



Impact of magnetic field quality on machine performance, from initial assumptions to today's status

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11th HL-LHC Collaboration Meeting, CERN - 19-22 October 2021

HIGH LUMINOSITY LHC / HL-LHC

11th

HL-LHC Collaboration Meeting
CERN, 19 - 22 October 2021



for the 5th Cost and Schedule Review, which is scheduled for 8-10 November 2021.

The 11th HL-LHC Collaboration Meeting will be held in digital format and will take place from 19 to 22 October 2021. This format was chosen after consultations with all collaboration partners and tries to address the preferences of all HL-LHC collaborators given the persisting travel restrictions and limitations for social gatherings due to COVID-19.

Based on the traditional programme with plenary and work package parallel sessions, this meeting will serve as a technical update forum

The main objectives will be to update all HiLumi collaborators on the results of key HL-LHC prototype tests, to highlight the progress made in the last year when all work still had to adapt to pandemic restrictions, and to update all collaborators on the latest schedule changes.

This year, all HL-LHC collaborators will be invited to follow the presentations 100% remotely. Participation in the meeting is by invitation only, and registration is mandatory and without fee.



Details and registration

CERN - Organizing Committee



hilumihc.web.cern.ch

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Outline

- Introduction
- Initial assumptions
- Evolution of the approach
- A selection of studies for HL-LHC V1.4
- Conclusions and outlook



We greatly acknowledge all BOINC volunteers who supported LHC@Home project, giving for free their CPU time and allowing these results to be produced

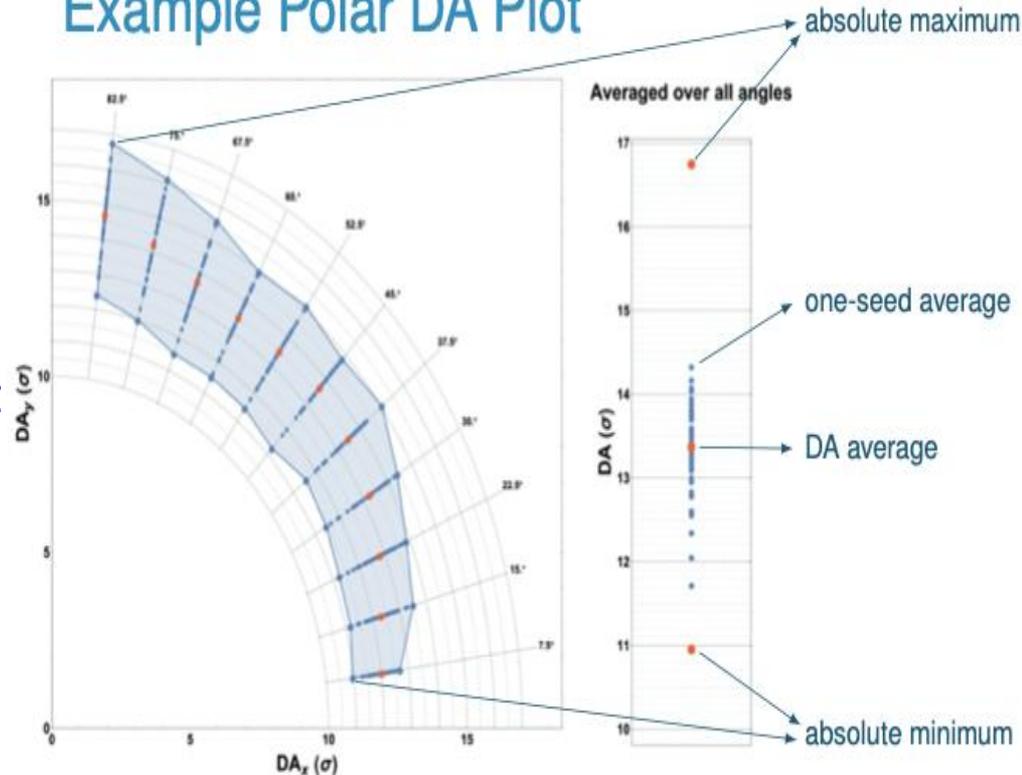
Introduction

- The performance indicator is the Dynamic Aperture (DA)
 - The extent of the phase space region in which the motion is bounded
 - The boundedness of an orbit is determined by numerical simulations performed to scan
 - the phase space and
 - the magnetic errors, using several realisations of the errors (seeds).
 - The target value for the DA is set differently depending on whether beam-beam is included.

