Phase 1 Optics: Merits and Challenges

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Introduction

The presentation will cover:

- a survey of the parameter space using a simplified model;
- results of studies for several upgrade optics implementation.

I will show a summary of the results.
For proposal and preliminary studies for phase 1 see: LHC project report 1000, 1008.
For the design process see: LHC project report 1051.
For full details of calculations (about 400 pictures and tables)) see: http://cern.ch/rdemaria/layouts/html.
A more detailed version of this presentation can be found in: http://cern.ch/liuwg/LIUWG_0003_18102007/rdm_LIUWG3.pdf

Phase 1 upgrade

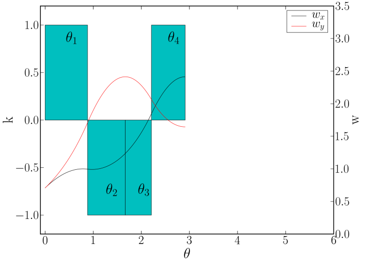
Phase 1 upgrade aims at:

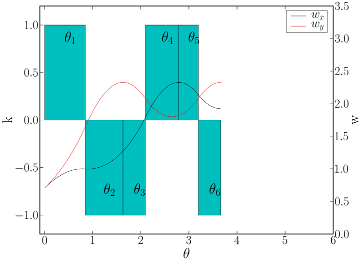
- $\beta^* = 25$cm, $L^* \geqslant 23$m;
- limiting the beam size in the focusing system (for reducing chromatic aberrations and errors sensitivities)
- maximizing the aperture margins in the focusing system (for reducing the heat load, radiation damage and increasing operational margin)
- making the final focusing system as short as possible (for reducing the number of long range beam beam interaction, reducing the field of D1/D2, reducing the cost)
- replacing less equipment as possible while maximizing the potential integrated luminosity gain.

The nominal LHC triplet cannot fulfill the Phase 1 targets because of aperture limitations.

Parameter space via simplified triplet and quadruplet

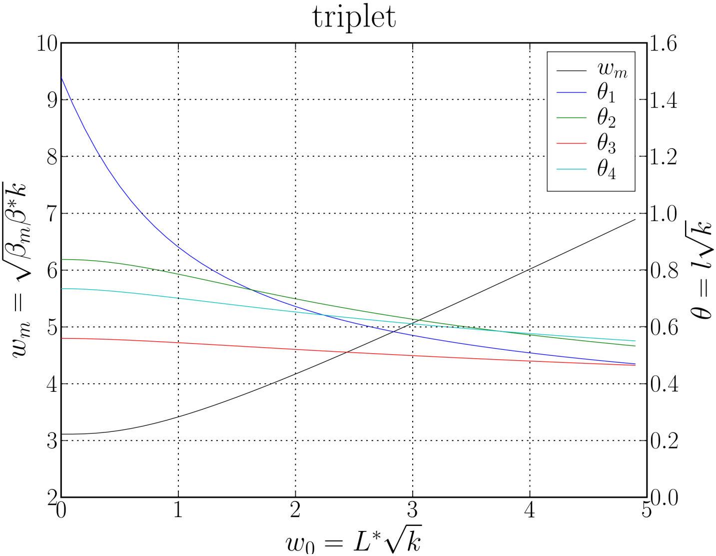
I used a simplified triplet and quadruplet, in order to study the parameter space.
They are gap-less point to parallel focus system.





If we fix the gradient, L^* and β^* we can find the smaller possible beam size (beta peak) in the triplet or quadruplet.

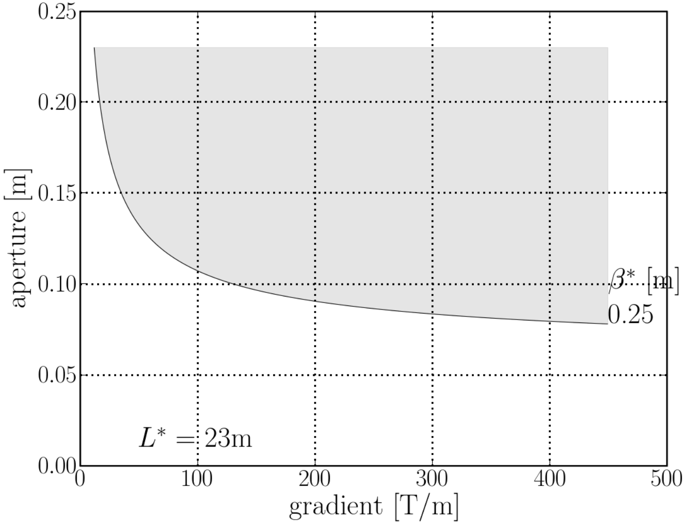
Triplet parameters



See LHC project report 1051 for more information.

