Research supported by the High Luminosity LHC project

HiLumi LHC
Update on MCBRD Field Quality

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Outline

1 Introduction

2 Reference Field Strength and Sign

3 DA Studies

4 Conclusion

Aim

- Develop robust error routines for the MCBRD magnets that handle all possible error signs correctly at all orders
- Investigate effect of the expected errors on DA
- Scan over different values of a_3 and b_3

- DA is calculated over 11 angles and 60 seeds
- HLLHC V1.0 optics; to have a well-studied configuration and quick results

$$\beta^* = 0.15/0.15/0.15/0.15\text{m},\ Q_x = 62.31,\ Q_y = 60.32$$
$$\mu_x^{1\to5} = 31.210°,\ \mu_y^{1\to5} = 30.373°$$
$$d_{\text{sep}}^{1,5} = 2\text{mm},\ \theta_c = 250\ \text{mrad}$$

Introduction

- MCBRD have two functions:
  - Create orbit bumps $\Rightarrow$ setting in optics file
  - Correct orbit distortions $\Rightarrow$ set during operation
- Magnets for horizontal and vertical planes $\Rightarrow$ 8 Magnets
- Power connections (latest layout from 2018):

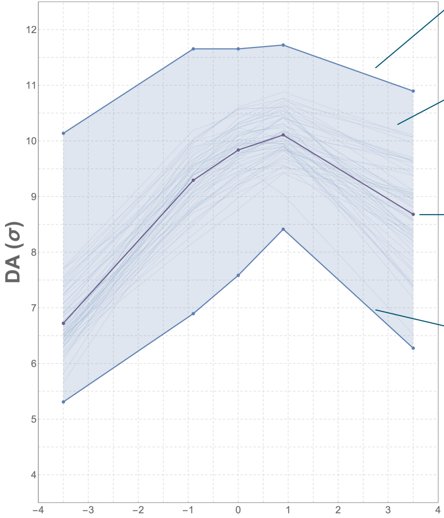
  IP … {=D2 =MCBRDH MCBRDV=} …

  $\Rightarrow$ MCBRDH.L and MCBRDV.R are inverted

  $\Rightarrow$ MCBRDH: iap=1 for Beam 1, iap=2 for Beam 2

  MCBRDV: iap=2 for Beam 1, iap=1 for Beam 2
- For V1.0, both apertures of one MCBRD magnet acted in the same plane (now they alternate planes)

Example DA plot



absolute maximum
(maximum angle over all seeds)

individual seed lines
(average over angles per seed)

average DA
(average over angles and over seeds)

absolute minimum
(minimum angle over all seeds)

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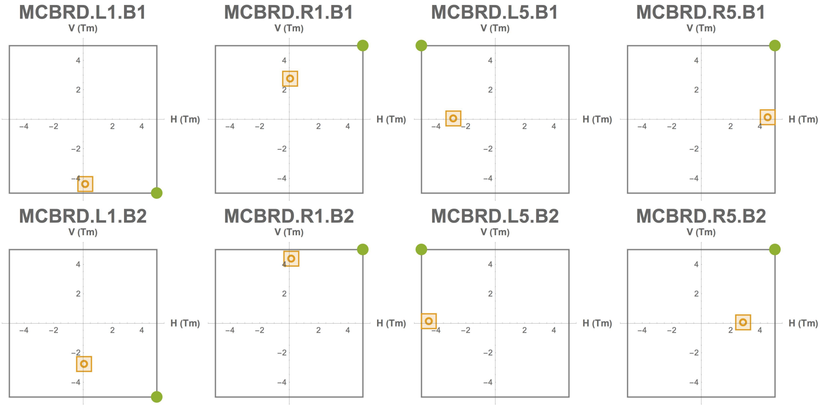
Sign of MCBRD Reference Field, Study 1

