Dynamic Aperture and Correction Circuits

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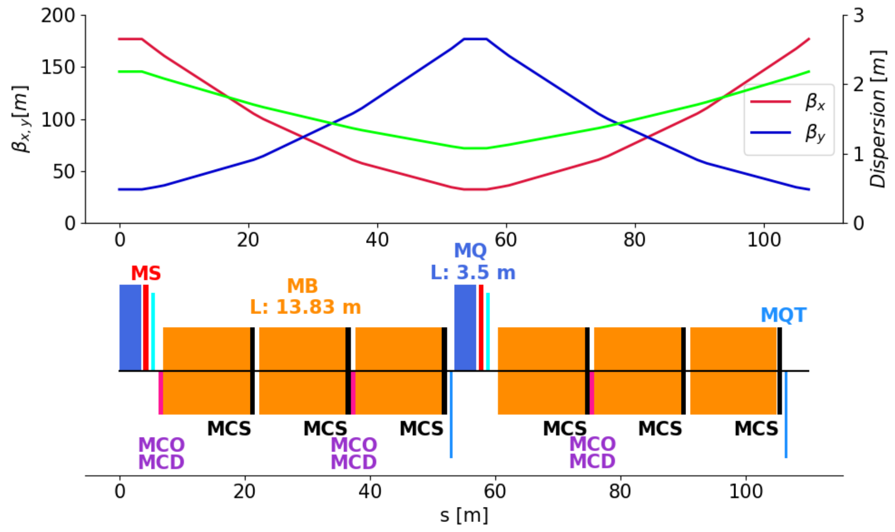
Introduction

- Study the impact of magnetic field imperfections on the Dynamic Aperture (DA) for the two HE-LHC lattices
- DA at collision energy determined by magnet errors in the triplet
  - Covered in Léon’s talk in the previous session
- At injection energy, the field quality of the main dipoles becomes critical

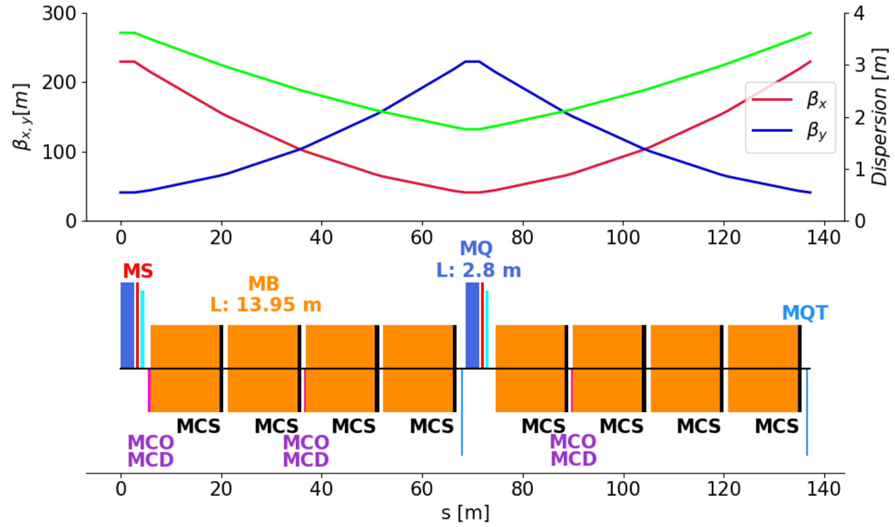
- Evaluate DA at injection energy with LHC-like correction scheme and, where needed, look into alternatives to achieve sufficient DA
- Current target DA is 12σ, as in the original LHC Design, providing some margin for special operation conditions (e.g. including Landau octupoles, higher chromaticity)

Lattices

- For the HE-LHC, two lattices are currently under study:
  - LHC-like Lattice with 23 Arc cells and 90 degree phase advance
    - Provides reasonable physical aperture
      at the lowest considered injection energy of 450 GeV
    - Limited in energy reach to 26 TeV
  - Lattice with 18 Arc cells and 90 degree phase advance
    - Can achieve 27 TeV while still providing some margin in the dipole field
- Current correction of dipole errors:
  - Sextupole component corrected by one spool piece (MCS) attached to each dipole, one family per arc
  - Three octupole and decapole corrector (MCO & MCD) per arc cell, also one family per arc



