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

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Outline

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

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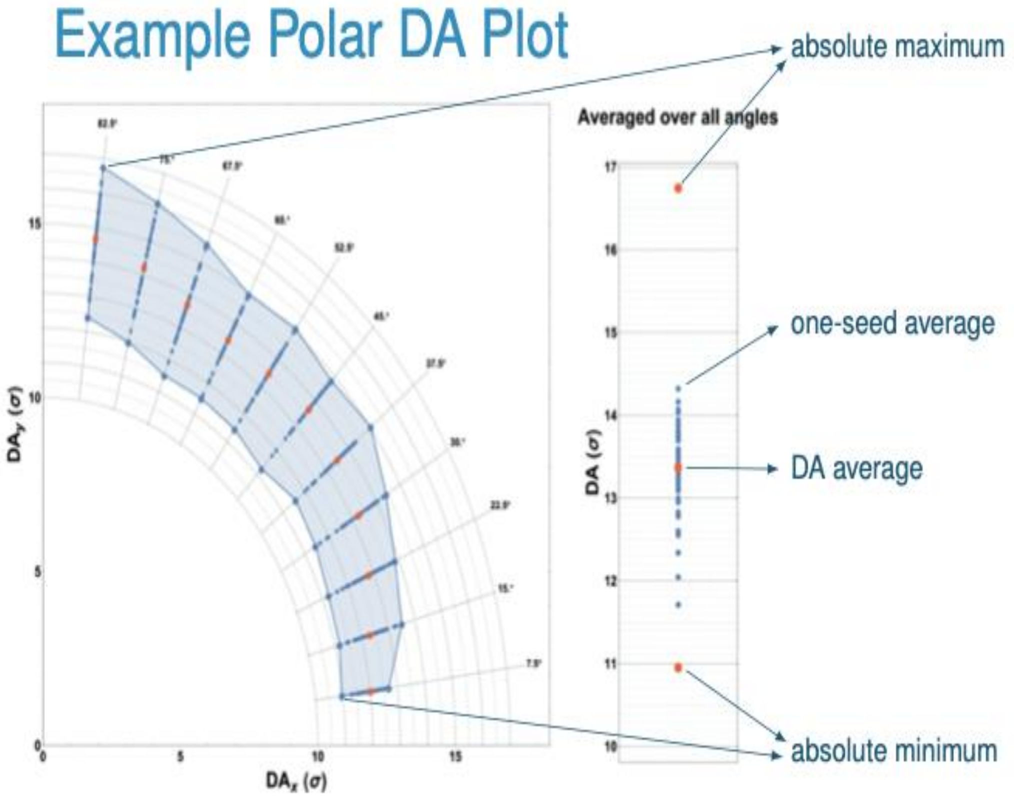
Introduction

- 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.