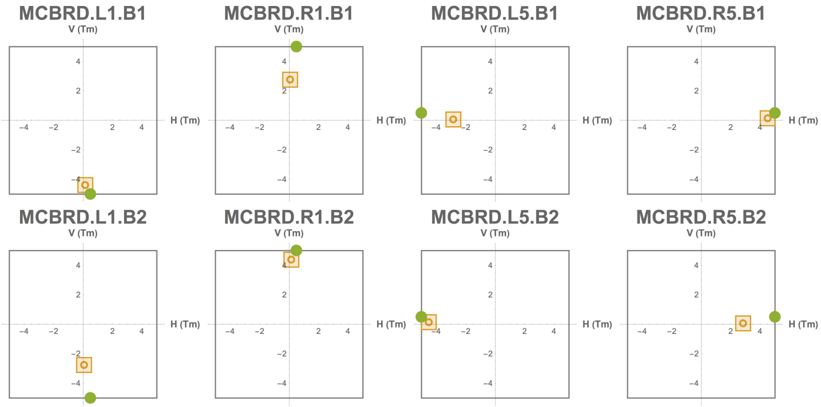
- sign of reference field is in some cases dominated by deterministic part
- fixed for 8 magnets (crossing plane)
- undefinable for 8 magnets (separation plane)
- when undefined, set positive


MCBRD.L1.B1
MCBRD.R1.B1
MCBRD.L5.B1
MCBRD.R5.B1
MCBRD.L1.B2
MCBRD.R1.B2
MCBRD.L5.B2
MCBRD.R5.B2
V (Tm)
H (Tm)


MCBRD.L1.B1
MCBRD.R1.B1
MCBRD.L5.B1
MCBRD.R5.B1
MCBRD.L1.B2
MCBRD.R1.B2
MCBRD.L5.B2
MCBRD.R5.B2
V (Tm)
H (Tm)
max range
optics setting
range for orbit correction
reference field for errors

Sign of MCBRD Reference Field, Study 2

- variable part is very small
- in the separation plane, deterministic part is nearly zero
- reference field much smaller than maximum
- sign in separation plane still undefinable, hence set positive


MCBRD.L1.B1
MCBRD.R1.B1
MCBRD.L5.B1
MCBRD.R5.B1
MCBRD.L1.B2
MCBRD.R1.B2
MCBRD.L5.B2
MCBRD.R5.B2
V (Tm)
H (Tm)

Errortable for MCBRD

- Nominal table in slhc/errors2/MCBRD_errortable_v3

- Only **systematic** errors (with $R_{\text{ref}} = 35$mm):

  $b_3 = -10$ (MCBRDH; all other orders zero)

  $a_3 = +10$ (MCBRDV; all other orders zero)

  Taken from 8th Annual HiLumi Meeting

  (*E. Todesco*, et_wp3_hilumi_2018-10-17.pdf)

- Reference fields:

  $B^{\text{ref}}_{\text{MCBRDH}} = 5\,\text{Tm}$ $B^{\text{ref}}_{\text{MCBRDV}} = 5\,\text{Tm}$

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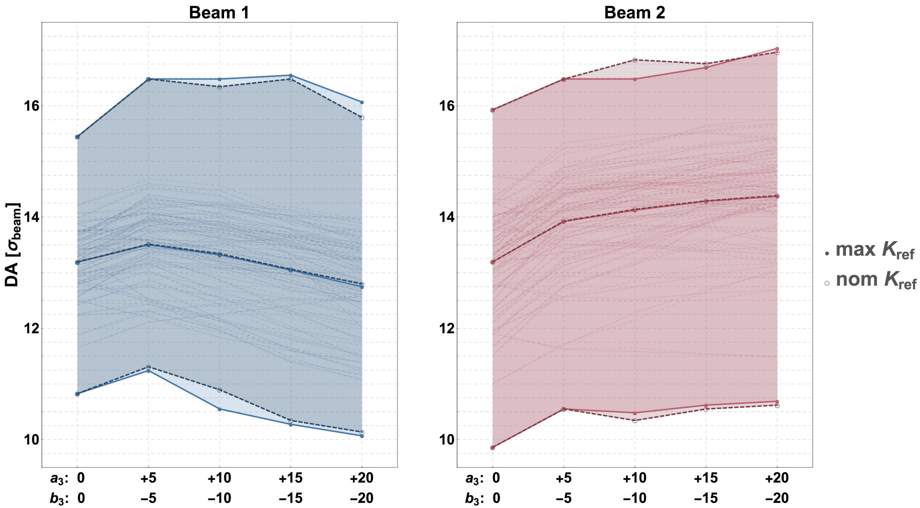
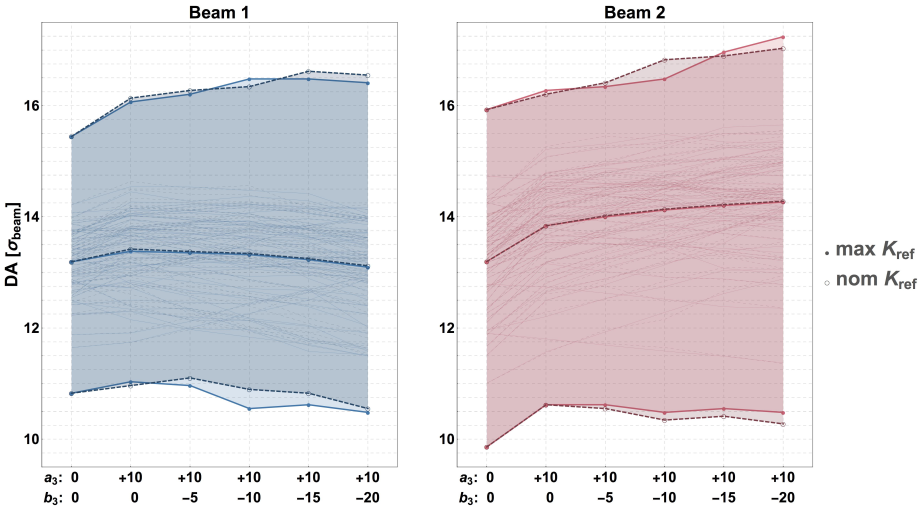
Scan