Beam size vs gradient

Beam size: $33\sigma + 22\text{mm}$. Cannot be too precise.



Beam size vs gradient

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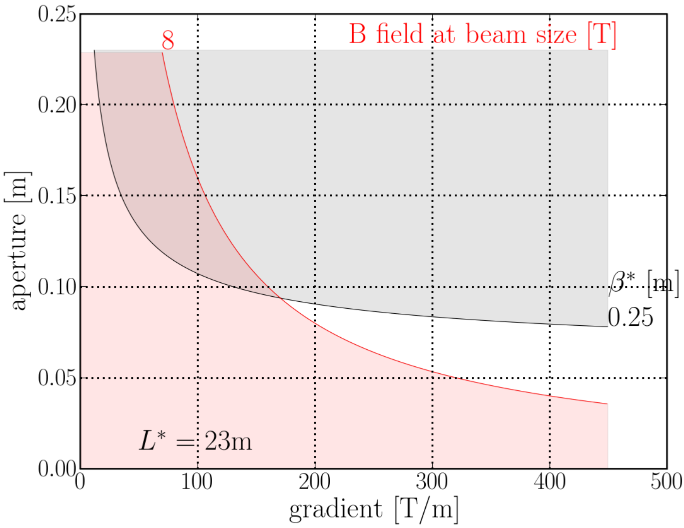

Beam size vs gradient

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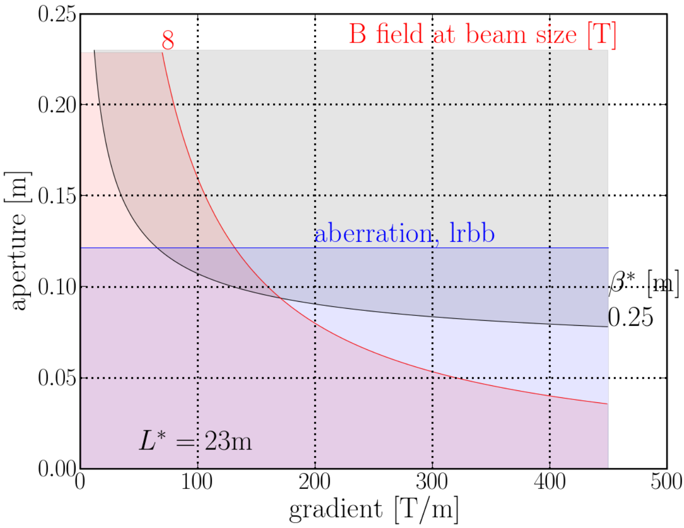
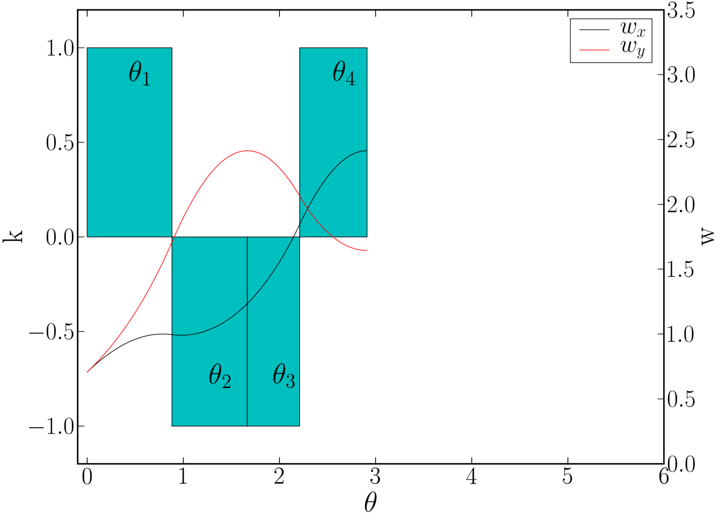


