LHC IR Upgrade

Dipole First
with Chromaticity and Dynamic Aperture Issues

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Introduction

A dipole first upgrade scenario has been developed
and the optics issues have been explored.

The main advantages of the dipole first layout are:

- reduced number of long range collision,
- more efficient use of the quadrupole apertures since the crossing scheme is upstream,
- reduce radiation level due to the spectrometer effect in the dipole.

The motivations for the studies are:

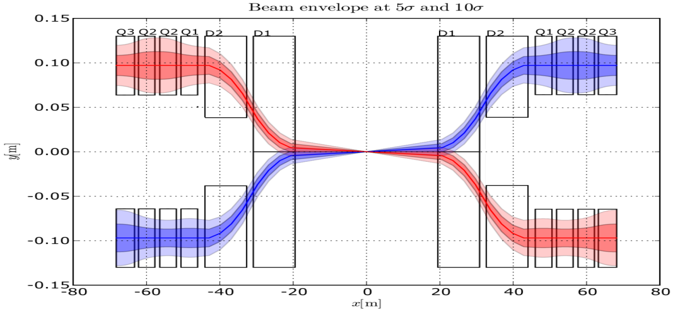
- test the feasibility of the layout,
- set a reference for comparison with other layouts.

Introduction (2)

The study performed are:

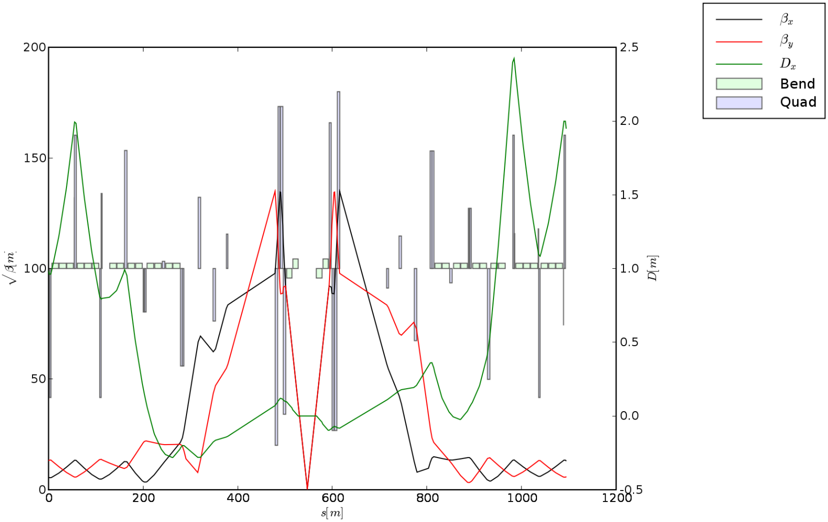
- specification of the magnets strengths and apertures,
- collision, injection and transition optics,
- crossing angle and parallel separation schemes,
- linear and non-linear chromaticity correction,
- dynamic aperture and field quality specifications.

Layout specifications



Mag.	Pos.	Length	Field	Inner D.
D1	19.45m	11.4m	15.0T	0.130m
D2	32.653m	11.4m	15.0T	0.080m
Q1	46.05m	4.5m	231.0T/m	0.080m
Q2A	51.87m	4.5m	-256.6T/m	0.080m
Q2B	57.69m	4.5m	-256.6T/m	0.080m
Q3	63.25m	5.0m	280.0T/m	0.080m

Collision Optics



Comments on Optics

- Maximum $\beta = 18$km,
- Q4-Q7 non zero dispersion,
- no left-right b1-b2 symmetry,
- Q4,Q5 high β values,
- tunability: $\frac{\delta\mu_x}{2\pi} = 0.016$, $\frac{\delta\mu_y}{2\pi} = 0.10$;
- a smooth path to an injection optics exists.

For a more detailed description refer to my talk at LUMI-05.

Crossing Angle Scheme

The crossing angle (440μrad needed for keeping 10σ separation), can be done, instead using orbit corrector:

- for the horizontal plane by powering differently D1 and D2
- for the vertical plane by tilting D1 and D2
  resulting in a vertical deflection

This implementation creates no dispersion mismatch and thus no dispersion beating.
In addition the triplets don't need margin due the crossing angle.