“LHC-like” 23 cell lattice



18 cell lattice

Tracking studies parameter

- Tracking conducted with Sixtrack
- Errors assigned following [1]

$b_n = b_{n_s} + \frac{\xi_U}{1.5} b_{n_u} + \xi_R b_{n_r}$

where ξ_U and ξ_r are random number with Gaussian distribution truncated at 1.5 σ and 3 σ respectively

n_{turns}	10^5
No. of seeds	60
No. of angles	5
ε_n	2.5 μm
$\Delta p/p$	$7.5 \cdot 10^{-4}$

- Same uncertainty component for all dipoles in one arc
- Even normal components change sign between dipole apertures
- For tracking a_1,a_2, b_1 and b_2 harmonics were excluded

[1] S. Fartoukh & O. Bruning,
Field Quality Specifications for the LHC Main Dipole Magnets, LHC Project Report 501

Magnet Field Quality I

Courtesy: S. I. Bermudez

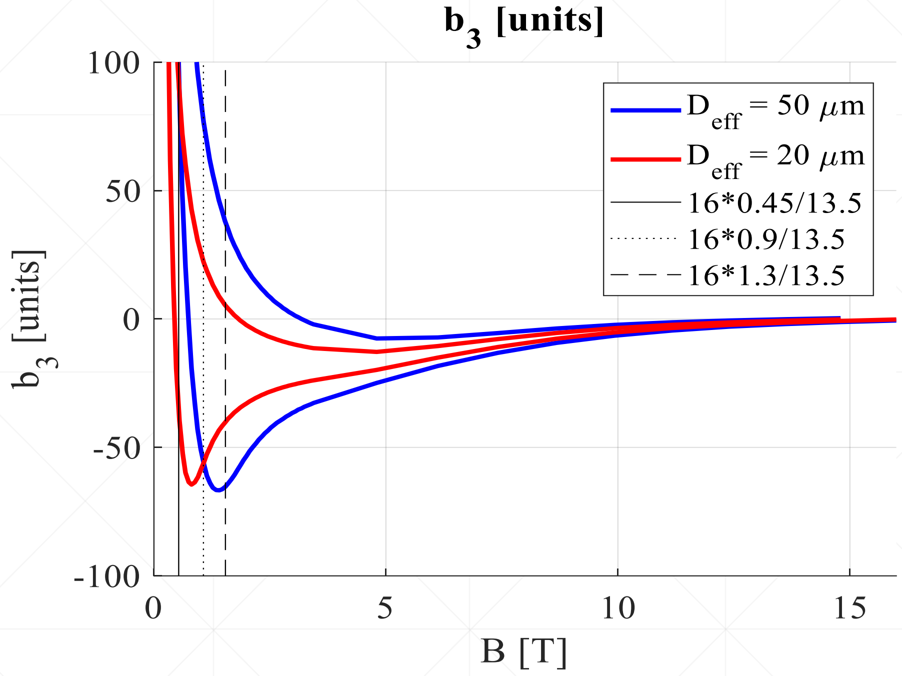
	450 GeV	900 GeV	1300 GeV
B2	S: -2.23 U: 0.922 R: 0.922	S: -2.23 U: 0.922 R: 0.922	S: -2.23 U: 0.922 R: 0.922
B3	S: -35 U: 10 R: 10	S: -55 U: 4 R: 4	S: -40 U: 3 R: 3
B4	S: 0 U: 0.449 R: 0.449	S: 0 U: 0.449 R: 0.449	S: 0 U: 0.449 R: 0.449
B5	S: 8 U: 1.5 R: 1.5	S: 8 U: 1.5 R: 1.5	S: 4 U: 0.8 R: 0.8
B6	S: 0 U: 0.176 R: 0.176	S: 0 U: 0.176 R: 0.176	S: 0 U: 0.176 R: 0.176
B7	S: 0.2 U: 0.211 R: 0.211	S: 0.6 U: 0.211 R: 0.211	S: 1.1 U: 0.211 R: 0.211