Introduction

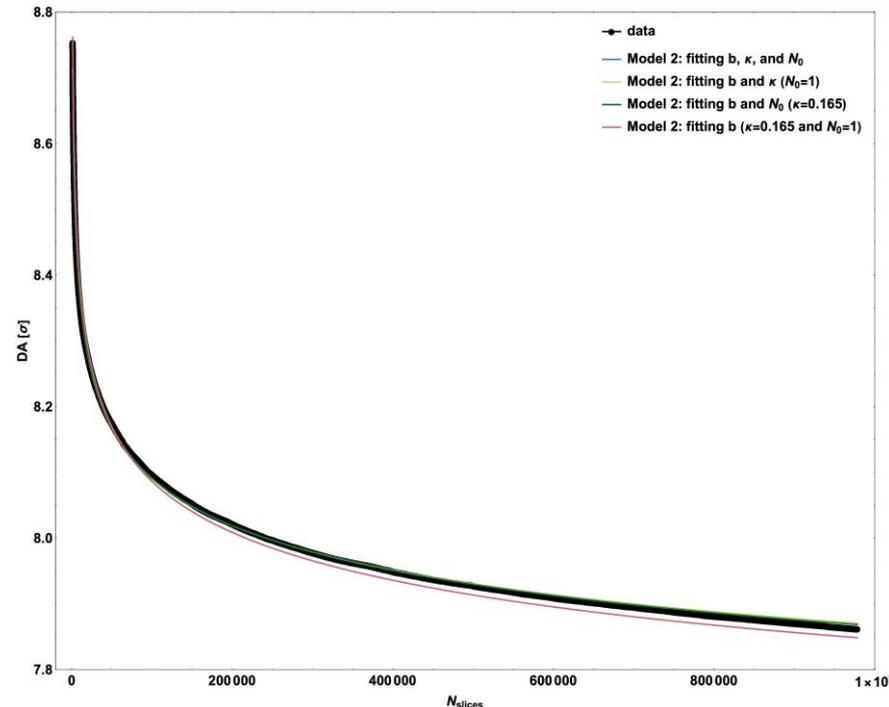
- A sample of the numerical data obtained from numerical simulations
 - Five phase-space angles
 - Sixty seeds
 - 10^5 turns
- The quantitative information extracted is
 - DA_{\min} : minimum over angles and seeds. **The target without beam-beam is 8σ .**
 - DA_{ave} : average DA over seeds (for a given angle)

Example Polar DA Plot



Introduction

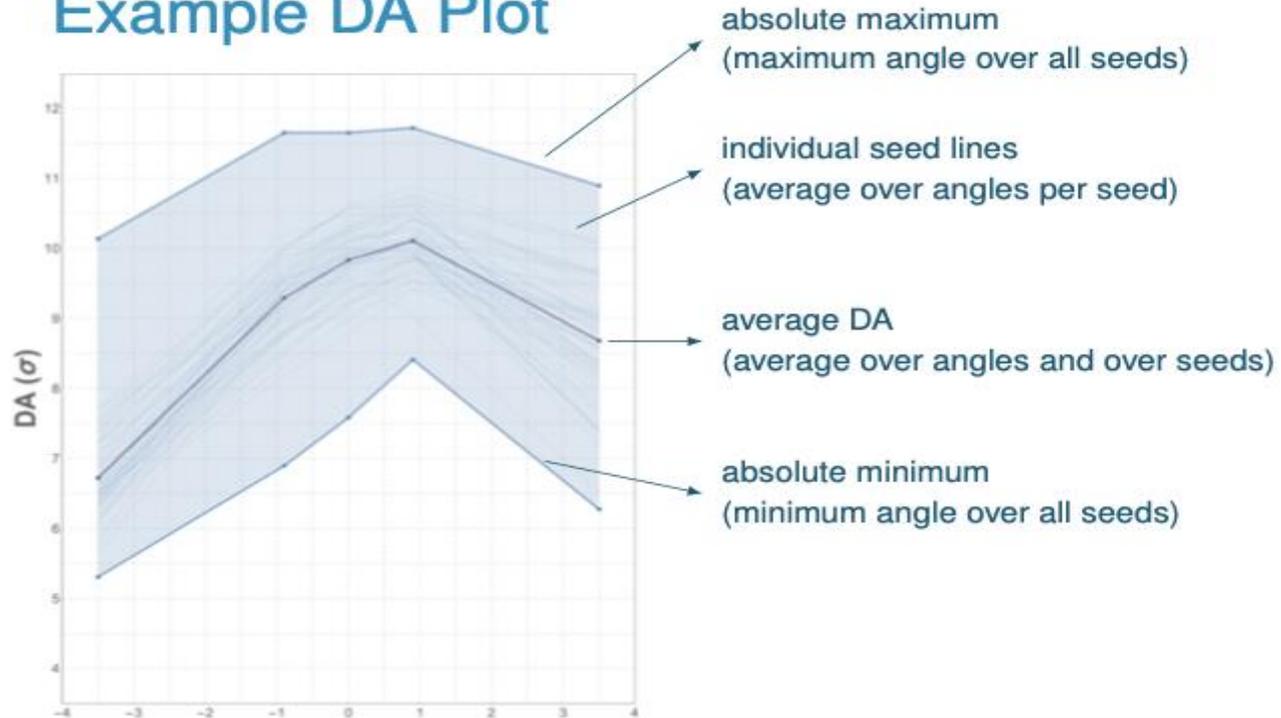
- A complementary analysis can be performed by extracting (from the same numerical data) the evolution of DA vs Turns
 - This provides a link to beam losses and lifetime
 - Not used (yet) for design optimisation



Introduction

- The information on DA can be used to derive trends as a function of particular multipoles

Example DA Plot



Introduction

- Other aspects of the computing protocol of DA
 - **Delta p** is selected different from zero to sample the off-momentum dynamics.
 - The **field quality of LHC magnets** is based on the measurement results.
 - The **field quality of HL-LHC magnets** is based on expected error tables, based on the usual representation of multipoles
 - Systematic
 - Uncertainty
 - Random.
 - The simulations are performed using the nominal HL-LHC configuration apart from detailed studies of the impact of specific **magnets/multipoles** on DA. In this case, Landau octupoles are set to zero, as they would cancel any detail on the dependence of DA vs. **magnets/multipoles**.

Initial assumptions (early years of HL-LHC)

- The DA was studied in detail as a function of single multipoles to determine upper bounds and provide feedback to magnet design.