For a more detailed description refer to my talk at LUMI-05.

Chromaticity

The tune dependence on the spread in energy (chromaticity) is enhanced by high β values.
For each of the 8 arcs in the LHC there are:

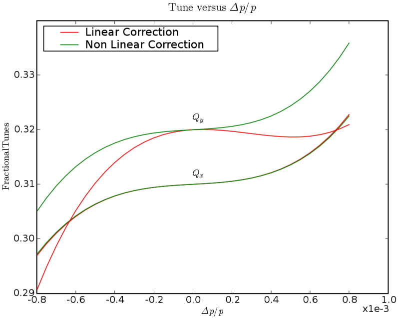
- two sext. families focusing ($B_{max} = 1.280$T at 17mm),
- two sext. families defocusing ($B_{max} = 1.280$T at 17mm),
- one sext. family of spool pieces ($B_{max} = 0.471$T at 17mm);

These elements can be used for correcting the first and second order chromaticity and the off-momentum beta-beat. They do not affect the long term stability as they are interleaved and at π phase advance.

More details will be given in the talk: "Limits on chromaticity correction" (A. Faus-Golfe, R de Maria, R. Tomas, this workshop)

Tune versus δ corrected by the Arc Sextupoles

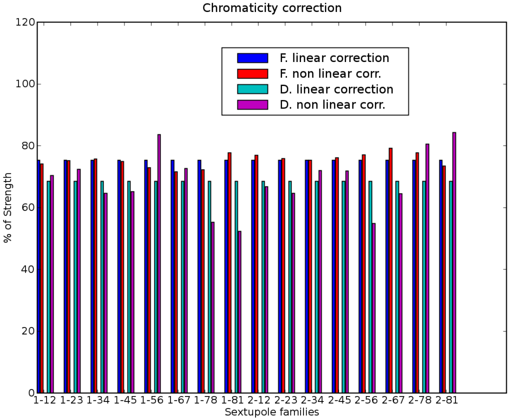
The linear and the second order chromaticity can be corrected in this dipole first layout.



An attempt to correct the chromaticity with local sextupoles in the triplet failed due to:

- large geometric aberrations from the strong sextupolar field
- absence of suitable places for compensating the aberrations
- high order dispersion emerging when the dispersion is increased to reduce the required sextupolar field

Corrector Strengths



70% of the spool pieces are used in addition to the arc sextupole families.
There is still budget for the beta-beat correction.
The present powering of the sextupole families cannot compensate third order chromaticity.

Dynamic Aperture and Field Quality Requirements

The dynamic aperture (DA) is estimated by tracking a particle distribution 10^5 turns in 60 realizations of the machine compatible with the error statistics.
The minimum of those 60 computed DAs should give the real dynamic aperture of the machine within a factor of 2 (see the LHC design report).
Therefore the aim is to find the maximum allowed multipole strength for a simulated DA of 12σ.
At collision the DA is dominated by the field quality of the elements in the high β regions, that is:

- in the quadrupole first designs by the triplets quadrupoles;
- in the dipole first designs by the triplets and the separation/recombination dipoles.

DA in the Dipole First Option

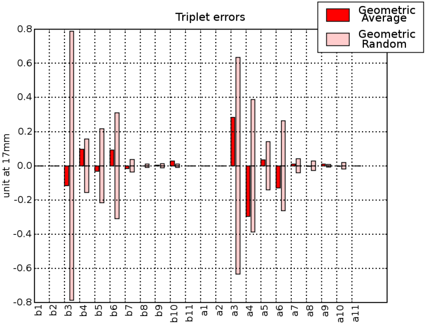
The parameter space for a strict specification of the field quality is too large to be explored systematically.
For a first estimation, the DA has been calculated including field errors only in the triplet.
The field errors of the rest of the machine should not have a big impact on the DA.
Including field errors of the sep./recom. makes difficult to extend the results to different layouts.
The parameter space has been probed by:

- using the field quality of existing magnets,
- using different scaling laws,
- using a multipole by multipole scan.

In the studies both IPs are in collision, no correction was applied and the beam-beam effect is not included.