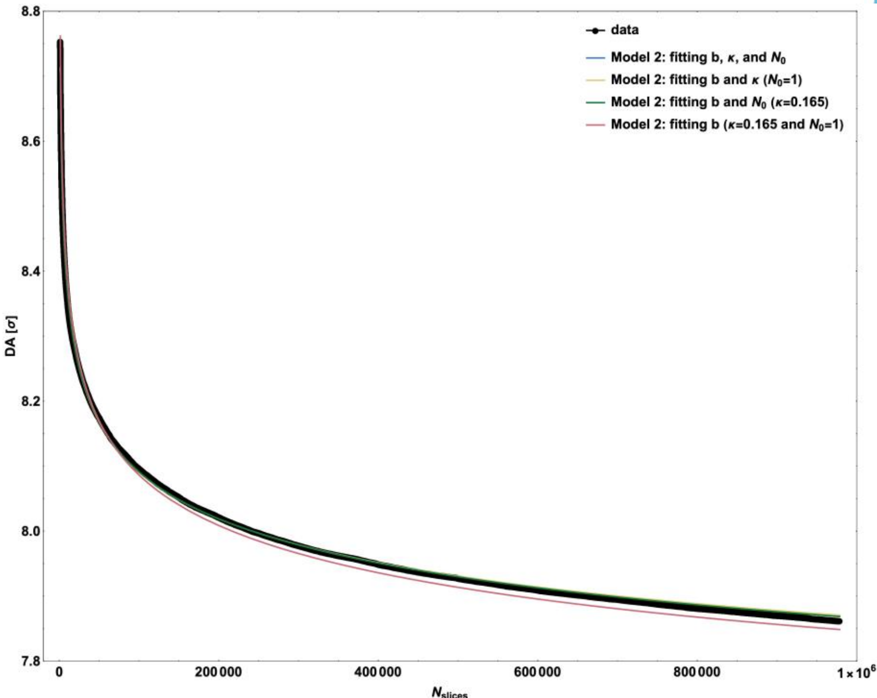
Introduction

- 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 8 σ.
  - DA_{ave}: average DA over seeds (for a given angle)



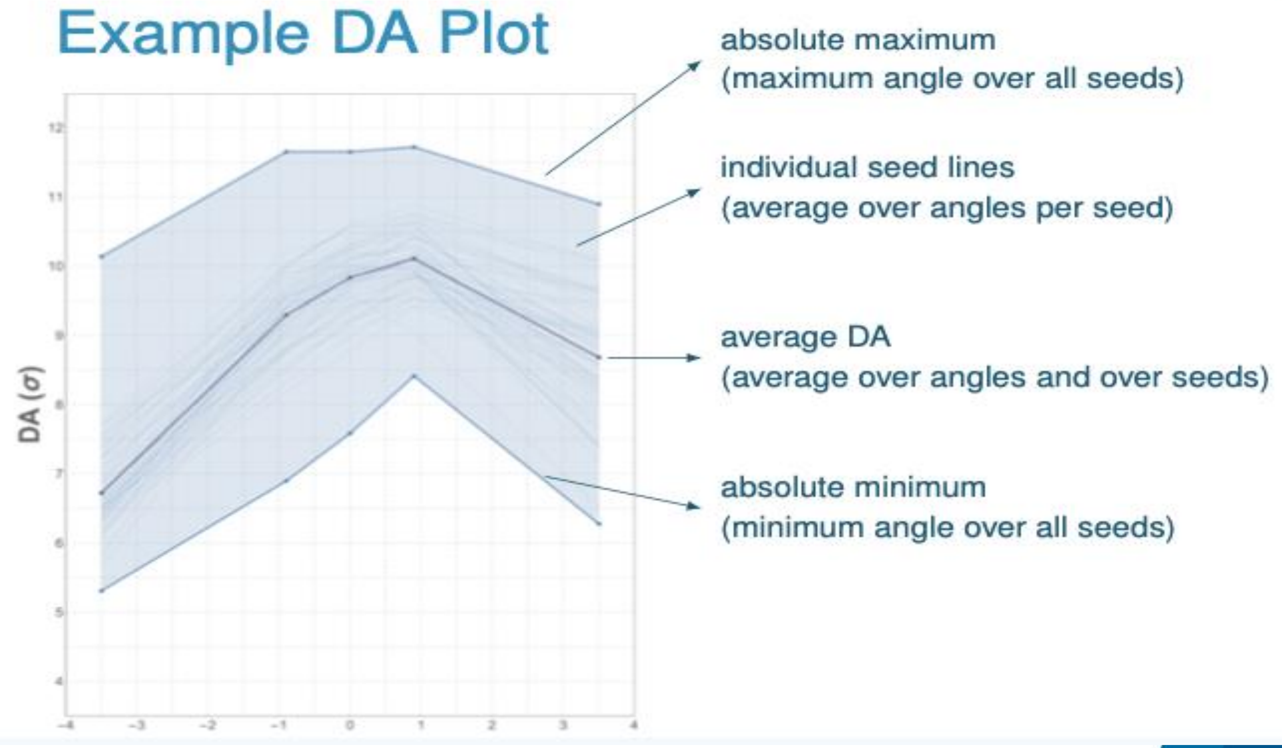
Introduction

- 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



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).