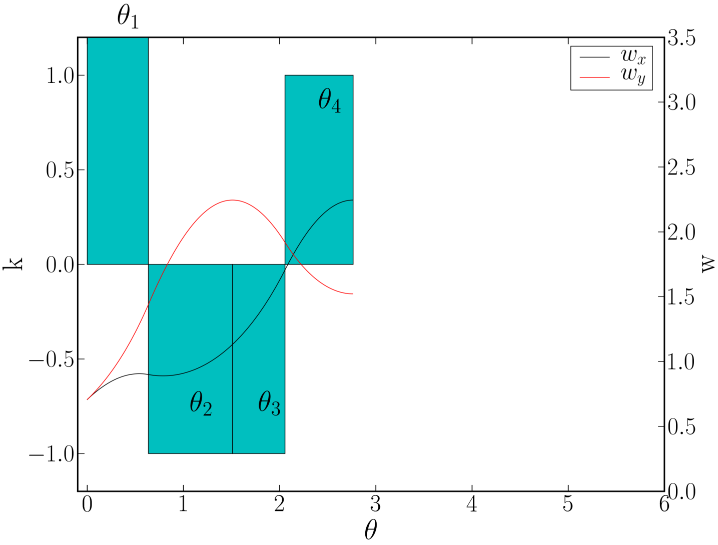
Realistic implementation

Starting from the ideal case



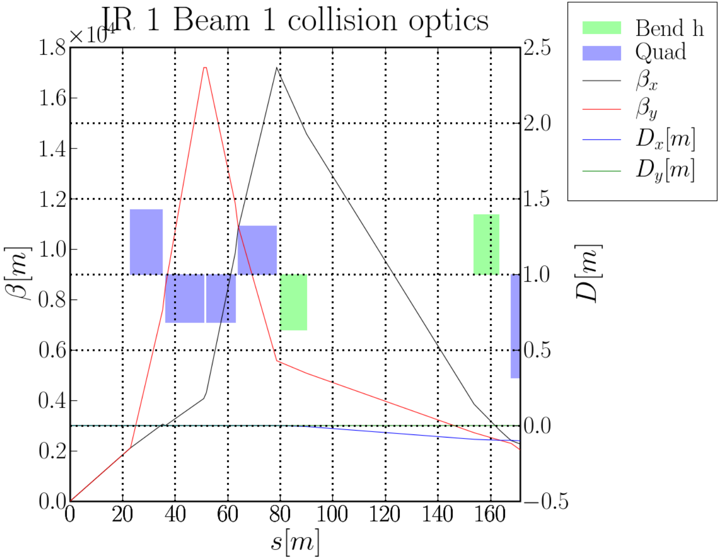
Realistic implementation

Optimize Q1



Then split and focus to match to the arc.

Compact



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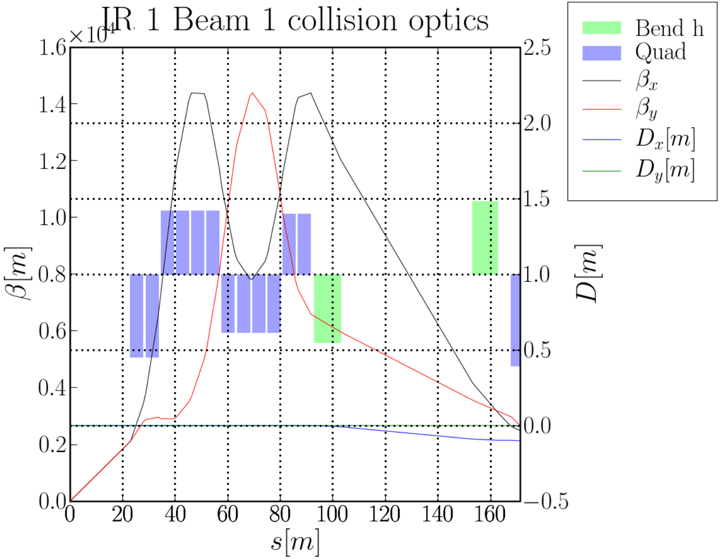
Modular