	450 GeV	900 GeV	1300 GeV
A2	S: 0 U: 1.040 R: 1.040	S: 0 U: 1.040 R: 1.040	S: 0 U: 1.040 R: 1.040
A3	S: 0 U: 0.678 R: 0.678	S: 0 U: 0.678 R: 0.678	S: 0 U: 0.678 R: 0.678
A4	S: 0 U: 0.450 R: 0.450	S: 0 U: 0.450 R: 0.450	S: 0 U: 0.450 R: 0.450
A5	S: 0 U: 0.317 R: 0.317	S: 0 U: 0.317 R: 0.317	S: 0 U: 0.317 R: 0.317
A6	S: 0 U: 0.205 R: 0.205	S: 0 U: 0.205 R: 0.205	S: 0 U: 0.205 R: 0.205
A7	S: 0 U: 0.116 R: 0.116	S: 0 U: 0.116 R: 0.116	S: 0 U: 0.116 R: 0.116

Magnet Field Quality II

Courtesy: S. I. Bermudez

	450 GeV	900 GeV	1300 GeV
B2	S: -2.23 U: 0.922 R: 0.922	S: -2.23 U: 0.922 R: 0.922	S: -2.23 U: 0.922 R: 0.922
B3	S: -35 U: 10 R: 10	S: -55 U: 4 R: 4	S: -40 U: 3 R: 3
B4	S: 0 U: 0.449 R: 0.449	S: 0 U: 0.449 R: 0.449	S: 0 U: 0.449 R: 0.449
B5	S: 8 U: 1.5 R: 1.5	S: 8 U: 1.5 R: 1.5	S: 4 U: 0.8 R: 0.8
B6	S: 0 U: 0.176 R: 0.176	S: 0 U: 0.176 R: 0.176	S: 0 U: 0.176 R: 0.176
B7	S: 0.2 U: 0.211 R: 0.211	S: 0.6 U: 0.211 R: 0.211	S: 1.1 U: 0.211 R: 0.211



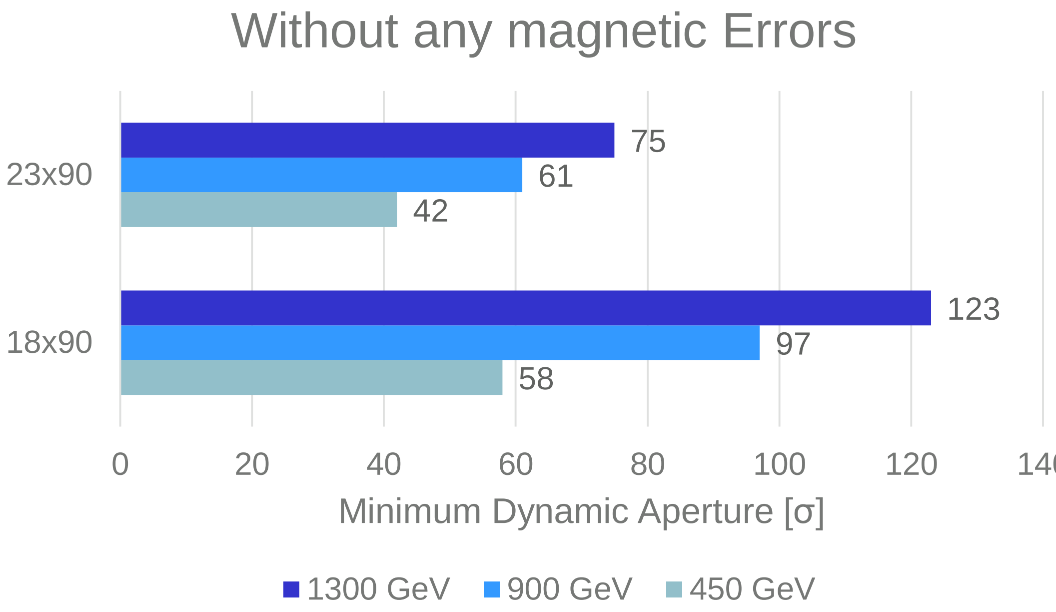
- Intermediate injection energy (900 GeV) of particular interest as the field quality becomes worse during the ramp due to increased persistent current contribution