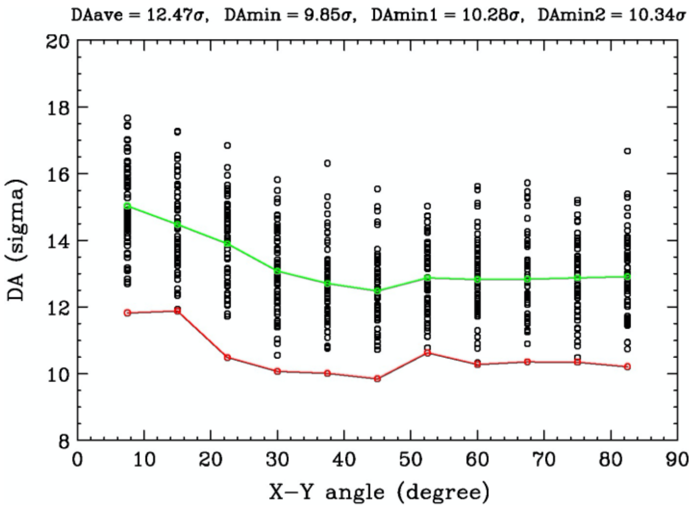
skew	mean	uncertainty	random
a3	0	0.800	0.800
a4	0	0.650	0.650
a5	0	0.430	0.430
a6	0	0.310	0.310
a7	0	0.152	0.095
a8	0	0.088	0.055
a9	0	0.064	0.040
a10	0	0.040	0.032
a11	0	0.026	0.0208
a12	0	0.014	0.014
a13	0	0.010	0.010
a14	0	0.005	0.005

normal	mean	uncertainty	random
b3	0	0.820	0.820
b4	0	0.570	0.570
b5	0	0.420	0.420
b6	0.40	0.550	0.550
b7	0	0.095	0.095
b8	0	0.065	0.065
b9	0	0.035	0.035
b10	-0.39	0.100	0.100
b11	0	0.0208	0.0208
b12	0	0.0144	0.0144
b13	0	0.0072	0.0072
b14	-0.67	0.0115	0.0115

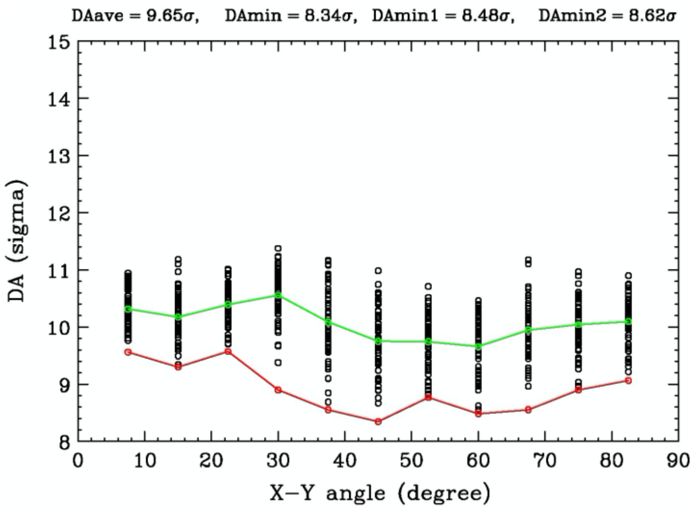
DA at collision energy with updated IT field quality

The other magnets: D1_errortable_v1_spec", "D2_errortable_v5_spec", "Q4_errortable_v1_spec", "Q5_errortable_v0_spec".

IT_errortable_v3_spec



IT_errortable_v66_4



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

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

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

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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