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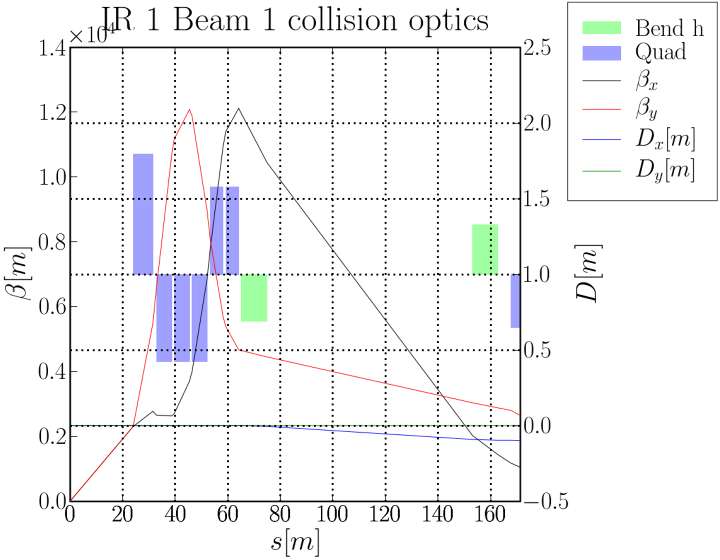
Lowbetamax



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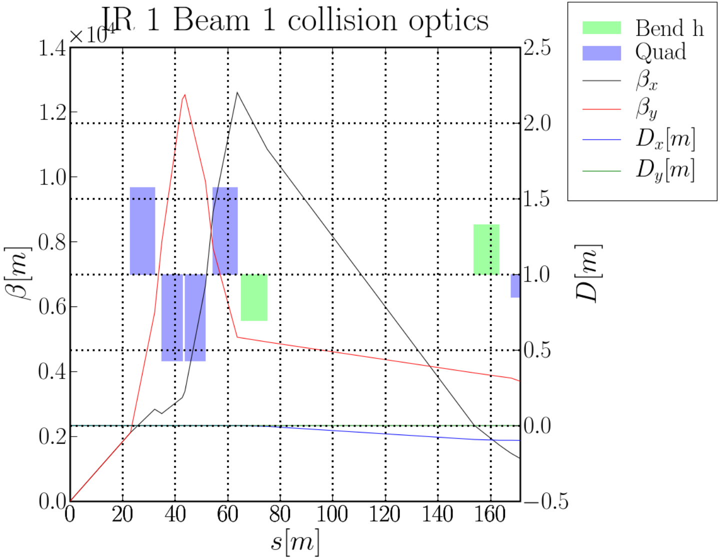
Symmetric