Updated estimate of IT field quality at collision energy ($r_0 = 50$ mm)

Previous specification: “IT_errortable_v3_spec” (same as “IT_errortable_v66”).

New reference: “IT_errortable_v66_4” (based on the new estimate in

“IT_errortable_v4” combined with previously optimized terms (in red below) in

“IT_errortable_v3_spec”). New estimates are indicated in green. Reduced b6m (0.8 -> 0.4), but significantly increased **b10m** (0.075 -> -0.39) and **b14m** (-0.02 -> -0.67).

skew	mean	uncertainty	random	normal	mean	uncertainty	random
a3	0	0.800	0.800	b3	0	0.820	0.820
a4	0	0.650	0.650	b4	0	0.570	0.570
a5	0	0.430	0.430	b5	0	0.420	0.420
a6	0	0.310	0.310	b6	0.40	0.550	0.550
a7	0	0.152	0.095	b7	0	0.095	0.095
a8	0	0.088	0.055	b8	0	0.065	0.065
a9	0	0.064	0.040	b9	0	0.035	0.035
a10	0	0.040	0.032	b10	-0.39	0.100	0.100
a11	0	0.026	0.0208	b11	0	0.0208	0.0208
a12	0	0.014	0.014	b12	0	0.0144	0.0144
a13	0	0.010	0.010	b13	0	0.0072	0.0072
a14	0	0.005	0.005	b14	-0.67	0.0115	0.0115

4th Joint HiLumi LHC-LARP Annual Meeting
17-21 November 2014
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

The HiLumi LHC Design Study project is organizing its 4th Annual Meeting in collaboration with LARP. The meeting will assess the progress in the design and the RIT HiLumi work packages, as well as other work packages. The meeting will be held in the traditional format of plenary and work package parallel sessions.

The main objective will be the approval of the High Luminosity LHC Preliminary Design Report, a key deliverable of the RIT project, as a critical step toward the Technical Design Report due at the end of the RIT HiLumi LHC Design Study. The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 294604.

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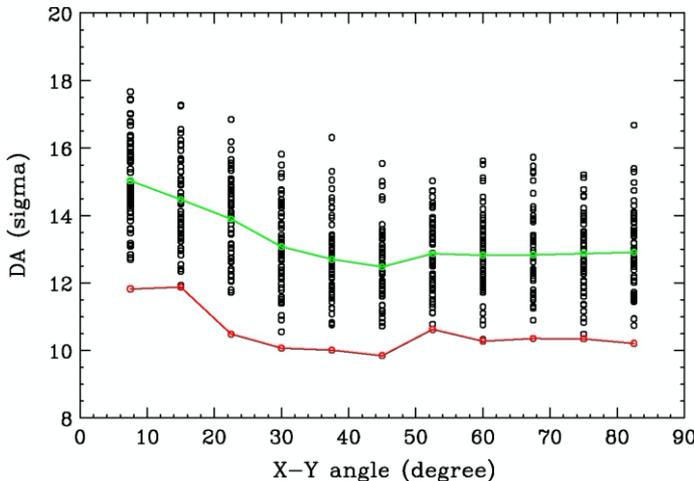
For more details and free registration:
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DA at collision energy with updated IT field quality

The other magnets: D1_errortable_v1_spec”, “D2_errortable_v5_spec”, “Q4_errortable_v1_spec”, “Q5_errortable_v0_spec”.

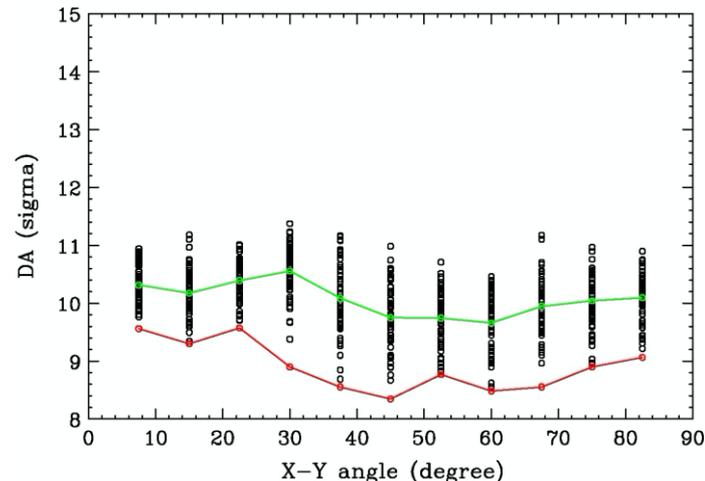
IT_errortable_v3_spec

DA_{ave} = 12.47σ, DA_{min} = 9.85σ, DA_{min1} = 10.28σ, DA_{min2} = 10.34σ



IT_errortable_v66_4

DA_{ave} = 9.65σ, DA_{min} = 8.34σ, DA_{min1} = 8.48σ, DA_{min2} = 8.62σ



Significantly reduced DA at collision with the field quality of “IT_errortable_v66_4”.

Next step: scan and adjust the b10m and b14m terms.

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Evolution of the initial assumptions

- The initial approach has been changed around 2017-18.
- We abandoned the specification field error tables and used **only** the estimates from WP3, checking specific multipoles following the communications about measurement results.

Example: Main results of FQ studies for



HL-LHC V1.0



CERN-ACC-2018-0054

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Dynamic aperture studies for HL-LHC V1.0

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Abstract

Intense efforts have been devoted to the detailed study of the dynamic aperture of the HL-LHC V1.0 optics and layout version, without beam-beam effects, for several configurations, differing by optical properties or properties of the field quality of the new magnets for HL-LHC. In this report, the outcome of these studies is summarised and discussed.

