Research supported by the High Luminosity LHC project
HiLumi LHC:
Impact of MCBXF Field Quality on DA and Possible Mitigation Strategies

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Outline

1. Introduction
2. Large Impact of MCBXF
3. Possible Mitigation
4. Conclusions and Outlook
Aim

- Magnetic field imperfections can deteriorate beam quality
- Essential to understand which type of errors, in which magnetic families, are dominant
- Well-known that e.g. IT has huge impact
  - mitigated with non-linear corrector package
- MCBXF also has large impact...
  - which orders are dominant?
  - which sub-families?
  - other contributing factors (reference field, ...)?
  - how to improve the situation?
Dynamic Aperture

- DA is a tool to estimate beam quality
- Smallest connected volume in phase space that is stable for at least $N$ turns (100 000)
- Tracking in 6D, initial conditions in 2D (11 angles)
- Repeated over 60 random machine realisations (‘seeds’)
Setup of Studies

- Very CPU-intensive (300k+ jobs)
  ⇒ submission to BOINC

Many thanks to A. Mereghetti for maintaining the scripts, and to the numerous LHC@Home volunteers

Studies are performed:

- using HL-LHC v1.4 round collision optics
- for minimum $\beta^*$ (15/1000/15/150 cm)
- without octupoles and with low chromaticity
- with nominal settings for all other values
- nominal errors are assigned from 3rd to 15th order for LHC, and HL-LHC (IT, D1, D2, MCBRD, and MBH)
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MCBXF

- Two sub-families:
  - MCBXFA in corrector package
  - MCBXFB around Q2
- Two main functions:
  - create orbit bumps
  - correct triplet misalignments
- Power setting in optics file is for bumps, triplet correction is set during operation (orbit correction phase)
  $\Rightarrow$ exact setting not known in advance
Impact on DA of MCBXF Errors

(assuming maximum strength for the reference field)
Impact on DA of MCBXF Errors

- Drop of $\sim 2.5\sigma$ on $DA_{av}$ in Beam 1
- Drop of $\sim 4\sigma$ on $DA_{min}$ in Beam 1
- Drop of $\sim 3.5\sigma$ on $DA_{av}$ in Beam 2
- Drop of $\sim 3\sigma$ on $DA_{min}$ in Beam 2

$\Rightarrow$ is there a dominant sub-family?
$\Rightarrow$ is there a dominant multipole order?
Comparing MCBXFA with MCBXFB

Beam 1

Beam 2

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Impact of MCBXF on DA 6/13
Comparing MCBXFA with MCBXFB

- Adding MCBXFB errors does not influence DA much
- Adding MCBXFA errors alone has the same impact as adding both

⇒ MCBXFA is the culprit

(not entirely unexpectedly, as MCBXFA has double the integrated strength compared to MCBXFB)
Comparing Multipole Errors

Beam 1

nominal (no MCBXF)  nominal + MCBXF  nominal + MCBXF (only $b_3/a_3$)

Beam 2

nominal (no MCBXF)  nominal + MCBXF  nominal + MCBXF (only $b_3/a_3$)
Comparing Multipole Errors

- Adding only 3rd order multipole errors to MCBXF has the same impact as adding errors at all orders

⇒ loss in DA comes from large $b_3/a_3$
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Possible Mitigation

- DA drop from large $b_3/a_3$ can be due to
  - Pure multipole error
  - Beta-beating via feed-down

- Studies have shown drop is due to pure error
  ⇒ can these be corrected by non-linear CP?
Effectiveness of MCBXF Correction

Beam 1

Beam 2

nominal (no MCBXF)  nominal + MCBXF  nominal + MCBXF (corr)

nominal (no MCBXF)  nominal + MCBXF  nominal + MCBXF (corr)
Effectiveness of MCBXF Correction

- DA with correction same as baseline
  ⇒ correction algorithm works for MCBXF

- But is this realistic?
  ⇒ size of errors is relative to reference field,
    which is related to actual powering
    (unknown due to triplets misalignment)
Alternatives

- Track dependence on powering (difficult: hysteresis)
  Depending on powering, clear compensation effects exist

- Keep operation close to nominal powering cycle:
  Full Remote Alignment System might be mitigation measure
  ⇒ MCBXF does not need to correct IT misalignments
  ⇒ setting only defined by optics!
Full Remote Alignment System

Beam 1

Beam 2

nominal (no MCBXF)  nominal + MCBXF  nominal + MCBXF (fras)

nominal (no MCBXF)  nominal + MCBXF  nominal + MCBXF (fras)

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Full Remote Alignment System

- Assuming Full Remote Alignment System is implemented, the drop in DA for Beam 1 is almost completely recovered.
- However, for Beam 2, around 50% of the drop remains
  
  \(-2\sigma \text{ on } D_A^{av} \text{ and } -1.5\sigma \text{ on } D_A^{min}\)

  ⇒ difference might stem from compensation effects in IRs
  ⇒ still some optimisation possible (i.e. phase advance)

- Is there a dependence on crossing angle?
  (important for luminosity levelling via crossing angle)
Dependence on Crossing Angle

Beam 1

Beam 2

$\frac{\theta_x}{2} [\mu rad]$ vs $DA [\sigma]$ for different crossing angle vs $DA [\sigma]$ for different crossing angle across MCBXF configurations.
Dependence on Crossing Angle

- Indeed, for Beam 1 the impact of the MCBXF errors on the DA is acceptable
- However for Beam 2, and especially for larger crossing angles, the drop in DA is still big

⇒ this might potentially be solved by correcting the errors (justified in case FRAS is implemented)
⇒ difference appears at first point \( \frac{\theta_c}{2} = 50 \)
can be investigated further
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Conclusions and Outlook

- Beam quality very sensitive to size of $b_3/a_3$ multipole error in MCBXFA.
- DA can be recovered in simulations by using the CP to correct MCBXF.
- Assuming the FRAS will be in place, the reference field of the MCBXF becomes deterministic:
  - almost no remaining impact for Beam 1.
  - still a large drop in DA persists for Beam 2 but without beam-beam, DA is still acceptable.
Conclusions and Outlook

- TODO
  - can the drop in Beam 2 be recovered by using the CP to correct MCBXF?
  - correct with middle value of $\frac{\theta_c}{2}$ but apply to all $\frac{\theta_c}{2}$ in levelling
  - check impact of MCBXF for $\beta^* = 30$cm: do we need correction during first years of HL-LHC?
Thank you for your attention!
Example Polar DA Plot

- Absolute maximum
- One-seed average
- DA average
- Absolute minimum

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Impact of MCBXF on DA
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)