Contents

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

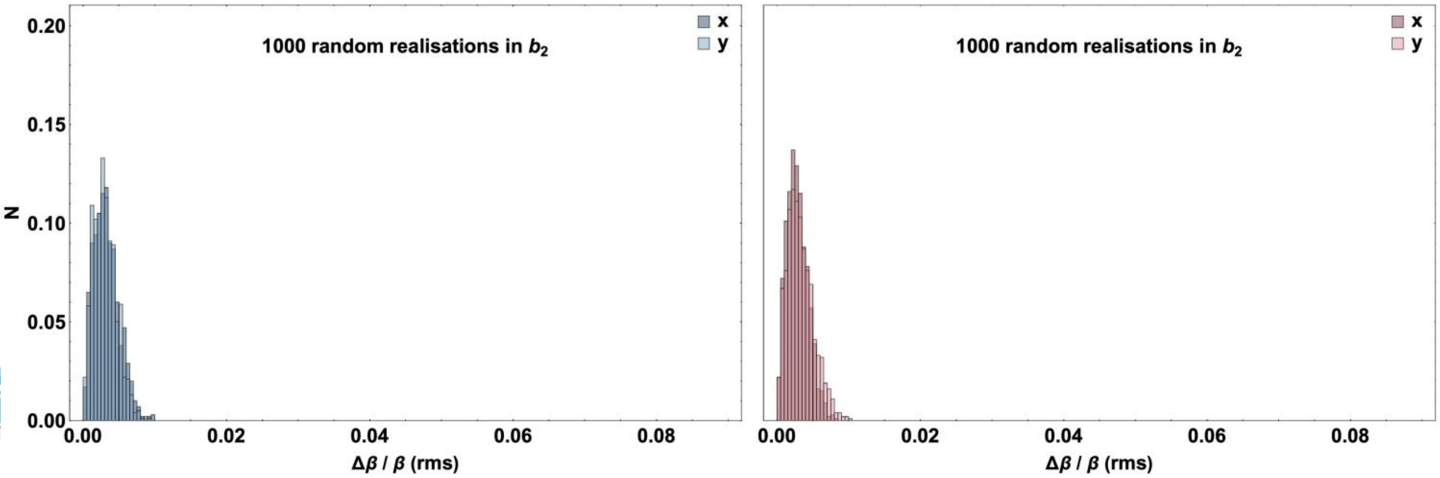
Acceptance criteria and DA

- 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**
  - a3/b3: ± 10 units (centrered 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