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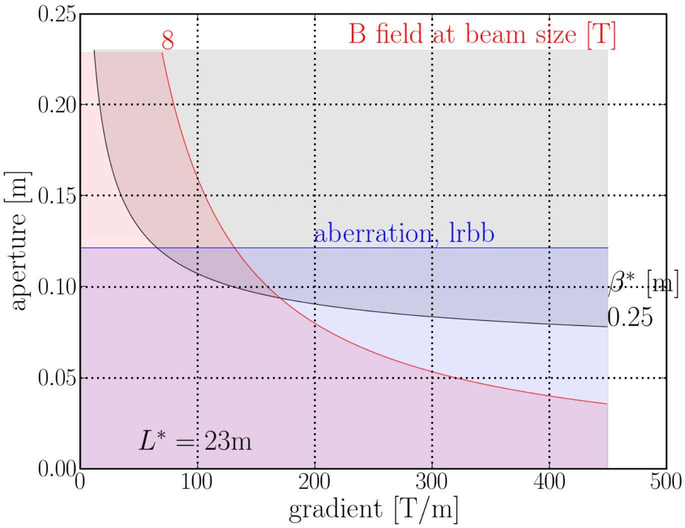
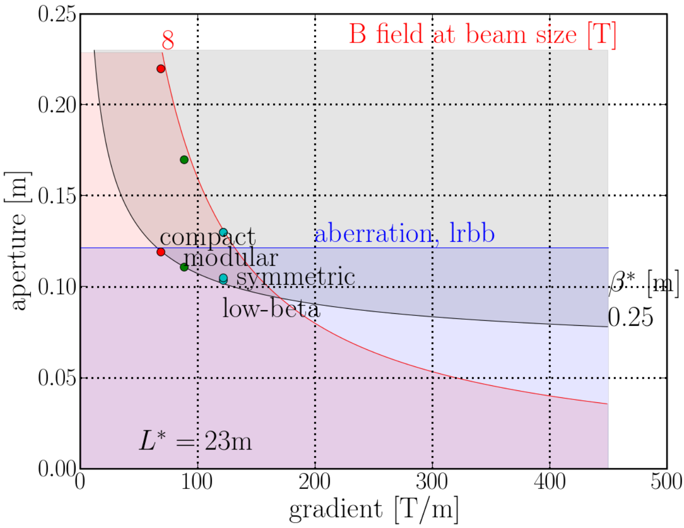
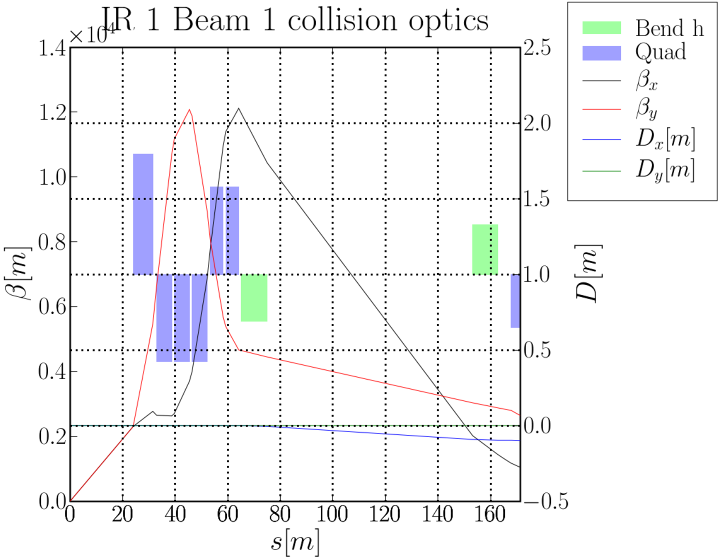
Choice of the gradient



Choice of the gradient



Fine tuning and match



The last choice to be made is the slope at the end of the triplet.

Fine tuning and match

For this kind of tuning the first three layouts present more flexibility due a larger number of parameters used.
The last layout can use the gaps between quadrupole as additional parameters, but the solution may drift away from the optimum (larger overall length, bigger beam size).
The strategy used was to simplifies the matching with the LSS. I did not use all the flexibility to optimize apertures in D2, Q4 and Q5.
The triplets has a lot of flexibility for selecting the aperture in Q4 but the LSS has very little flexibility in accepting too large a or too small aperture (as a general rule what is gained aperture is lost in strength and viceversa).

Layout

	Compact	Modular	Lowbetamax	Symmetric
L* [m]	23	23	24	23
Gradient [T/m]	91,68	115,88,82,84	168,122	122
Module L [m]	12.2,14.6,11	4.8	7.4,5.7,4.9	9.2,7.8
Total L [m]	55	68	40	41
LRBB	23	26	19	19
Aper. MQX [mm]	170,220	130,170	90,130	130
B.S. MQX [mm]	74,79;99,104	54,59;99,104	34,39;54,59	54,59
B.S. D1 [mm]	50,64;45,64	50,64;45,64	50,64;45,64	50,64;45,64

Triplet apertures proposed by Franck Borgnolutti, Ezio Todesco and they are the one which gives the largest aperture margins. What to do with this aperture is an open question (shielding, magnet or beam operational margins). D1 apertures proposed by Stephane Fartoukh.

The beam screen apertures are given in term of half gap and radius. For the MQX the two couple refers to the twos aperture, while for D1 refer to IP1 and IP5.

Layout

	LHC
L* [m]	22.965
Gradient [T/m]	205
Module L [m]	6.37,5.5
Total L [m]	30
LRBB	17
Aper. MQX [mm]	70
B.S. MQX [mm]	24,28.9
B.S. D1 [mm]	26.5,64

The beam screen apertures are given in term of half gap and radius.