DA Results using Field Quality of Existing Magnets

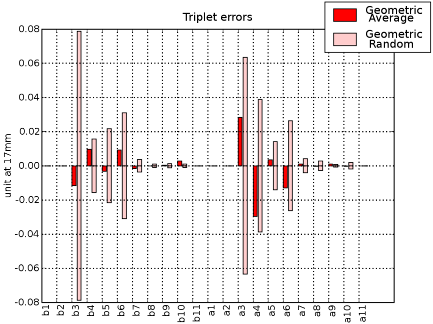
Using the field quality of:



- MQXB
  $\rightarrow DA = 3\sigma.$

DA Results using Field Quality of Existing Magnets

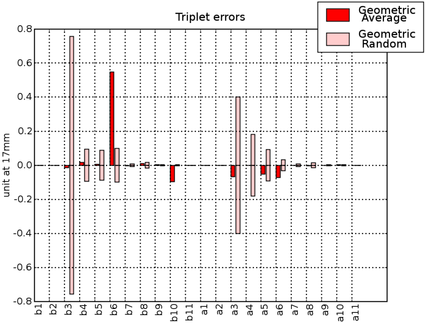
Using the field quality of:



- MQXB
  $\rightarrow DA = 3\sigma$.
- 10% of MQXB
  $\rightarrow DA = 8.3\sigma$.

DA Results using Field Quality of Existing Magnets

Using the field quality of:

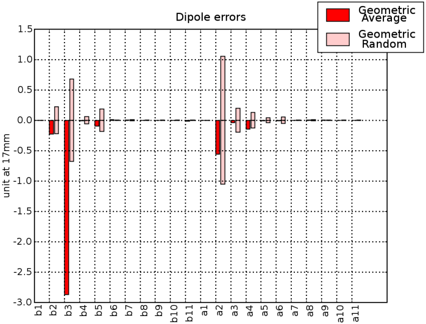


- MQXB
  $\rightarrow DA = 3\sigma$.
- 10% of MQXB
  $\rightarrow DA = 8.3\sigma$.
- MQY scaled [1] by
  $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$
  $\rightarrow DA = 2\sigma$.

[1] B.Bellesia, J.P. Koutchouk, E. Todesco. To be published.

DA Results using Field Quality of Existing Magnets

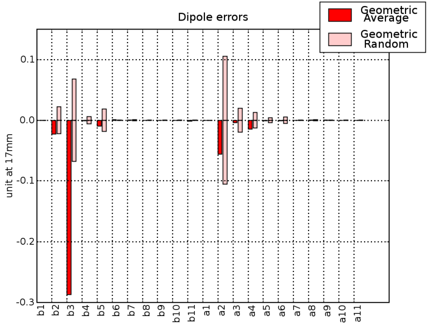
Using the field quality of:



- MQXB
  $\rightarrow DA = 3\sigma$.
- 10% of MQXB
  $\rightarrow DA = 8.3\sigma$.
- MQY scaled [1] by
  $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$
  $\rightarrow DA = 2\sigma$.
- MQXB and MBRCL
  $\rightarrow DA = 0.8\sigma$.

DA Results using Field Quality of Existing Magnets

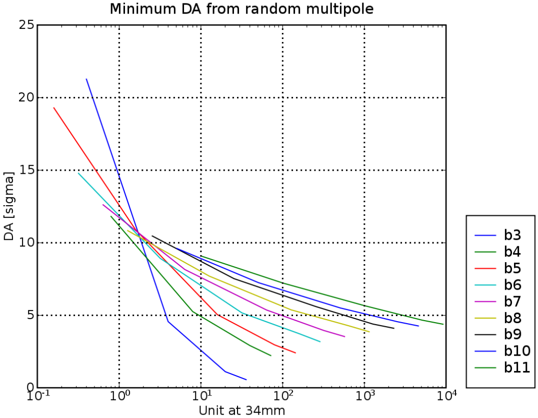
Using the field quality of:



- MQXB
  $\rightarrow DA = 3\sigma$.
- 10% of MQXB
  $\rightarrow DA = 8.3\sigma$.
- MQY scaled [1] by
  $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$
  $\rightarrow DA = 2\sigma$.
- MQXB and MBRCL
  $\rightarrow DA = 0.8\sigma$.
- 10% of MQXB and MBRCL
  $\rightarrow DA = 6\sigma$.