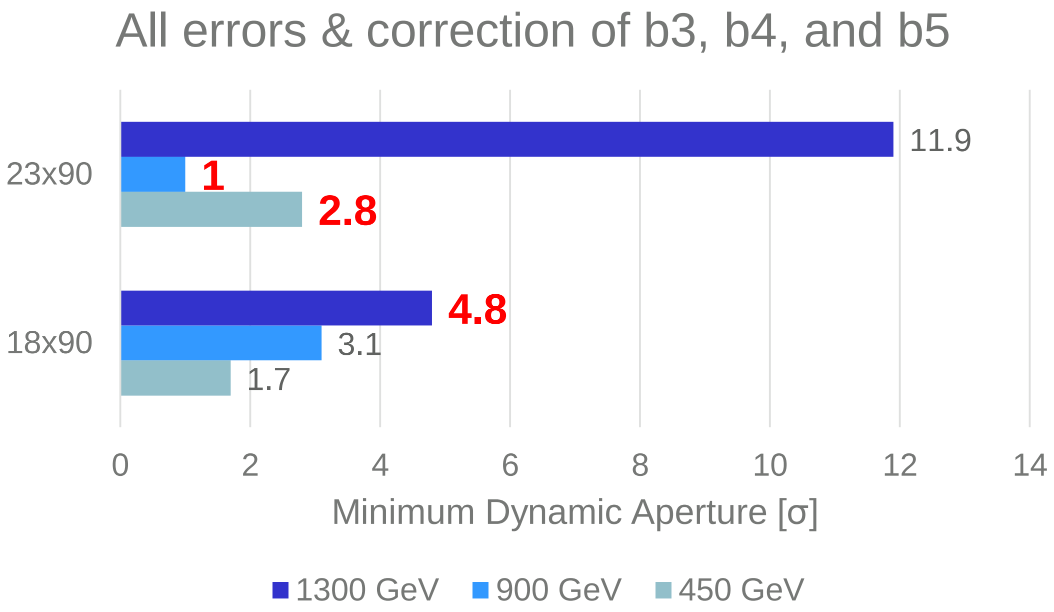
Dynamic Aperture at injection

- Without magnetic errors, the 18 arc cell lattice achieves higher DA than the LHC-like lattice

- However, with magnetic error and corrections, both lattices feature similarly low DA at the lower injections energies

- Currently only in the case of the LHC-like lattice and 1300 GeV injection energy,
we (almost) meet the target DA of 12 σ of the LHC





