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LHC Preliminary IR Analysis and Compensation Schemes

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sorting

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About this talk:

- preliminary, "educated guess"
  (with RHIC magnet construction experience)
- to present ideas and to initiate discussion
- to get feedback for future detailed studies
- magnetic field quality issues only; no beam-beam; pre-assumed β^* and crossing angle Φ

1. Introduction

Lattice 5.0:

Crucial factors for IR performance:

β^* at IP $\Longrightarrow \beta_{max}$ at HGQ and D1

crossing angle $\Phi \Longrightarrow \pm 100\ \mu$r ± 5 mm ($\beta^* = 0.5$ m)

Crossing angle and β^* for LHC collision

	IP	nominal	option
β^* (m)	1	0.5	0.5?
	5	0.5	0.5?
	2	50–250	0.25 - 0.5?
	8	33	?
crossing angle	1	± 100	± 175?
(μr)	5	± 100	± 175?
	2	± 100	?
	8	± 100	?

Expected High Gradient Quad errors ($R_0 = 2.2$ cm):

Order, n	Normal			Skew		
BODY [unit]	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
2	—	—	—	—	—	—
3	0.0	0.5	2.9	0.0	0.5	2.9
4	0.0	0.5	2.0	0.0	0.5	2.0
5	0.0	0.5	1.0	0.0	0.5	1.0
6	0.0	0.5	1.4	0.0	0.5	0.7
7	0.0	0.5	0.4	0.0	0.5	0.4
8	0.0	0.5	0.3	0.0	0.5	0.3
9	0.0	0.5	0.4	0.0	0.5	0.4
10	0.0	0.5	0.3	0.0	0.5	0.3
LEAD END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	—	—	—	18.1	—	—
6	4.6	—	—	-0.4	—	—
10	-0.8	—	—	-0.2	—	—
RETURN END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
6	0.6	—	—	0.0	—	—
10	-0.7	—	—	0.0	—	—

Note:

- Body harmonics converted from the HGQ harmonics (after correction of systematic errors) of Tables 5 and 6 (storage only) of the paper by Sabbi et. al.
- End harmonics converted from Tables 5 of the paper by Caspi and Chow.
- Coil id is 7.0 cm.
- Quoted harmonic values are given in "units" of 10^{-4} of the main quad field at 2.2 cm reference radius. European convention: b1 is dipole!

Expected High Gradient Quad errors ($R_0 = 1.0$ cm):

Order, n	Normal			Skew		
BODY [unit]	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
2	—	—	—	—	—	—
3	0.0	0.2	1.3	0.0	0.2	1.3
4	0.0	0.09	0.4	0.0	0.09	0.4
5	0.0	0.04	0.09	0.0	0.04	0.09
6	0.0	0.02	0.06	0.0	0.02	0.03
7	0.0	0.01	0.008	0.0	0.01	0.008
8	0.0	0.004	0.003	0.0	0.004	0.003
9	0.0	0.002	0.0016	0.0	0.002	0.0016
10	0.0	0.0009	0.0005	0.0	0.0009	0.0005
LEAD END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	—	—	—	18.1	—	—
6	0.20	—	—	−0.015	—	—
10	−0.0015	—	—	−0.0004	—	—
RETURN END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
6	0.027	—	—	0.0	—	—
10	−0.0013	—	—	0.0	—	—

Note:

- Body harmonics from the HGQ harmonics (after correction of systematic errors) of Tables 5 and 6 (storage only) of the paper by Sabbi et. al.
- End harmonics converted from Tables 5 of the paper by Caspi and Chow.
- Coil id is 7.0 cm.
- Quoted harmonic values are given in "units" of 10^{-4} of the main quad field at 1.0 cm reference radius. European convention: b1 is dipole!

