misalign HL-LHC Triplets



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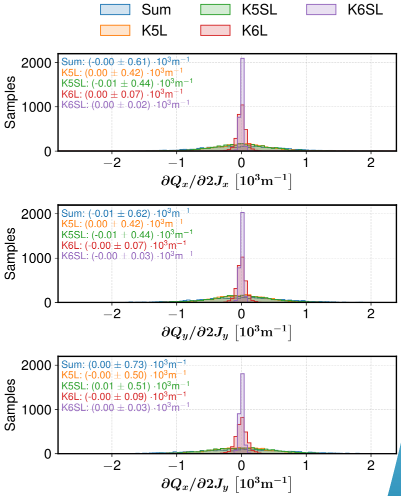
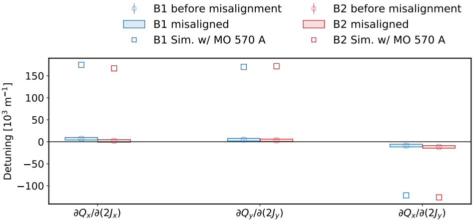


Figure: Beam 2

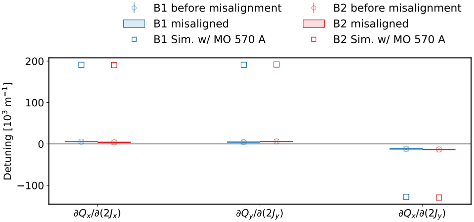
Misalign Triplets

… and compare to highly powered MO's

LHC



HL-LHC



- MO powering of 570 A causes amplitude detuning to increase from $\sim 5 \cdot 10^3 \mathrm{m}^{-1}$ up to $\sim 170 \cdot 10^3 \mathrm{m}^{-1}$ in the direct terms.