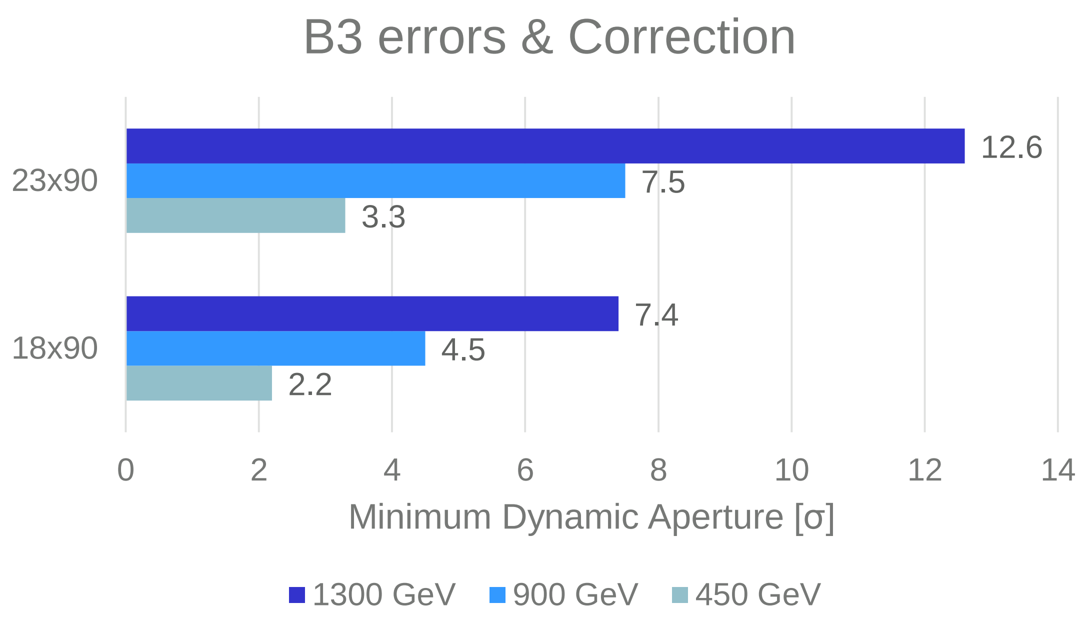
b_3 Errors

- To see the impact of the different components further tracking studies including only one component at a time

- Here b_3 corrected by one sextupole spool piece (MCS, L=0.11m) attached to each dipole

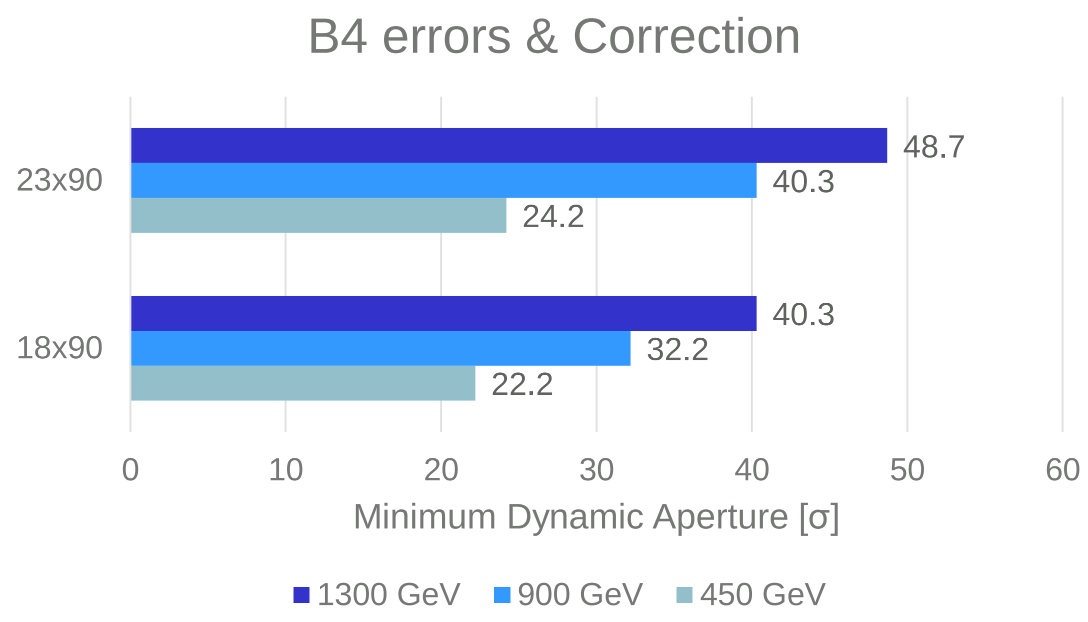
- Especially at lower injection energies b_3 correction needs improvements

- MCS also exceed max. Gradient of 3000 T/m² at 1300 GeV and length will be increased in the next iteration of the lattices