Expected IR dipole errors ($R_0 = 2.5$ cm):

Order, n	Normal			Skew		
BODY [unit]	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
2	0.0	1.0	0.4	-2.0	1.0	1.5
3	0.0	4.0	2.0	-1.1	0.1	0.2
4	0.0	0.3	0.1	-0.5	0.3	0.4
5	0.4	1.0	0.6	0.2	0.05	0.1
6	0.0	0.1	0.03	-0.1	0.2	0.05
7	1.3	0.5	0.2	-0.1	0.03	0.03
8	0.0	0.01	0.01	0.0	0.03	0.05
9	0.05	0.1	0.03	0.02	0.02	0.01
10	0.0	0.03	0.01	0.0	0.01	0.01
11	-0.5	0.1	0.03	-0.01	0.01	0.01
LEAD END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	-2.0	2.0	1.0	2.0	4.0	1.0
3	21.0	2.0	2.0	-10.0	1.0	1.0
4	0.3	0.2	0.2	0.0	1.0	1.0
5	1.0	0.5	0.2	2.0	0.5	0.3
6	0.0	0.2	0.2	0.0	1.0	0.2
7	1.0	0.5	0.1	-0.9	0.2	0.2
8	0.0	0.1	0.1	0.0	0.1	0.1
9	-0.2	0.2	0.1	0.3	0.1	0.1
10	-0.2	0.2	0.2	0.0	0.1	0.1
11	0.1	0.1	0.1	-0.1	0.1	0.1
RETURN END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	1.4	1.0	1.0	3.0	0.5	1.0
3	-1.0	4.0	1.0	-0.8	0.5	1.0
4	0.3	0.1	0.1	0.2	0.3	0.5
5	08	0.5	0.2	0.2	0.1	0.1
6	0.0	0.1	0.1	0.2	0.1	0.2
7	0.0	0.1	0.1	0.1	0.05	0.1
8	0.0	0.1	0.1	0.0	0.05	0.1
9	-0.2	0.1	0.1	0.1	0.05	0.1
10	-0.2	0.1	0.1	0.0	0.05	0.1
11	-0.1	0.1	0.1	0.0	0.05	0.1

Note:

- Body and end harmonics provided by R. Gupta.
- Coil id is 8.0 cm.
- Quoted harmonic values are given in "units" of 10^{-4} of the main dipole field at 2.5 cm reference radius. European convention: b1 is dipole!

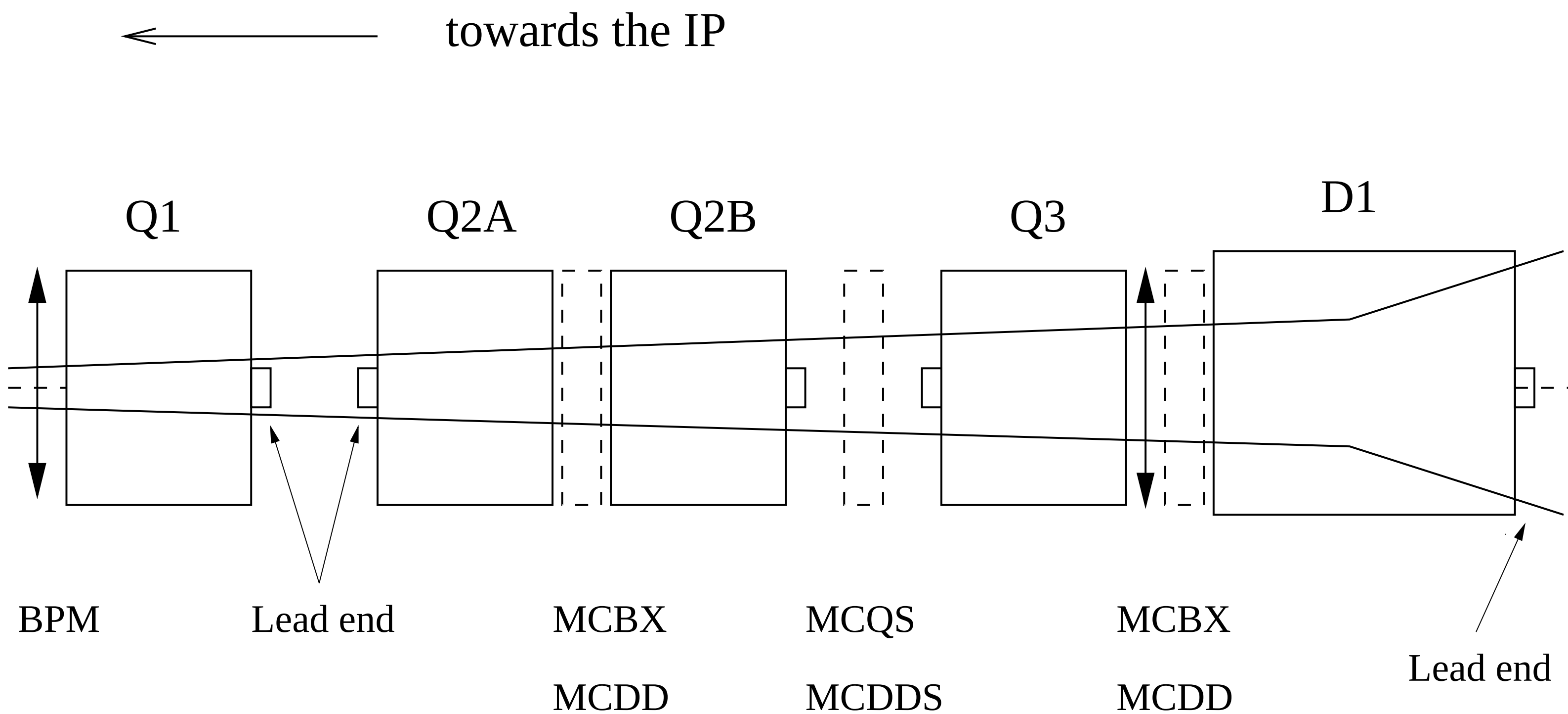
Expected IR dipole errors ($R_0 = 1.0$ cm):