DA Results using Single Multipole Scan

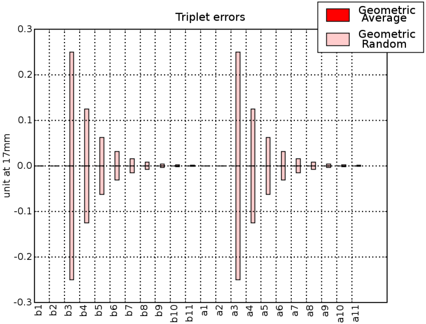
An upper bound on the minimum DA can be found by probing one multipole error at the time.



Taking all multipole together at 1 unit at 34mm...

DA Results using Field Quality of Existing Magnets

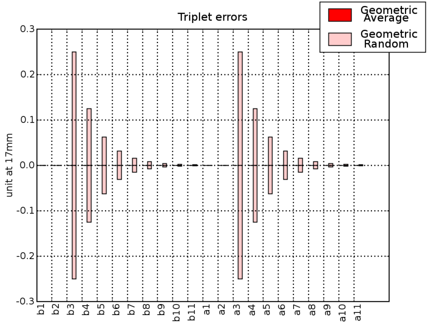
Using the field quality of:



- MQXB
  $\rightarrow DA = 3\sigma$,
- 10% of MQXB
  $\rightarrow DA = 8.3\sigma$,
- MQY scaled [1] by
  $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$
  $\rightarrow DA = 2\sigma$.
- MQXB and MBRCL
  $\rightarrow DA = 0.8\sigma$,
- 10% of MQXB and MBRCL
  $\rightarrow DA = 6\sigma$,
- 1 unit at 34mm
  $\rightarrow DA = 4.5\sigma$.

DA Results using Field Quality of Existing Magnets

Using the field quality of:



- MQXB
  $\rightarrow \mathrm{DA} = 3\sigma$,
- 10% of MQXB
  $\rightarrow \mathrm{DA} = 8.3\sigma$,
- MQY scaled [1] by
  $b_n(d_1) = (d_0/d_1)^n b_n(d_0)$
  $\rightarrow \mathrm{DA} = 2\sigma$.
- MQXB and MBRCL
  $\rightarrow \mathrm{DA} = 0.8\sigma$,
- 10% of MQXB and MBRCL
  $\rightarrow \mathrm{DA} = 6\sigma$,
- 1 unit at 34mm
  $\rightarrow \mathrm{DA} = 4.5\sigma$.
- Nominal LHC no correction
  $\rightarrow \mathrm{DA} = 13\sigma$.

Conclusion (1)

- A dipole first scenario with the relevant optics configuration has been developed
- The required aperture is compatible with the element specifications
- Probably Q5 should be replaced with 1.9K MQY
- Doubling Q6 may help increasing the tunability but is not necessary
- The crossing schemes is completely managed by D1 D2 and there is no dispersion mismatch due the crossing angle
- Less long range beam-beam interaction due the early separation of the beam

Conclusion (2)

- The linear and second order chromaticity can be corrected by the sextupoles in the arcs.
- The third order chromaticity does not affect the beam in the bucket but is a limitation in operational margins (i.e. chromaticity measurement)
- The off-momentum beta-beat is under control in the triplet but not in the arc. It should be possible to compensate using the available budget.

Conclusion (3)

- The field quality of the present magnet production cannot assure alone the required DA.
- The better field quality expected from a large aperture does not help.
- b3 seems responsible for lowest DA but scales quickly. b6, b8, b10 scale slowly and might represent a bottle neck.
- The multipole errors should be smaller than 1 unit at 34mm for upgrade scenarios where beta-max is larger than 18km.
- An effective corrector package is needed to reach the required DA.

Conclusion (4) and Further Studies

- the radiation damage due the debris has not been addressed so far
- the layout allows a natural magnetic TAS (racetrack magnets) for the charged debris
- it is not clear how to cope with neutral debris.

These items will the subject of the next studies, as well as sensitivity to the closed orbit due triplet misalignment, tune modulation due current ripples.

not included. . .