Keywords

HL-LHC, dynamic aperture, field quality

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How to deal with...

- Multipoles with large impact on DA
 - Ask WP3 to review the magnet design (see Ezio's talk).
 - Be creative with the use of the existing hardware.
- An example: use nonlinear correctors in the CP to cope with the field quality of the D2
 - b3 considered first and successfully corrected by Frederik.
 - b5 considered later, harder to deal with (see Joschua's talk for the latest results).
- Another example: use FRAS to reduce the strength of the MCBXF magnets and hence reduce the impact of their field quality on DA.
 - An important message: we are not asking to use FRAS as an orbit corrector, i.e. every HL-LHC cycle!!!

Evolution of the initial assumptions

- The initial approach has been changed around 2017-18.
- We abandoned the specification field error tables and used only the estimates from WP3, checking specific multipoles following the communications about measurement results.
- In the same period
 - In-depth revision of error routines to reflect the hardware detail, e.g. magnet orientation. **An important message: due to such a revision, comparing DA results for different optics versions is not trivial (not always possible)!!!**
 - Move to the acceptance criteria approach

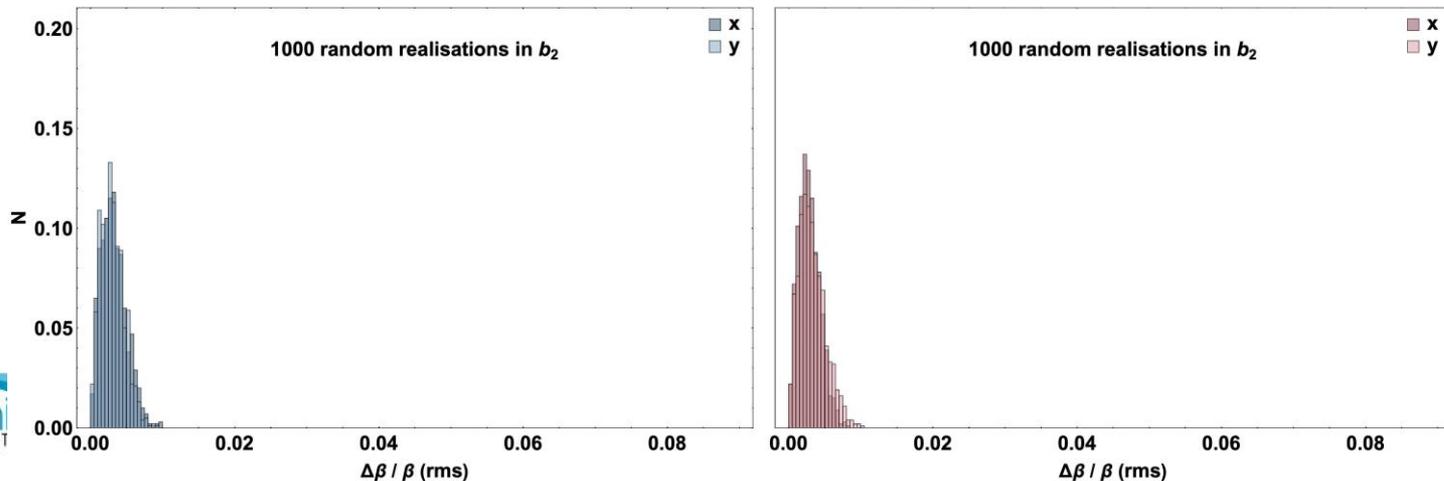
Acceptance criteria and DA

- The establishment of acceptance criteria imposes a change of paradigm in DA simulations
 - One needs to define a set of intervals for the measured multipoles so that if the magnet's field quality belongs to all the intervals specified, the magnet can be accepted (NB: **in the case of the LHC, no magnet was ever rejected based on field quality considerations**).
 - The split of the multipoles in three components is no more appropriate (the statistics of field quality for a given magnet class is not known, in principle, when a magnet is accepted).
- This change has been implemented by
 - Disabling the uncertainty component
 - Set the random component to $\frac{\text{specification_interval}}{\sqrt{12}}$

A selection of studies for HL-LHC V1.4

- **MCBRD acceptance criteria**
 - a_3/b_3 : ± 10 units (centred around the systematic value of 10 units)
 - Other multipoles: ± 3 units
- Nominal collision optics
- No octupoles
- Low chromaticity
- Nominal settings for all other errors and parameters
- High statistics: 1000 seeds