Order, n	Normal			Skew		
BODY [unit]	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
2	0.000000	0.400000	0.160000	-0.800000	0.400000	0.600000
3	0.000000	0.640000	0.320000	-0.176000	0.016000	0.032000
4	0.000000	0.019200	0.006400	-0.032000	0.019200	0.025600
5	0.010240	0.025600	0.015360	0.005120	0.001280	0.002560
6	0.000000	0.001024	0.000307	-0.001024	0.002048	0.000512
7	0.005325	0.002048	0.000819	-0.000410	0.000123	0.000123
8	0.000000	0.000016	0.000016	0.000000	0.000049	0.000082
9	0.000033	0.000066	0.000020	0.000013	0.000013	0.000007
10	0.000000	0.000008	0.000003	0.000000	0.000003	0.000003
11	-0.000052	0.000010	0.000003	-0.000001	0.000001	0.000001
LEAD END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	-0.800000	0.800000	0.400000	0.800000	1.600000	0.400000
3	3.360000	0.320000	0.320000	-1.600000	0.160000	0.160000
4	0.019200	0.012800	0.012800	0.000000	0.064000	0.064000
5	0.025600	0.012800	0.005120	0.051200	0.012800	0.007680
6	0.000000	0.002048	0.002048	0.000000	0.010240	0.002048
7	0.004096	0.002048	0.000410	-0.003686	0.000819	0.000819
8	0.000000	0.000164	0.000164	0.000000	0.000164	0.000164
9	-0.000131	0.000131	0.000066	0.000197	0.000066	0.000066
10	-0.000052	0.000052	0.000052	0.000000	0.000026	0.000026
11	0.000010	0.000010	0.000010	-0.000010	0.000010	0.000010
RETURN END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	0.560000	0.400000	0.400000	1.200000	0.200000	0.400000
3	-0.160000	0.640000	0.160000	-0.128000	0.080000	0.160000
4	0.019200	0.006400	0.006400	0.012800	0.019200	0.032000
5	0.204800	0.012800	0.005120	0.005120	0.002560	0.002560
6	0.000000	0.001024	0.001024	0.002048	0.001024	0.002048
7	0.000000	0.000410	0.000410	0.000410	0.000205	0.000410
8	0.000000	0.000164	0.000164	0.000000	0.000082	0.000164
9	-0.000131	0.000066	0.000066	0.000066	0.000033	0.000066
10	-0.000052	0.000026	0.000026	0.000000	0.000013	0.000026
11	-0.000010	0.000010	0.000010	0.000000	0.000005	0.000010

Note:

- Body and end harmonics provided by R. Gupta.
- Coil id is 8.0 cm.
- Quoted harmonic values are given in "units" of 10^{-4} of the main dipole field at 1.0 cm reference radius. European convention: b1 is dipole!