Aperture bottlenecks

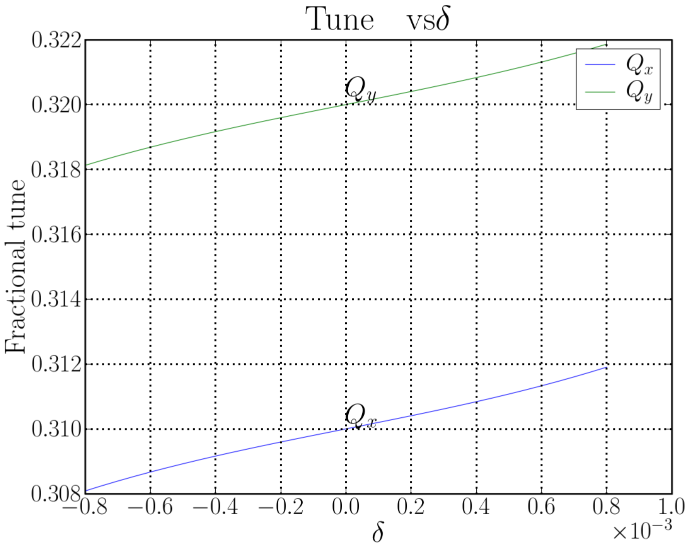
	Compact	Modular	Lowbeta	Symmetric	LHC
MQX, ap 1	20.026	14.141	7.821	15.466	7.215
MQX, ap 2	16.953	12.633	8.830	8.438	6.845
D1	5.303	6.379	7.607	7.323	7.431
D2	5.372	4.271	7.959	6.518	15.152
Q4	7.387	6.432	8.685	7.184	15.615
Q5	4.701	3.859	10.425	7.028	16.871

Aperture in terms on n1. Some beam screen are rotated in Q4, Q5 according to the crossing scheme as proposed by Stephane Fartoukh (see http://cern.ch/liuwg/LIUWG_0002_27092007/sf_LIUWG_2.ppt).
Lowbetamax and symmetric provide a better balance between apertures in triplets and LSS than compact and modular.

Beam-Beam

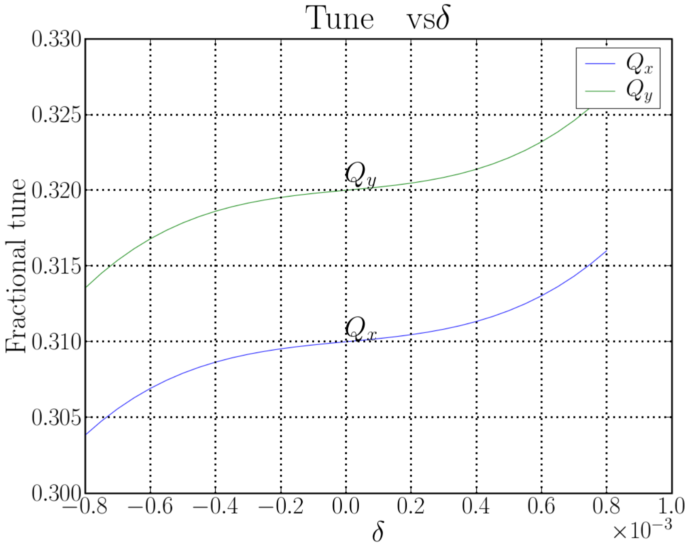
The number of beam beam interaction should be kept as small as possible. A large number would require larger crossing angle or less proton per bunch and therefore smaller luminosity.
More details will be given in the talk of Ulrich Dorda.

Chromaticity: LHC

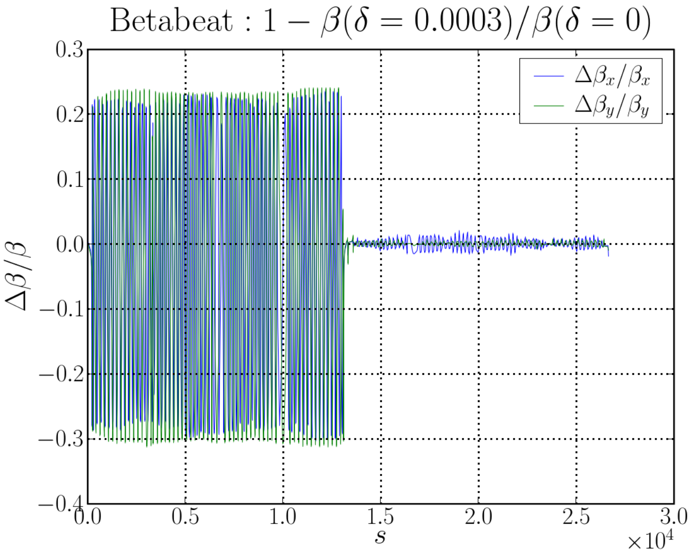


The machine became more chromatic due the reduction of β^*.