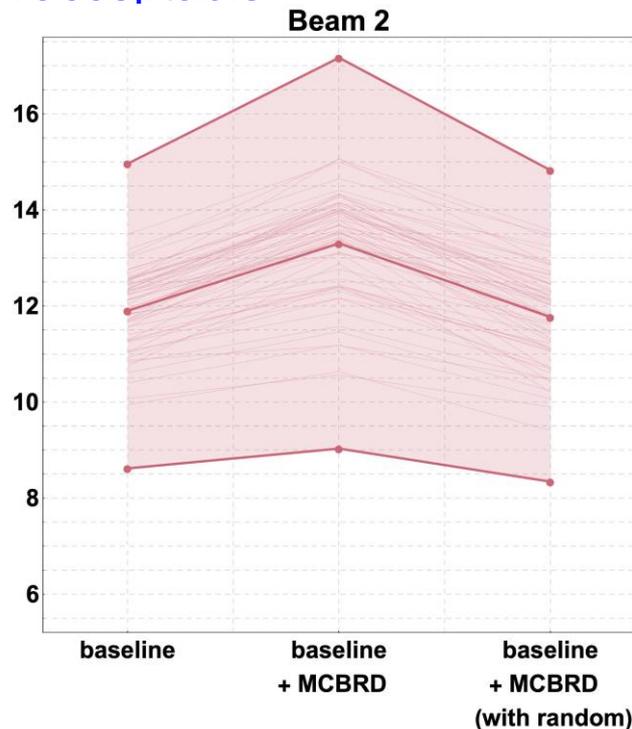
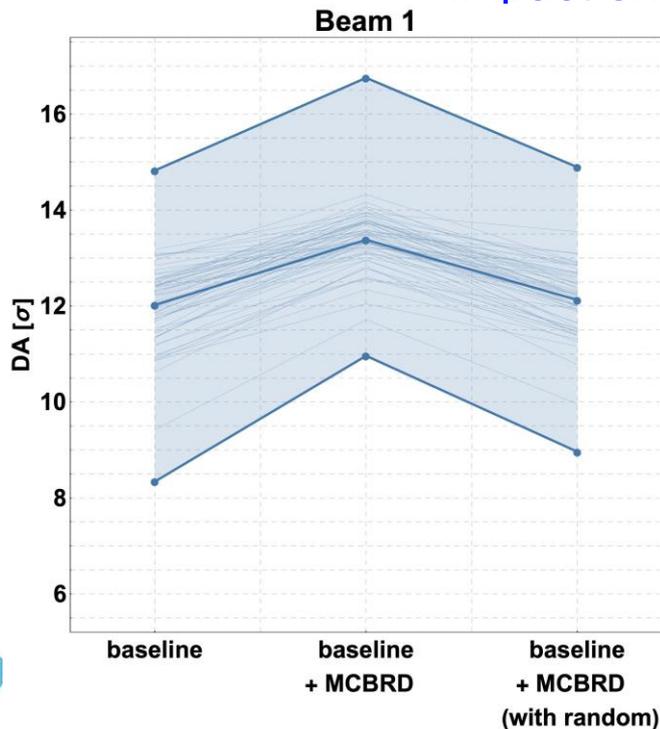
Beta-beating manageable



A selection of studies for HL-LHC V1.4

- MCBRD acceptance criteria
- MCBXF errors not assigned (they would dominate DA)
- High statistics: 240 seeds

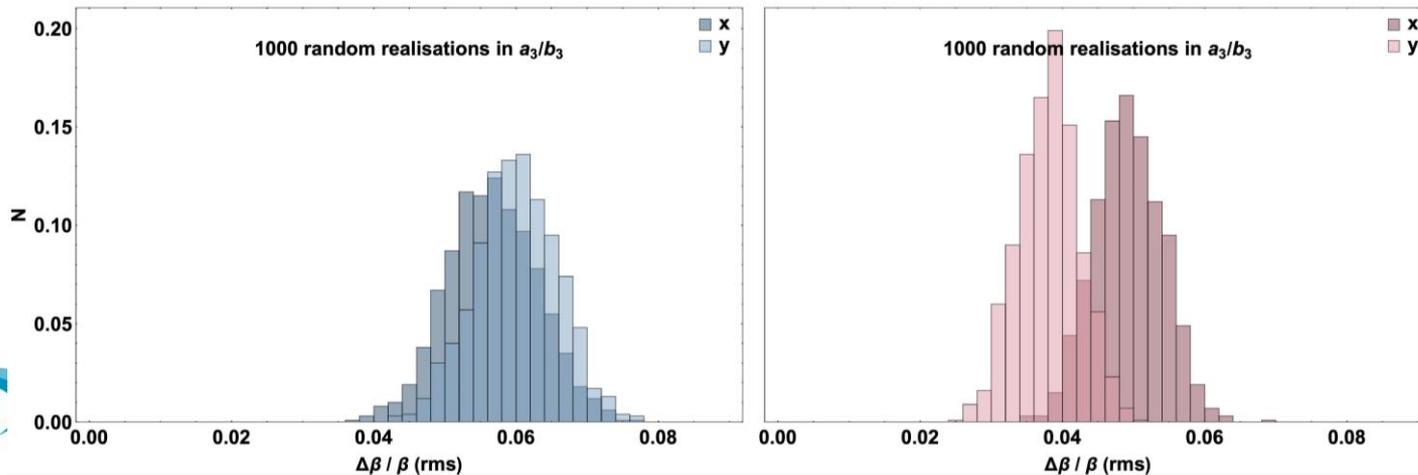
Impact on DA acceptable



A selection of studies for HL-LHC V1.4

- **MCBXF acceptance criteria**
 - a_3/b_3 : ± 20 units (centred around the systematic values, see Tables in the appendix)
 - Other multipoles: ± 5 units
- Nominal collision optics
- No octupoles
- Low chromaticity
- Nominal settings for all other errors and parameters
- High statistics: 1000 seeds