- Observation:
  - Systematic errors at magnet lead end is significant for both HGQ and IR dipole
  - Variation in β is large across each individual HGQ or D1 magnet
  - betatron phase advance is negligible across HGQ and D1


towards the IP
Q1
Q2A
Q2B
Q3
D1
BPM
Lead end
MCBX
MCDD
MCQS
MCDDS
MCBX
MCDD
Lead end

LHC version 5.0, collision optics

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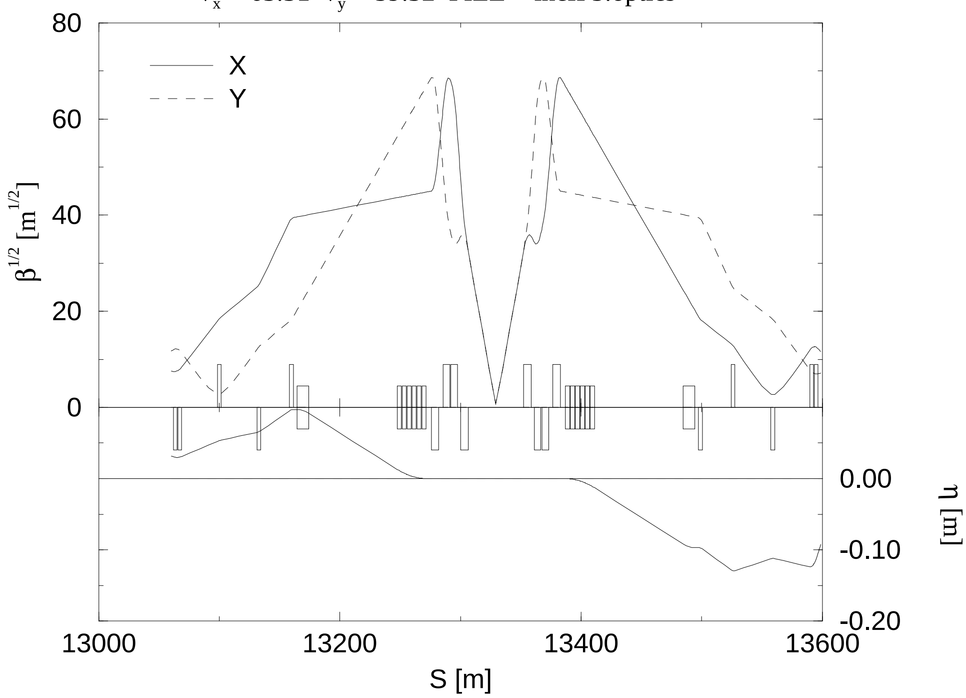

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LHC version 5.0, collision optics

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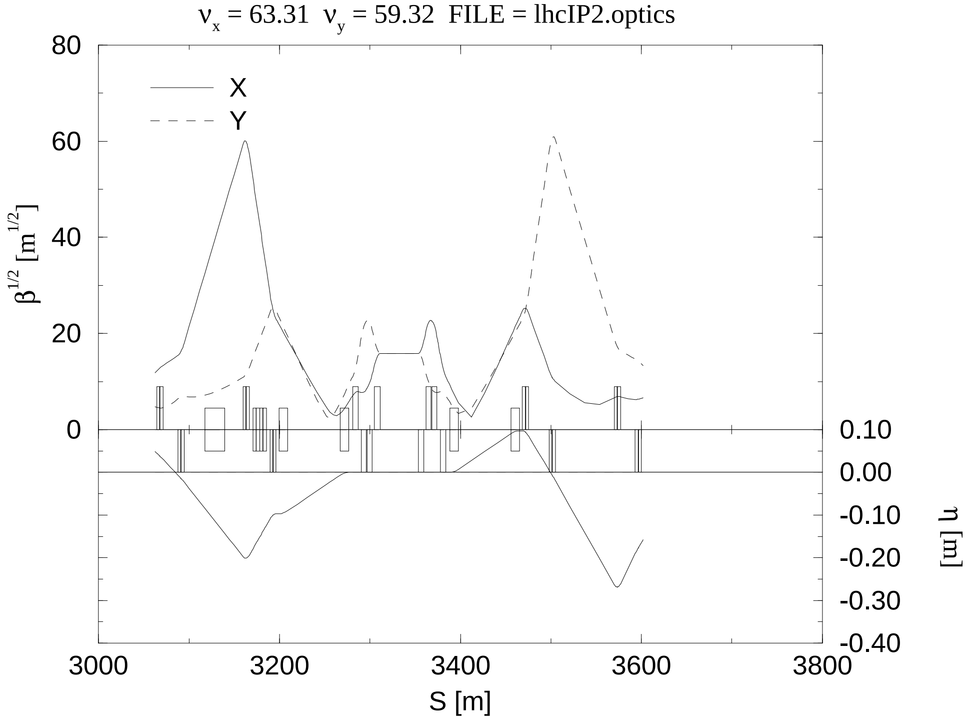