DA using Single Multipole Scan

An upper bound on the minimum DA can be found by probing one multipole error at the time.

If and only if there is one single multipole error the DA follows a simple scaling law. When several multipoles coexist and their statistics is large enough the DA is lower than the one of the single multipoles.

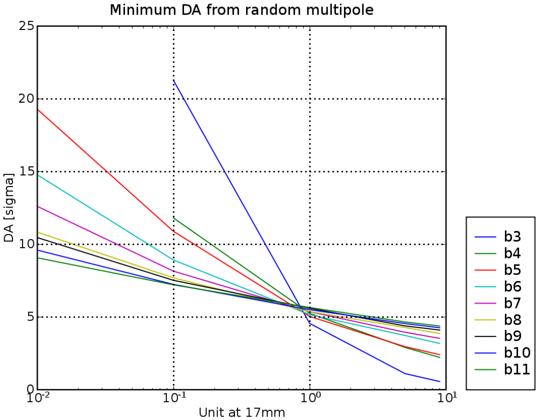
In the present production of the triplets the field quality is dominated by:

- the systematic error for the allowed multipoles (b6,b10),
- the random errors for the non-allowed multipoles.

A multipole scan is performed for systematic and random errors.

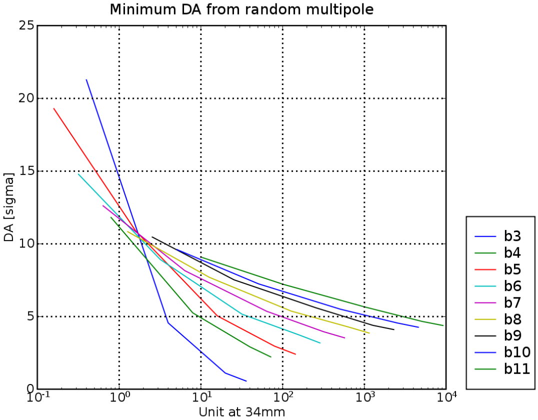
This strategy has been used for finding a working point in the parameter space of the multiple errors and for starting an analysis. The study is on going.

DA Results using Single Multipole Scan



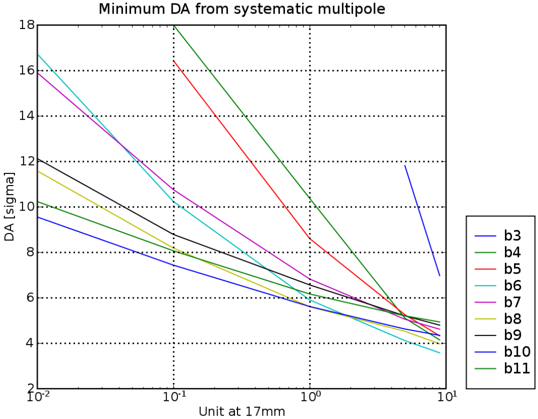
The curves reproduce the theoretical scaling law:
$\log(da_n) \sim -\frac{1}{n-2}$.

DA Results using Single Multipole Scan



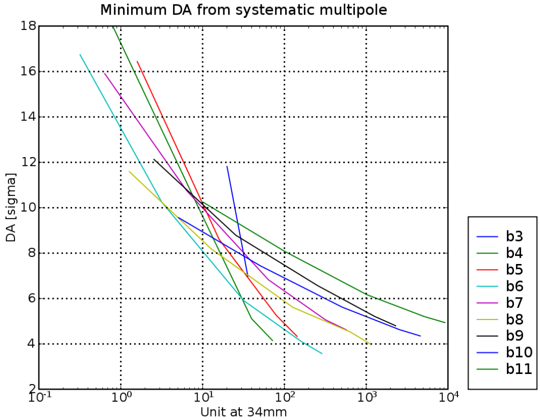
The plot looks more natural when the reference radius is 12σ.

DA Results using Single Multipole Scan



The systematics DA is affected by the compensation due internal symmetries.

DA Results using Single Multipole Scan



b6, b8 ,b10 looks dangerous and the same effect in observed for in the simulation for the nominal LHC.

DA Results using Single Multipole Scan