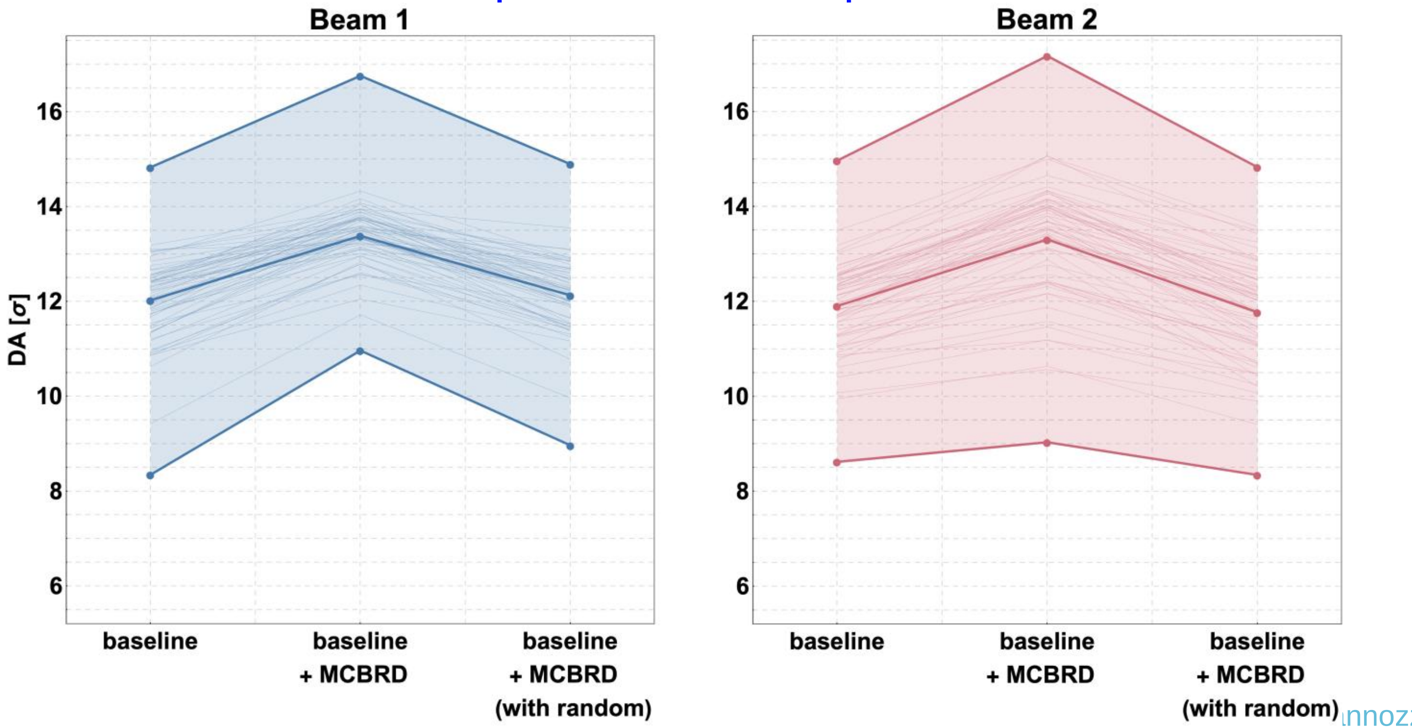
Beta-beating manageable



A selection of studies for HL-LHC V1.4

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

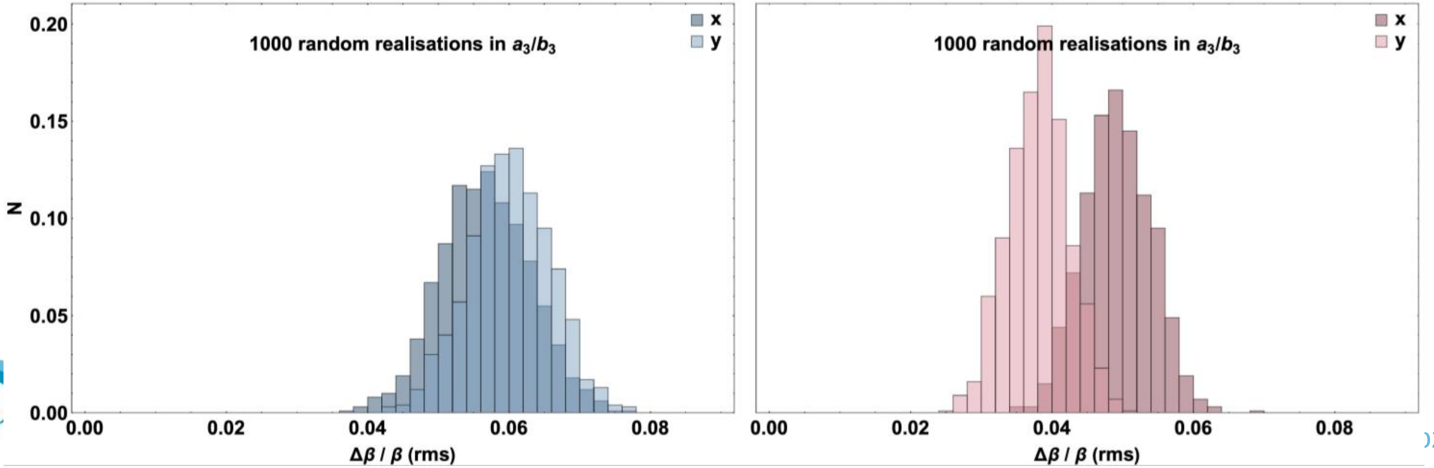
Impact on DA acceptable



A selection of studies for HL-LHC V1.4

- **MCBXF acceptance criteria**
  - a3/b3: ± 20 units (centrered 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