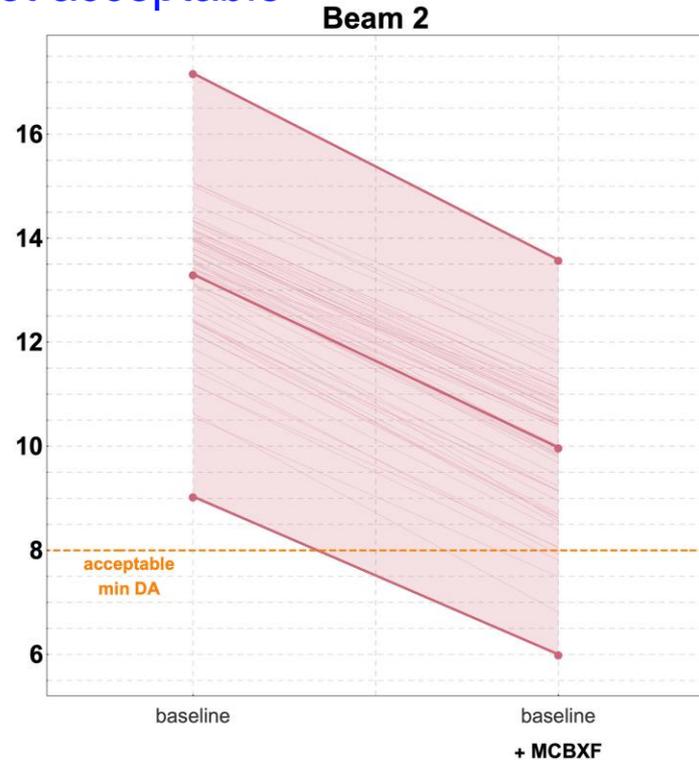
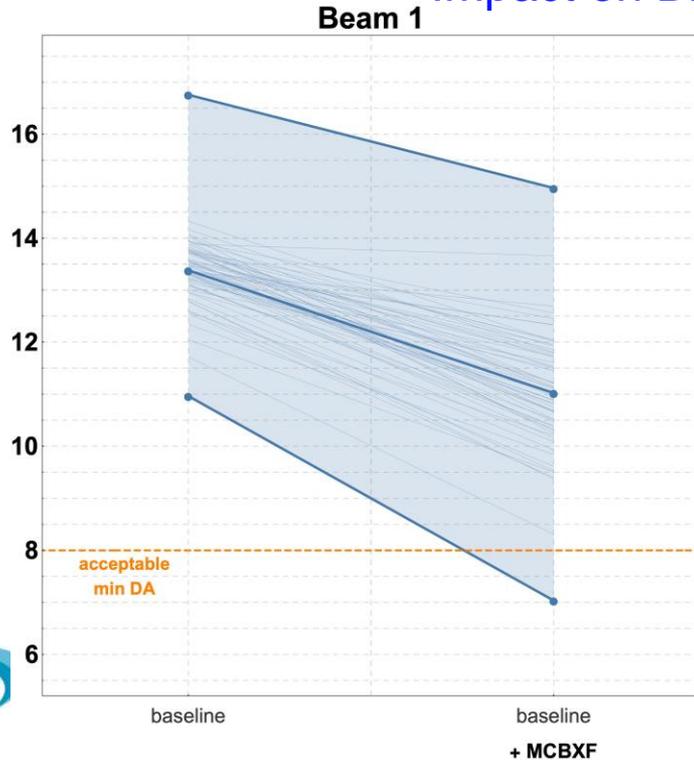
Beta-beating manageable