Chromaticity: Lowbetamax



Off momentum beta beat: lowbetmax Beam 1 $\delta = 3 \cdot 10^{-4}$



Chromatic aberrations

	Compact	Modular	Lowbeta	Symmetric	LHC
Sextupoles [%]	88,56	87,58	74,46	75,46	48,28
Beat. $\delta = 3 \cdot 10^{-4}$ [%]	40	40	30	30	10
Beat. $\delta = 8 \cdot 10^{-4}$ [%]	150	150	100	105	30

For a given β^*, solutions with lower gradient are more chromatic.
The off momentum beta beat may reduce the collimation efficiency or tollerances.

Dynamic aperture

	Compact	Modular	Lowbeta	Symmetric	LHC
Full	16	11	14	12	12
Triplet only	22	17	14	12	
Triplet excluded	16	11	20	16	

Results confirm the trend: more aperture margin more DA. The aperture bottlenecks in the LSS affect the DA. The difference between symmetric and lowbetamax, which should have similar performance, may be explained within the error bars of this kind of studies (the average DA looks more similar indeed).

Field quality estimates and scalings provided by Ezio Todesco (see LHC Project Report 1010).
DA computed without multipole and coupling correction, with measured errors for the rest of machine. Field quality of D1, D2 is not included. The values are the minimum DA over 60 seeds.

For DA with correction see the talk of Rogelio Tomas.

Transition to injection

The collision optics must be able smoothly change to an injection optics where $\beta^* > 5$m with a constant phase advance. This is particular chalenging, because:

- tight aperture requirements in LSS
- very different phase advances for some optics (i.e. extreme optimization of aperture in Q4).

A preliminary study show that is possible to keep the phase advance of the insertion for a large range of β^* only for lowbetamax and symmetric.

Strengths limitations

The LSS flexibility is not always sufficient for finding a optics.
Limitations of strengths and apertures may occur.
For the optics presented Q6 needs to be doubled for the Compact and Modular option.

Crossing scheme and antisymmetry

Two crossing schemes are implemented.
The first optimizes strength and aperture, and it is used for aperture and DA calculations. No antisymmetry imposed (the optics is not).
The second keeps the left-right antisymmetry up to Q3, but it shows strength limitation of the orbit correctors for compact and modular layout.
It is opportune to check whether the experiments or operation rely on this symmetry for high luminosity operations.

Conclusions 1

The exercise was useful for understanding the actual limitations for the implementation of a new focusing system compatible with the targets of Phase 1 upgrade.
At this stage of the studies, the outstanding issues are:

- Apertures in D2-Q4-Q5. Serious bottleneck for compact and modular. The bottleneck of D2 for the symmetric may be solved by a redesign of the focus system.
- Even vertical aperture of 100-110 mm gap D1 is a bottleneck for all options (more severe for compact and modular and for vertical crossing). It makes the aperture gain in the triplet useless.
- Off momentum beta beat. It is unavoidable, it must be studied carefully.
- The compact and modular requires additional Q6.

Conclusions 2

Many refinements are still needed for a final solution:

- check whether the heat load and radiation damage levels are compatible with the new elements.
- redesign the final focus system to reduce the beam size at Q4
- make sure that an injection optics exists
- determine whether the gaps between quadrupoles are in the right location for the BPM (far from the LRBB interactions), if not move the whole assembly or find a different splitting.
- check whether the larger off momentum beta beat affects the operation or the protection of the machine.

General remarks

From this studies it is possible to conclude:

- the LSS is pushed to the limits, it is necessarry to understand them better by exploring all the corners of the remaning flexibility in order to design efficiently new optics or propese localized but effective upgrade;
- optimization at the percent level gives rather large difference in performance (see difference between lowbetamax symmetric). The design of a soltution will require many iterations;
- flat beams will be probably the preferred scheme for pushing performance at the edge. This option should be studied as well during the design process to reduce avoidable bottlenecks.

General remarks

This study gives a wealth of complete models to be used as test bench, for instance, for testing the impact of energy deposition and the feasibility of protection strategies in several conditions.
But it does not give the final design yet.