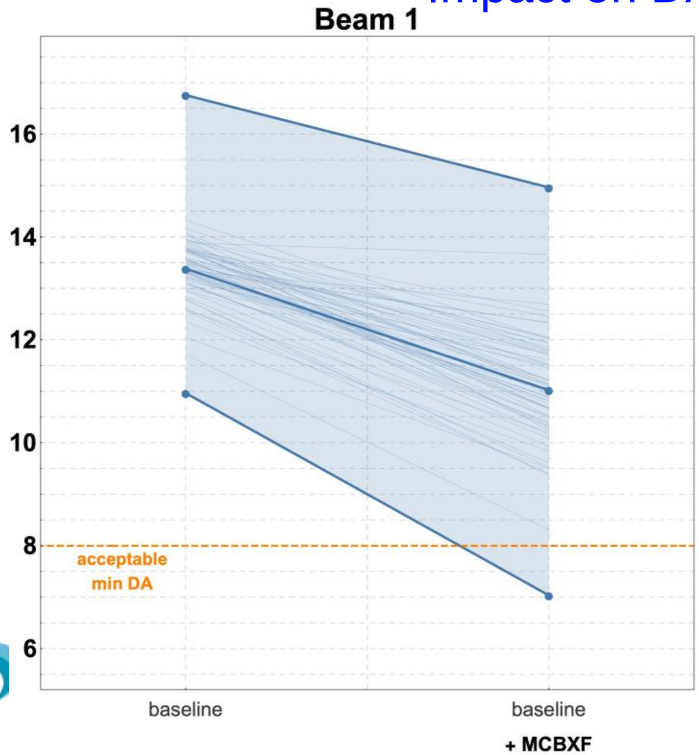
Beta-beating manageable

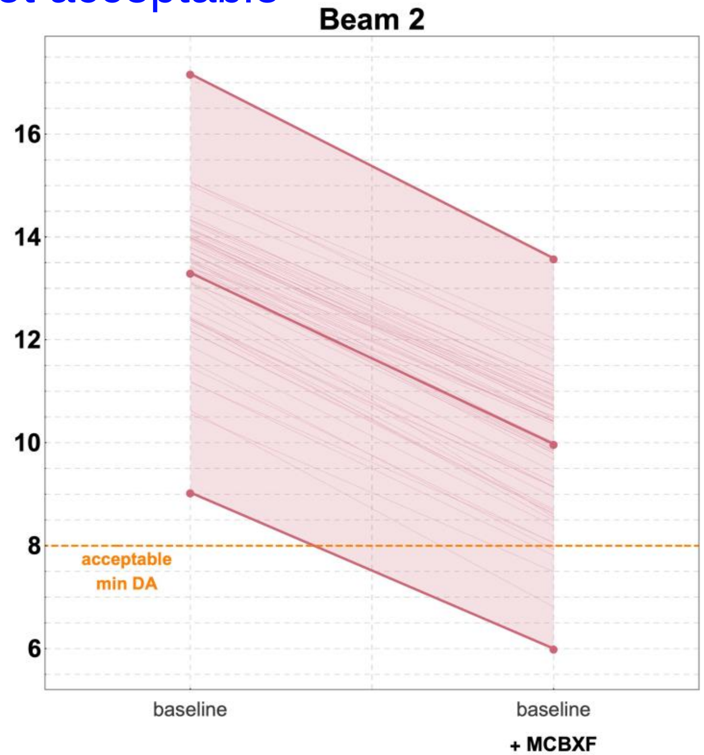


A selection of studies for HL-LHC V1.4

- **MCBXF acceptance criteria**
- High statistics: 240 seeds

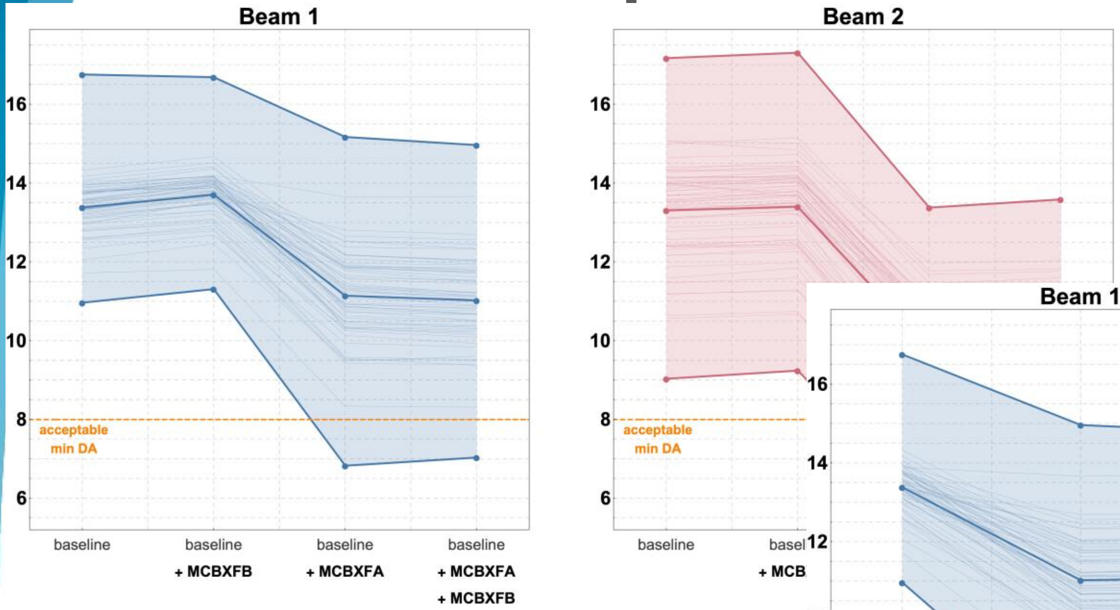