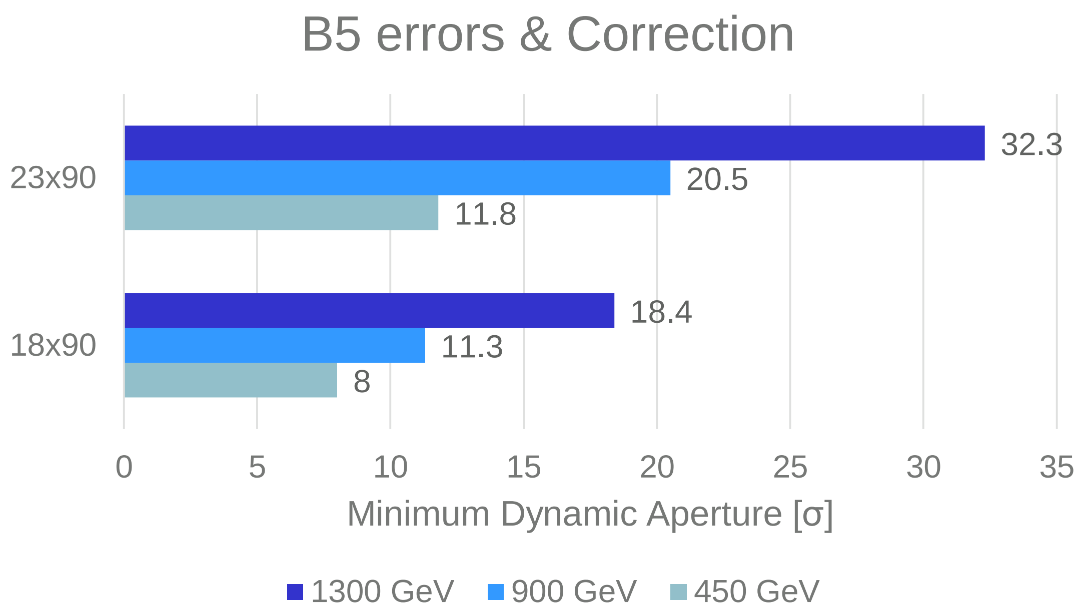


b_4 and b_5 Errors

- Octupole component corrected by three octupole correctors (MCO) per cell, one family per arc
- With current correction scheme b_4 is well corrected