A selection of studies for HL-LHC V1.4

- MCBXF acceptance criteria
- High statistics: 240 seeds

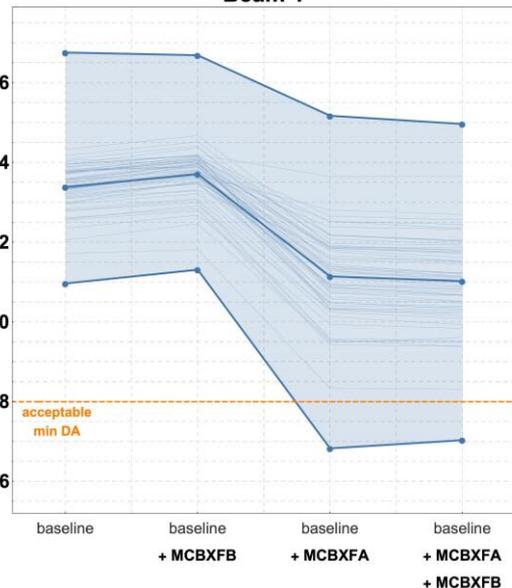
Impact on DA not acceptable



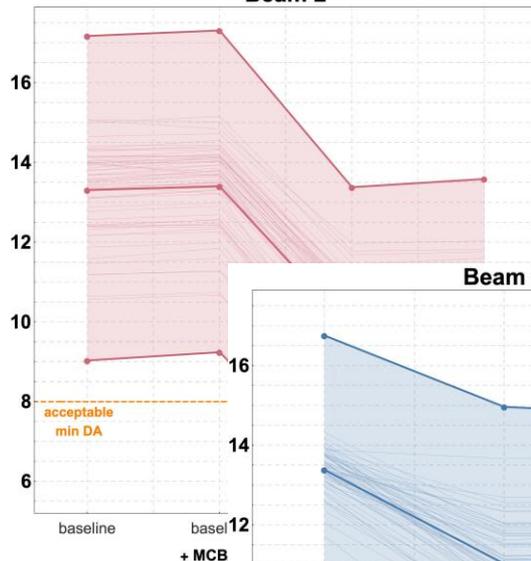
A selection of studies for HL-LHC V1.4

■ MCBXF acceptance criteria

Beam 1

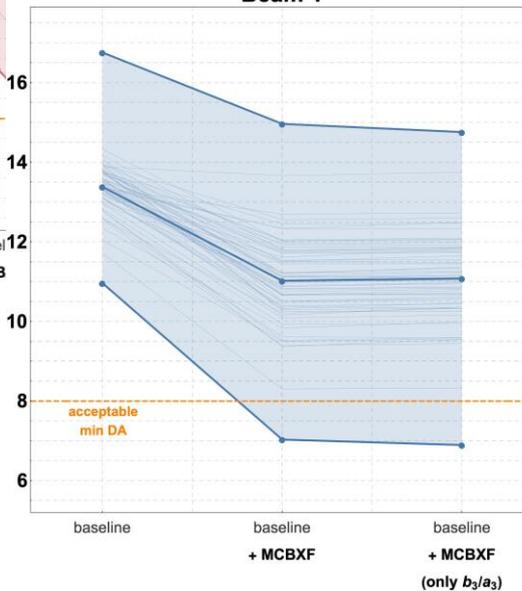


Beam 2

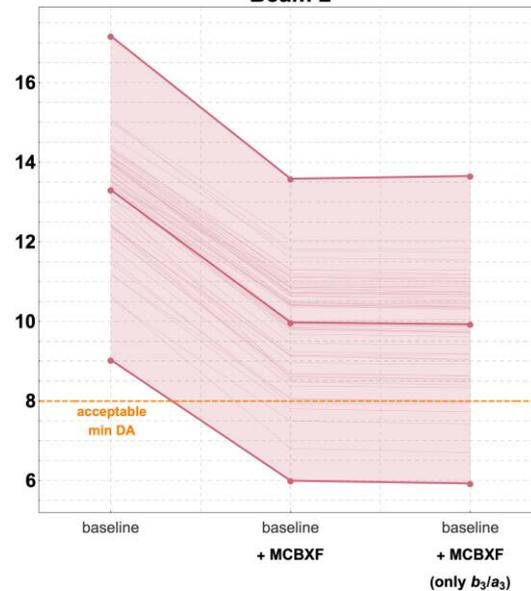


Comparing MCBXFA and MCBXFB
MCBXFA is the culprit of DA reduction

Beam 1



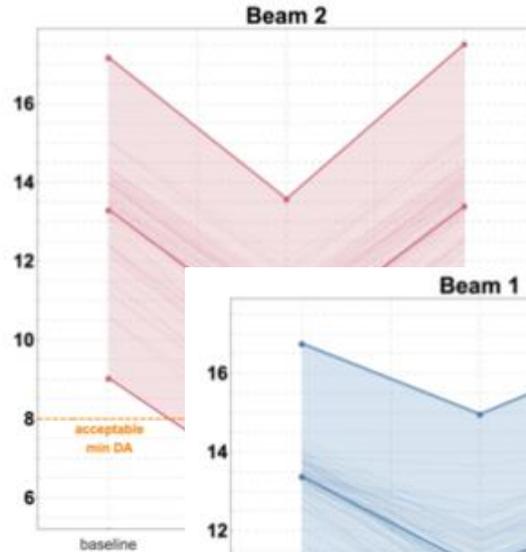
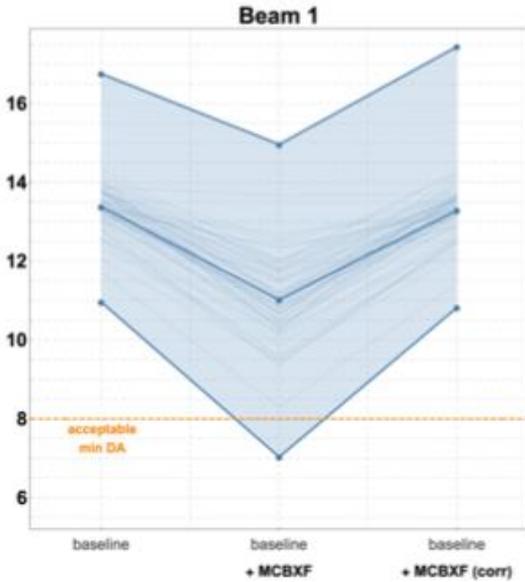
Beam 2



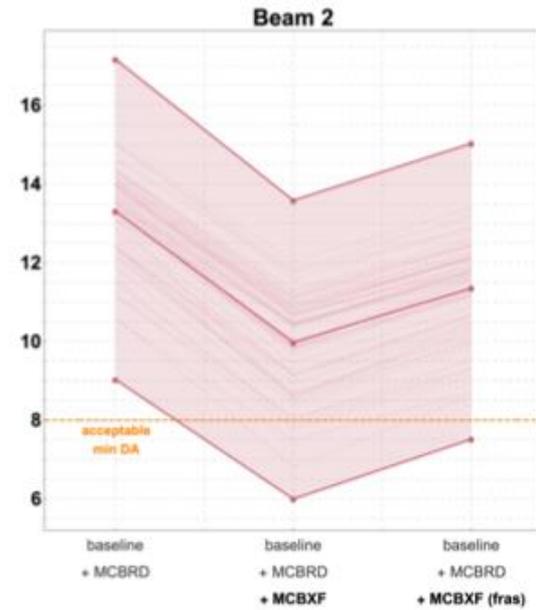
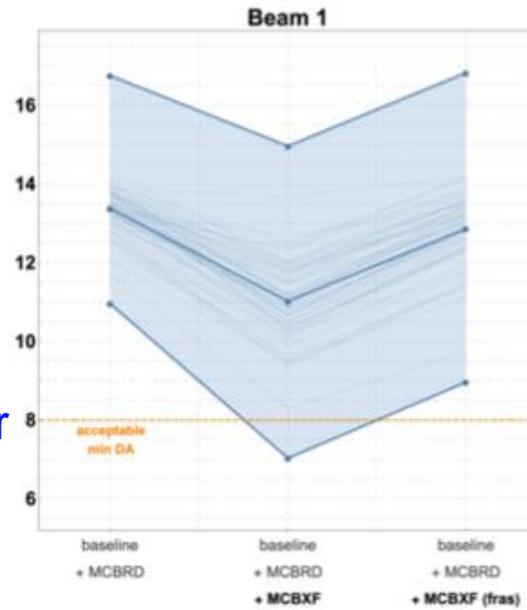
Comparing multipole errors
 a_3/b_3 are the culprit of DA
reduction