Impact on DA not acceptable



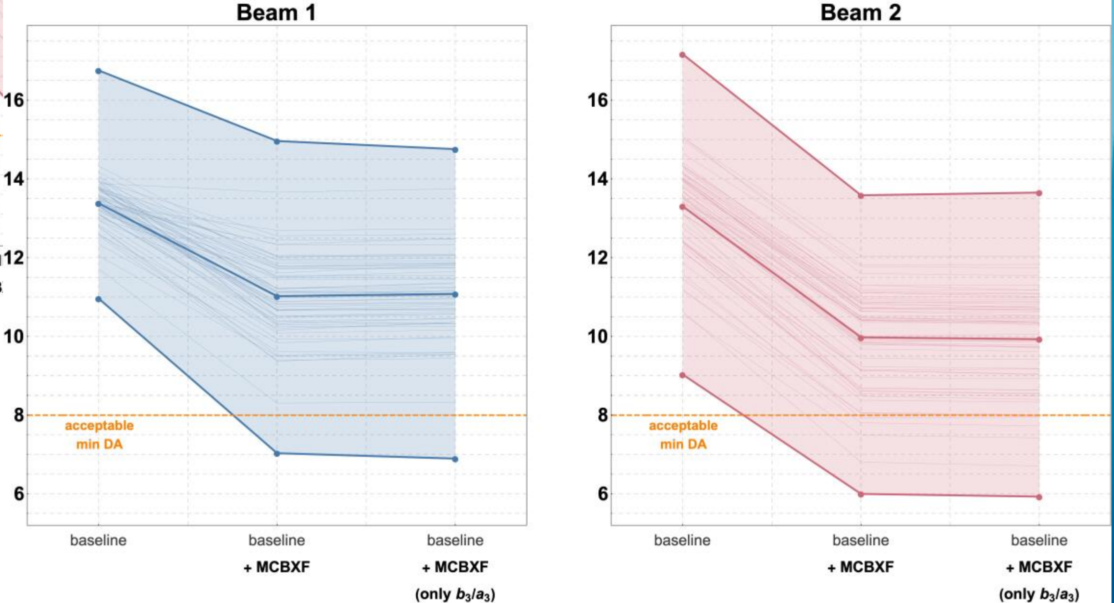


A selection of studies for HL-LHC V1.4

- MCBXF acceptance criteria



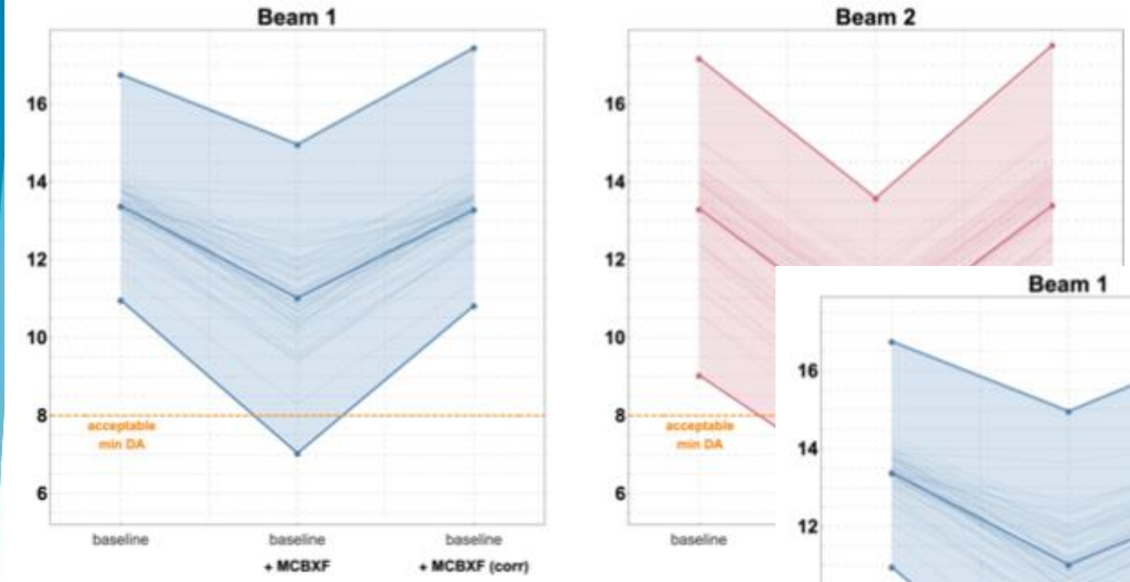
Comparing MCBXFA and MCBXFB
MCBXFA is the culprit of DA reduction