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2. Effects of IR Magnet Errors

Figure of merit:

$$\left|\frac{\Delta J_{x,y}}{J_{x,y}}\right| = \frac{1}{4\pi\rho}\sum_{\text{magnet}} L\beta_{x,y}\left[(2\beta_{x,y}J)^{1/2} + \frac{\Delta_{sep}}{2}\right]^{n-2} b_n \tag{1}$$

$$2J = \frac{N_{GF}^2 \epsilon_n}{\beta\gamma}, \quad N_{GF} = 8 \tag{2}$$

$$\Delta_{sep,max} \approx \Phi\hat{L} \approx \Phi\sqrt{\beta^*\beta_{max}} \tag{3}$$

$$b_n = \begin{cases} \left(\dfrac{R_0 G_0}{B_0}\right)\dfrac{10^{-4} b_n'}{R_0^{n-1}} & \text{(quad)} \\[2ex] \dfrac{10^{-4} b_n'}{R_0^{n-1}} & \text{(dipole)} \end{cases} \tag{4}$$

Target:

$$\left|\frac{\Delta J_{x,y}}{J_{x,y}}\right| < 5 \times 10^{-3} \quad \text{(for } 8\sigma\text{)} \tag{5}$$

List of injection and collision parameters:

Quantity	Unit	Injection	Collision
E	TeV	0.45	7
β^*	m	> 18	0.5
β_{max}	m	~ 200	4500
Φ	μr	350	200
$\sigma_{x,y,IR}$	mm	1.3	1.5
$\sigma_{x,y,arc}$	mm	1.2	0.3
$\Delta_{sep}/2$	mm	8.3	4.7
$8\sigma_{x,y,max} + \Delta_{sep}/2$	mm	18.3	16.7

- During collision ($\beta^* = 0.5$ m), IR field quality determines machine performance
- During collision at IPs of high β^*, beam excursion is about a factor of 2 smaller; IR field quality is determined by injection requirements
- During injection, IR field quality is also important if a large crossing angle is desired

persistent current, snap-back, etc.

IR High Gradient Quads:

Action-kick sensitivity to HGQ field errors at collision:

Multipole	$\lvert\Delta J/J\rvert$ $(\times 10^{-3})$
b_3/a_3	2.5
b_4/a_4	1.9
b_5/a_5	1.5
b_6/a_6	1.1
b_7/a_7	0.87
b_8/a_8	0.68
b_9/a_9	0.52
b_{10}/a_{10}	0.41

Note:

- 1 unit multipole error on one (Q2A+Q2B) quad set
- $\beta^* = 0.5$ m; 8σ amplitude ($N_{GF} = 8$); $\Phi = 200$ μr
- order factor 0.77

IR High Gradient Quads:

Action-kick sensitivity to HGQ field errors at collision:

Multipole	$\lvert\Delta J/J\rvert$ ($\times 10^{-3}$)
b_3/a_3	2.7
b_4/a_4	2.4
b_5/a_5	2.1
b_6/a_6	1.8
b_7/a_7	1.5
b_8/a_8	1.3
b_9/a_9	1.2
b_{10}/a_{10}	1.0

Note:

- 1 unit multipole error on one (Q2A+Q2B) quad set
- $\beta^* = 0.5$ m; 8σ amplitude ($N_{GF} = 8$); $\Phi = 300\ \mu$r
- order factor 0.87

IR dipoles:

Action-kick sensitivity to D1 field errors at collision:

Multipole	$\|\Delta J/J\|$ $(\times 10^{-3})$
b_2/a_2	4.3
b_3/a_3	2.8
b_4/a_4	1.8
b_5/a_5	1.2
b_6/a_6	0.78
b_7/a_7	0.51
b_8/a_8	0.34
b_9/a_9	0.22
b_{10}/a_{10}	0.14
b_{11}/a_{11}	0.09

Note:

- 1 unit multipole error on one D1 dipole
- $\beta^* = 0.5$ m; 8σ amplitude ($N_{GF} = 8$); $\Phi = 200$ μr
- order factor 0.65

Multipole feeddown due to non-zero crossing angle:

$$\tilde{b}_n \approx \frac{n\Phi\hat{L}}{2R_0} b_{n+1} \tag{6}$$

$$\tilde{a}_n \approx \frac{n\Phi\hat{L}}{2R_0} a_{n+1} \tag{7}$$

3. Possible Compensation Schemes

Magnet lead end orientation

IR dipole D1

- lead end away from IP

IR HGQ

- cancellation among F and D quads

Amplitude-weighted body-ends compensation

$$b_6(\text{body}) = -\frac{B_{6L} \sum\limits_{L.E.,} G_i \beta_{xi}^3 \Big|_{\text{FDF,DFD}} + +B_{6R} \sum\limits_{R.E.} G_i \beta_{xi}^3 \Big|_{FDF,DFD}}{\sum\limits_{\text{body}} \int G_i \beta_x^3 ds \Big|_{\text{FDF,DFD}}}. \qquad (8)$$

$$b_6 = -0.10\ B_{6L} - 0.23\ B_{6R} = -0.6\ (\text{unit}). \qquad (9)$$

- same target b_6 for all HGQ magnets
- smaller body b_6 than individual compensation
- coefficients show proper magnet orientation
- true for $\beta^* = 0.5$ m (IP1, IP5)
- crossing angle contribution not considered
- similar for b_3 compensation in D1 dipole

Tuning shims and multipole candidates

- can individually correct each IR HGQ quad and D1 dipole after it is constructed and measured

- with 8 slots for shimming, can correct 8 body harmonics (b_3/a_3, b_4/a_4, b_5/a_5, b_6/a_6)

- limited by measurement uncertainty and field variation with quench and thermal cycles

Corrector layers, locations, and arrangement

Possible IR triplet correction strategy:

Order, n	Normal, b_n	Skew, a_n
1	MCBX	MCBX
2	trim	MCQS
3	S	S
4	B, S	S
5	S	S
6	B+, S+, MCDD (2)	B+, S, MCDDS
8	B	
10	B	

B: coil cross-section iteration

B+: coil cross-section iteration plus body-ends compensation

S: using tuning shims

S+: using tuning shims on random b_5 after body-ends compensation

MCBX: local normal/skew dipole corrector

MCQS: local skew quad corrector

MCDD: local b_6 corrector (2 per IP)

MCDDS: local a_6 corrector

Local higher-order IR corrector:

- valuable “knobs” for beam-based correction
- especially useful if measurement uncertainty and quench/thermal cycle dependence is large
- large expected b_3/a_3, b_4/a_4 uncertainty requires correction
- possible added layers and locations?

4. Summary and Discussion

- Field quality requirements of HGQ quads and D1 dipoles depend heavily on the most demanding operational condition (β^* and Φ) at IP2 and IP8

- Compensation schemes can greatly improve machine performance

  - choosing lead end orientation
  - amplitude-weighted body-ends compensation
  - tuning shims
  - sorting (best HGQ for IP5)

- Higher-order IR correctors highly desired

- Detailed simulation/tracking studies planned

Future plans:

- up-to-date on expected multipole errors for both body and fringe fields in all IR dipoles and quads
- action-kick analysis to evaluate the impact of expected IR magnet errors on LHC performance under various collision schemes of crossing angle and β^*
- tracking with FTPOT and/or SIXTRACK with magnet errors on IR magnets only for tune footprint evaluation and dynamic aperture evaluation
- MAD tracking to "validate" and spot-check FTPOT and/or SIXTRACK results
- create Standard Machine Format (SMF) LHC description
- develop triplet filter, crossing-angle filter, and slice filter to simulate compensation schemes
- track the SMF LHC lattice with compatible codes including TPOT++