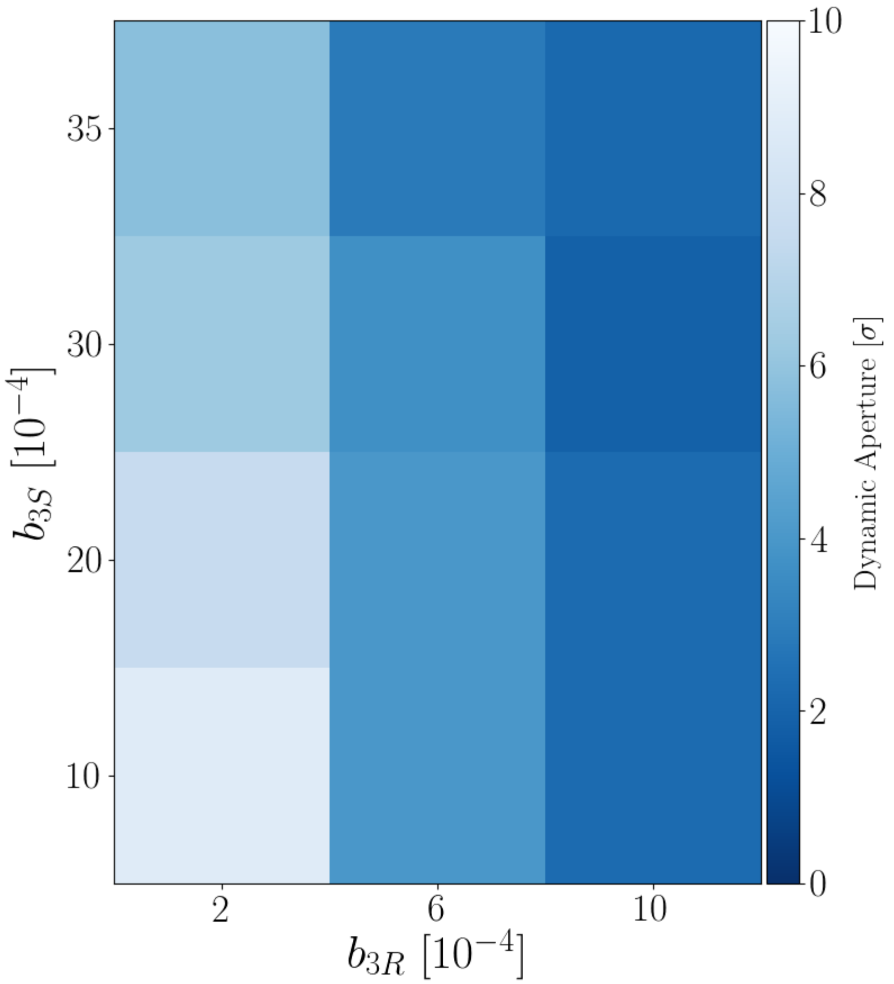


- Decapole component correction same as b_4
- Currently only at 450 GeV correction needs improvements



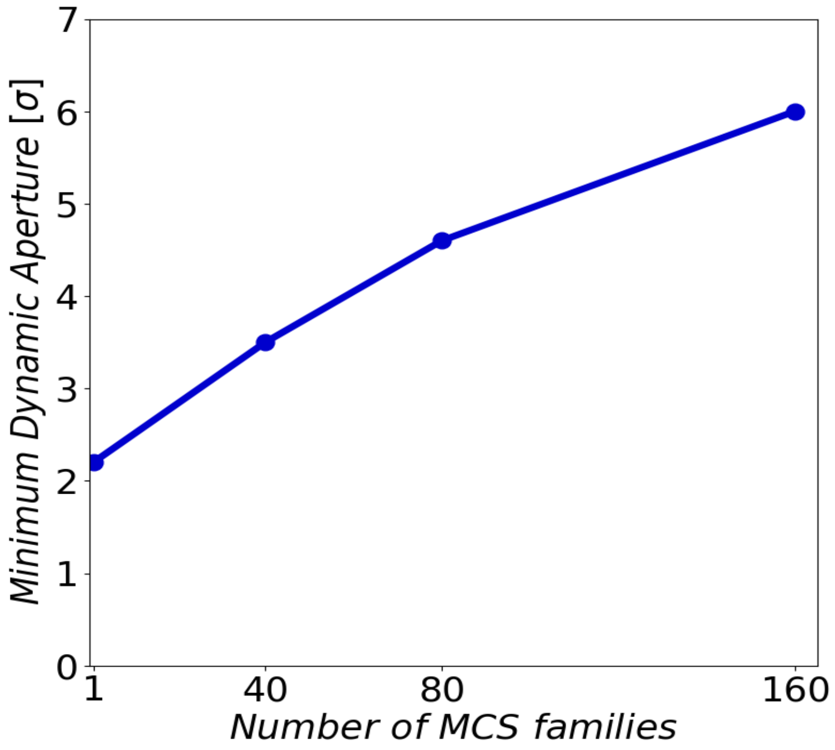
Correction Circuits I

- So far, the sextupole component of the dipoles has the biggest impact on the DA and requires better correction
- For further tracking studies, only the 18 cell lattice at 450 GeV injection energy was studied in more detail
- Tracking without b_{3R} and only correcting the systematic and uncertainty component of the dipoles yields a DA of **9.8 σ** , going up to **11.2 σ** if b_{3S} is reduced by 5 units
- Random component requires a better (more local) correction



Correction Circuits II

- To correct b_3 more locally,
  the option to use more MCS families was studied
- Only at very large number of families,
  significant improvements in DA
- Even when correcting on a per dipole basis,
  we do not reach the same DA as
  without random errors → currently under study
- Further studies to improve DA:
  - Study also interleaved schemes and
    impact on DA when reducing sextupolar resonant driving terms
  - Study the impact of changes in the linear optics
  - Measuring dipoles and look into sorting strategies



Conclusion

- The current status of the dynamic aperture in both lattices and for 3 different injections energies was presented using the latest field quality estimates
- With the current corrections, DA only in the case of the LHC-like lattice at the highest considered injection energy meets the target DA
- Sextupole component of the dipoles has the biggest impact on DA and requires better corrections
- To improve the DA, b_3 correction strategy will be refined and alternative ways such as sorting will be explored