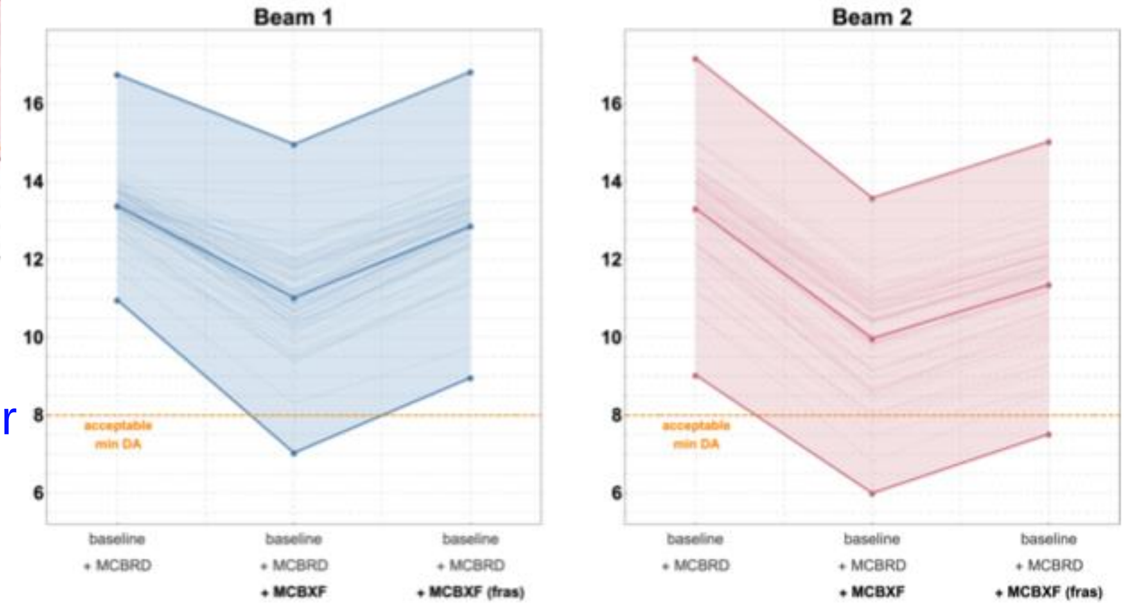
Comparing multipole errors a3/b3 are the culprit of DA reduction

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).

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

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