A selection of studies for HL-LHC V1.4

- MCBXF acceptance criteria: mitigation measures



Correct the field quality using the non-linear correctors in the CP: very efficient!



Use the FRAS to limit the MCBXFs strength (in addition to the needs for crossing and separation bumps).

A selection of studies for HL-LHC V1.4

- **MCBXF acceptance criteria: summary**
 - Impact of the MCBXFs field quality on DA is strong for nominal HL-LHC conditions.
 - During the initial stages of the beam commissioning and operations, the impact of the field quality is very limited.
 - When approaching nominal running conditions two mitigation measures have been studied
 - Using the FRAS to limit the strength of the MCBXFs
 - Using the nonlinear correctors to compensate for the field quality of the MCBXFs
 - NB: the differences between the two beams might be improved by acting on the phase advance between IP1 And IP5.

Conclusions and outlook

- The target DA is still within reach, in spite of several difficulties.
- Next steps
 - Resume tracking activities to pursue the needed follow ups related with field quality.
 - Get ready to provide fast feedback when the results of magnetic measurements become available.
 - Get ready for the activities related with magnets allocation (remember the LHC MEB).
 - **Establish a firm link between DA and beam lifetime (already in done for individual studies, but not used at the design level, yet).**



Thank you for your attention!



Appendix

MCBXFA New error table

MCBXFAH					MCBXFAV						
	ξ_M	ξ_R									
a_1	0	0	b_1	0	0	a_1	0	0	b_1	0	0
a_2	0	2.887	b_2	0	2.887	a_2	0	2.887	b_2	0	2.887
a_3	0	2.887	b_3	-16.65	2.887	a_3	20.12	2.887	b_3	0	2.887
a_4	0	2.887	b_4	0	2.887	a_4	0	2.887	b_4	0	2.887
a_5	0	2.887	b_5	-0.35	2.887	a_5	-3.04	2.887	b_5	0	2.887
a_6	0	2.887	b_6	0	2.887	a_6	0	2.887	b_6	0	2.887
a_7	0	2.887	b_7	0.98	2.887	a_7	-3.98	2.887	b_7	0	2.887
a_8	0	0	b_8	0	0	a_8	0	0	b_8	0	0
a_9	0	0	b_9	0.07	0	a_9	-0.62	0	b_9	0	0
a_{10}	0	0	b_{10}	0	0	a_{10}	0	0	b_{10}	0	0
a_{11}	0	0	b_{11}	4.3	0	a_{11}	0.02	0	b_{11}	0	0
a_{12}	0	0	b_{12}	0	0	a_{12}	0	0	b_{12}	0	0
a_{13}	0	0	b_{13}	0	0	a_{13}	0	0	b_{13}	0	0
a_{14}	0	0	b_{14}	0	0	a_{14}	0	0	b_{14}	0	0
a_{15}	0	0	b_{15}	0	0	a_{15}	0	0	b_{15}	0	0

MCBXFB New error table

MCBXFBH					MCBXFBV						
	ξ_M	ξ_R									
a_1	0	0	b_1	0	0	a_1	0	0	b_1	0	0
a_2	0	2.887	b_2	0	2.887	a_2	0	2.887	b_2	0	2.887
a_3	0	2.887	b_3	17.37	2.887	a_3	-10.33	2.887	b_3	0	2.887
a_4	0	2.887	b_4	0	2.887	a_4	0	2.887	b_4	0	2.887
a_5	0	2.887	b_5	2.49	2.887	a_5	-3.6	2.887	b_5	0	2.887
a_6	0	2.887	b_6	0	2.887	a_6	0	2.887	b_6	0	2.887
a_7	0	2.887	b_7	0.62	2.887	a_7	-3.26	2.887	b_7	0	2.887
a_8	0	0	b_8	0	0	a_8	0	0	b_8	0	0
a_9	0	0	b_9	-0.75	0	a_9	-0.58	0	b_9	0	0
a_{10}	0	0	b_{10}	0	0	a_{10}	0	0	b_{10}	0	0
a_{11}	0	0	b_{11}	3.6	0	a_{11}	0.12	0	b_{11}	0	0
a_{12}	0	0	b_{12}	0	0	a_{12}	0	0	b_{12}	0	0
a_{13}	0	0	b_{13}	0	0	a_{13}	0	0	b_{13}	0	0
a_{14}	0	0	b_{14}	0	0	a_{14}	0	0	b_{14}	0	0
a_{15}	0	0	b_{15}	0	0	a_{15}	0	0	b_{15}	0	0