- Baseline for HLLHC V1.0, with MCBRD errors (but without MCBXF errors), scanning over a_3 (vertical correctors) and/or b_3 (horizontal correctors)
- Reference strengths with nominal signs (when determined by optics)
- Two setups:
  - reference strengths always at maximum
  - reference strengths at 10% in separation plane

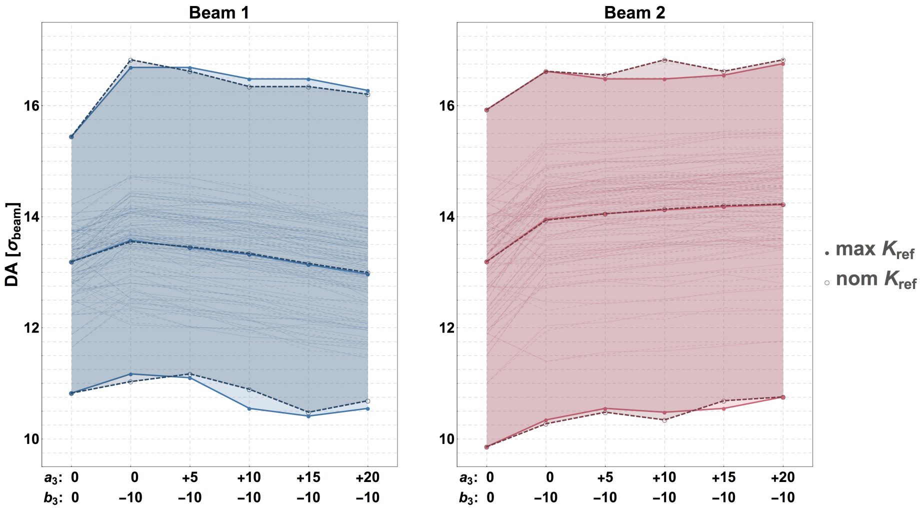
Error investigation of MCBRD (nominal signs), scan over a_3 and b_3



Error investigation of MCBRDH (nominal signs), scan over b_3



Error investigation of MCBRDV (nominal signs), scan over a_3



Outlook

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Conclusions & Outlook

- Slight trends in DA are visible: downwards (wrt. larger a_3/b_3) for Beam 1, and upwards for Beam 2
- Effect is stronger for vertical correctors than for horizontal
- Using 10% strength in the separation plane has no effect

  $\Rightarrow$ behaviour is dominated by crossing plane

- Todo:
  - Investigate source of difference between Beam 1 and 4
  - Investigate different signs of reference fields using a Monte Carlo approach to sample the space (2^8 configurations)

Thank you for your attention!