Thank you for your attention

Field Quality 450 GeV

	Systematic	Uncertainty	Random
b_2	-2.230	0.922	0.922
b_3	-35.000	10.000	10.000
b_4	0.000	0.449	0.449
b_5	8.000	1.500	1.500
b_6	0.000	0.176	0.176
b_7	0.200	0.211	0.211
b_8	0.000	0.071	0.071
b_9	3.800	0.500	0.500
b_{10}	0.000	0.027	0.027
b_{11}	0.750	0.028	0.028
b_{12}	0.000	0.009	0.009
b_{13}	0.000	0.011	0.011
b_{14}	0.000	0.003	0.003
b_{15}	0.000	0.004	0.004

	Systematic	Uncertainty	Random
a_2	0.000	1.040	1.040
a_3	0.000	0.678	0.678
a_4	0.000	0.450	0.450
a_5	0.000	0.317	0.317
a_6	0.000	0.205	0.205
a_7	0.000	0.116	0.116
a_8	0.000	0.071	0.071
a_9	0.000	0.041	0.041
a_{10}	0.000	0.025	0.025
a_{11}	0.000	0.016	0.016
a_{12}	0.000	0.000	0.009
a_{13}	0.000	0.000	0.005
a_{14}	0.000	0.000	0.003
a_{15}	0.000	0.000	0.002

Field Quality 900 GeV

	Systematic	Uncertainty	Random
b_2	-2.230	0.922	0.922
b_3	-55.000	4.000	4.000
b_4	0.000	0.449	0.449
b_5	8.000	1.500	1.500
b_6	0.000	0.176	0.176
b_7	0.600	0.211	0.211
b_8	0.000	0.071	0.071
b_9	4.200	0.500	0.500
b_{10}	0.000	0.027	0.027
b_{11}	0.860	0.028	0.028
b_{12}	0.000	0.009	0.009
b_{13}	0.000	0.011	0.011
b_{14}	0.000	0.003	0.003
b_{15}	0.000	0.004	0.004

	Systematic	Uncertainty	Random
a_2	0.000	1.040	1.040
a_3	0.000	0.678	0.678
a_4	0.000	0.450	0.450
a_5	0.000	0.317	0.317
a_6	0.000	0.205	0.205
a_7	0.000	0.116	0.116
a_8	0.000	0.071	0.071
a_9	0.000	0.041	0.041
a_{10}	0.000	0.025	0.025
a_{11}	0.000	0.016	0.016
a_{12}	0.000	0.000	0.009
a_{13}	0.000	0.000	0.005
a_{14}	0.000	0.000	0.003
a_{15}	0.000	0.000	0.002

Field Quality 1300 GeV

	Systematic	Uncertainty	Random
b_2	-2.230	0.922	0.922
b_3	-40.000	3.000	3.000
b_4	0.000	0.449	0.449
b_5	4.000	0.800	0.800
b_6	0.000	0.176	0.176
b_7	1.100	0.211	0.211
b_8	0.000	0.071	0.071
b_9	2.900	0.200	0.200
b_{10}	0.000	0.027	0.027
b_{11}	1.000	0.028	0.028
b_{12}	0.000	0.009	0.009
b_{13}	0.000	0.011	0.011
b_{14}	0.000	0.003	0.003
b_{15}	0.000	0.004	0.004

	Systematic	Uncertainty	Random
a_2	0.000	1.040	1.040
a_3	0.000	0.678	0.678
a_4	0.000	0.450	0.450
a_5	0.000	0.317	0.317
a_6	0.000	0.205	0.205
a_7	0.000	0.116	0.116
a_8	0.000	0.071	0.071
a_9	0.000	0.041	0.041
a_{10}	0.000	0.025	0.025
a_{11}	0.000	0.016	0.016
a_{12}	0.000	0.000	0.009
a_{13}	0.000	0.000	0.005
a_{14}	0.000	0.000	0.003
a_{15}	0.000	0.000	0.002