Backup Slides

Multipole Expansion

- Errors are expanded in **multipoles**:

$$\boldsymbol{B_y + iB_x = \sum_{n=0}^{\infty} \left(B_{n+1} + iA_{n+1}\right) \frac{(x+iy)^n}{R^n}}$$

$B_y(x,y)$ and $B_x(x,y)$, but $\frac{\partial B_n}{\partial x} = \frac{\partial B_n}{\partial y} = \frac{\partial A_n}{\partial x} = \frac{\partial A_n}{\partial y} = 0$

- $B_y = \text{Re}\left\{B_y + iB_x\right\}$ $\qquad$ $B_x = \text{Im}\left\{B_y + iB_x\right\}$

- Expansion is **not** automatically frame invariant!

Multipole Expansion: Signs

- If we interchange $x \to -x$ (e.g. Beam 4), we have to adapt the multipoles to keep $B_y \to B_y$:

$$B_y = \sum_{n=0}^{\infty} \left[B_{n+1} \sum_{m \text{ even}} (-)^{\frac{m}{2}} - A_{n+1} \sum_{m \text{ odd}} (-)^{\frac{m-1}{2}} \right] \binom{n}{m} \frac{y^m x^{n-m}}{R^n}$$

- If $x \to -x$ then

$$\boldsymbol{A}_{\text{odd}} \to -\boldsymbol{A}_{\text{odd}} \quad \text{and} \quad \boldsymbol{B}_{\text{even}} \to -\boldsymbol{B}_{\text{even}}$$

(i.e. skew dipole, regular quadrupole, skew sextupole, ...)

Reference Field

- Reference field is dominant order of magnet
- Errors are several orders of magnitude smaller
- No errors at orders below reference field by definition

$$\boldsymbol{B_n = 10^{-4}\,B_N\,b_n \qquad A_n = 10^{-4}\,B_N\,a_n}$$

or $$\boldsymbol{B_n = 10^{-4}\,A_N\,b_n \qquad A_n = 10^{-4}\,A_N\,a_n}$$

where $b_{n<N} = 0$

Reference Field: Signs

$$B_y + i\,B_x = 10^{-4}\,\frac{B_N}{R^N}\sum_{n=N}^{\infty}\left(b_{n+1} + i\,a_{n+1}\right)\frac{(x+i\,y)^n}{R^{n-N}}$$

- Main field can be regular (B_N) or skew (A_N)
- Sign of main field changes for B_{even} or A_{odd}
- If x-flip, multipoles have to change sign when

  $B_{\text{odd}}\,a_{\text{odd}},\ B_{\text{odd}}\,b_{\text{even}},\ A_{\text{even}}\,a_{\text{odd}},\ A_{\text{even}}\,b_{\text{even}},$

  $B_{\text{even}}\,a_{\text{even}},\ B_{\text{even}}\,b_{\text{odd}},\ A_{\text{odd}}\,a_{\text{even}},\ A_{\text{odd}}\,b_{\text{odd}}$

Implementation in Error Routines

- **1**: check if x-flip, if yes then **2**: flip correct order
- x-flip in case of:

  y-rotation, error convention, and Beam 4
- $\mathtt{y}_{\mathtt{fact}} = (-1)^{\mathtt{is\_inv} + \mathtt{magnetic\_sign} + \mathtt{is\_beam4}}$

- Define: $\mathtt{aaa} = \mathtt{y}_{\mathtt{fact}}$ $\mathtt{bbb} = 1$

$\mathtt{aaa} \cdot a_{\text{odd}}$	$\mathtt{aaa} \cdot b_{\text{even}}$
$\mathtt{bbb} \cdot b_{\text{odd}}$	$\mathtt{bbb} \cdot a_{\text{even}}$

Implementation in Error Routines

- Instead of changing the sign of the reference field, we change the sign of all multipoles
- Skew magnets are given negative reference radius $\Rightarrow$ `is_skew`
- **But** sign of reference field in case of Beam 4 is already taken into account in optics (due to `bv_aux` flag) or in Beam 4 sequence file
- $\mathtt{y_{factref}} = (-1)^{\mathtt{is\_inv} + \mathtt{magnetic\_sign}}$
- If $\mathtt{y_{factref}} = -1$: `sign` = $(-1)^{\mathtt{is\_skew} + \mathtt{order}}$ (`order` in k^n)
  else `sign` = +1
- $\mathtt{aaa} = \mathtt{sign} \cdot \mathtt{aaa} \qquad \mathtt{bbb} = \mathtt{sign} \cdot \mathtt{bbb}$

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