LHC interaction region upgrade

Riccardo de Maria

CERN AB-ABP-LCU, Geneva. EPFL, Lausanne. Switzerland

December 18, 2007

LHC performance and limitations

LHC Interaction region

Dipole first layouts

Quadrupole first layouts

Conclusion and future projects

Reference and literature

Most of the papers concerning the LHC upgrade are published in the proceedings of the CARE-HHH-APD workshops. Other sources are EPAC and PAC conferences, internal reports and journal (PRSTAB, NIMS) and internal reports.

Outline

LHC performance and limitations
- LHC Performance
- Top energy
- Limitations
- Peak luminosity: upgrade strategies

LHC Interaction region

Dipole first layouts

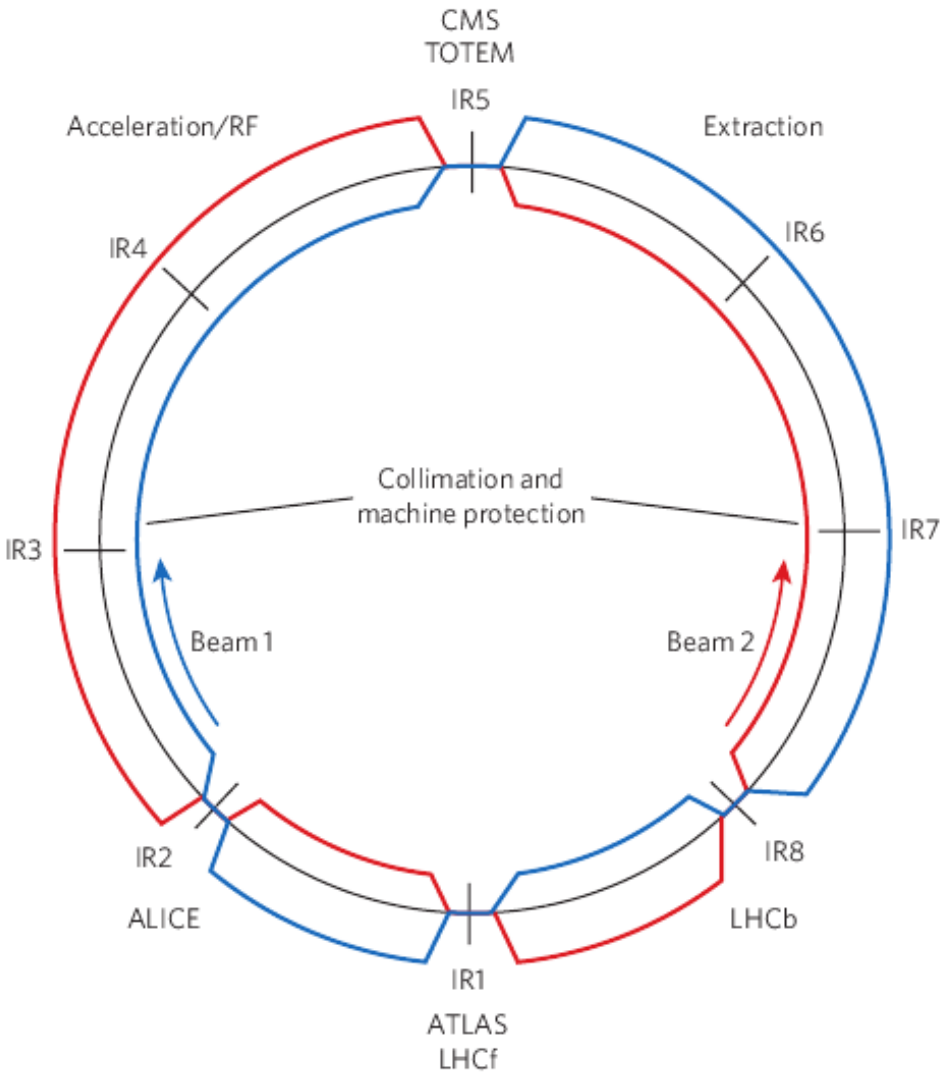
Quadrupole first layouts

Conclusion and future projects

LHC Performance

The scope of the Large Hadron Collider (LHC) is to find experimental evidence of the Higgs mechanism, gluon plasma, to perform precision measurements for validating the standard model theory and to explore new physics frontiers.
The LHC is a synchrotron that consists of a 26.7 km ring where two counter-rotating beams collides in four interaction points (IP). The is designed for unprecedented energies (14 TeV proton-proton collisions 5.52 TeV for nucleons in lead ions) and unprecedented luminosity ($10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, yielding 40 proton-proton collisions in two experiment every 25 ns).

LHC Performance



In 2002 CERN launched and R&D program of feasibility of an upgrade of the two key parameters, energy and luminosity (F. Ruggiero et al.)

Top Energy

The maximum energy achievable by the particles in the LHC is limited by the radius of tunnel arcs ($\rho = 3.5\,\mathrm{km}$), the maximum bending field generated by the dipole magnets ($B = 8.33\,\mathrm{T}$) and the dipole filling factor ($f_{\mathrm{bend}} = 78\%$).

$$\frac{p}{q} = f_{\mathrm{bend}} B \rho$$

For an increase of the energy only two options are possible:

- building a new tunnel and additional magnet with the same magnet technology,
- improve magnet technology and replace all the magnets.

Both options imply large costs and time.

Luminosity

The collision rate is determined by the luminosity which is a figure of merit defined by the particle beam parameters. It relates the cross section of an event to the event rate via the formula:

$$\frac{dR}{dt} = L\sigma \qquad\qquad [L] = [\,cm^{-2}\,s^{-1}]$$

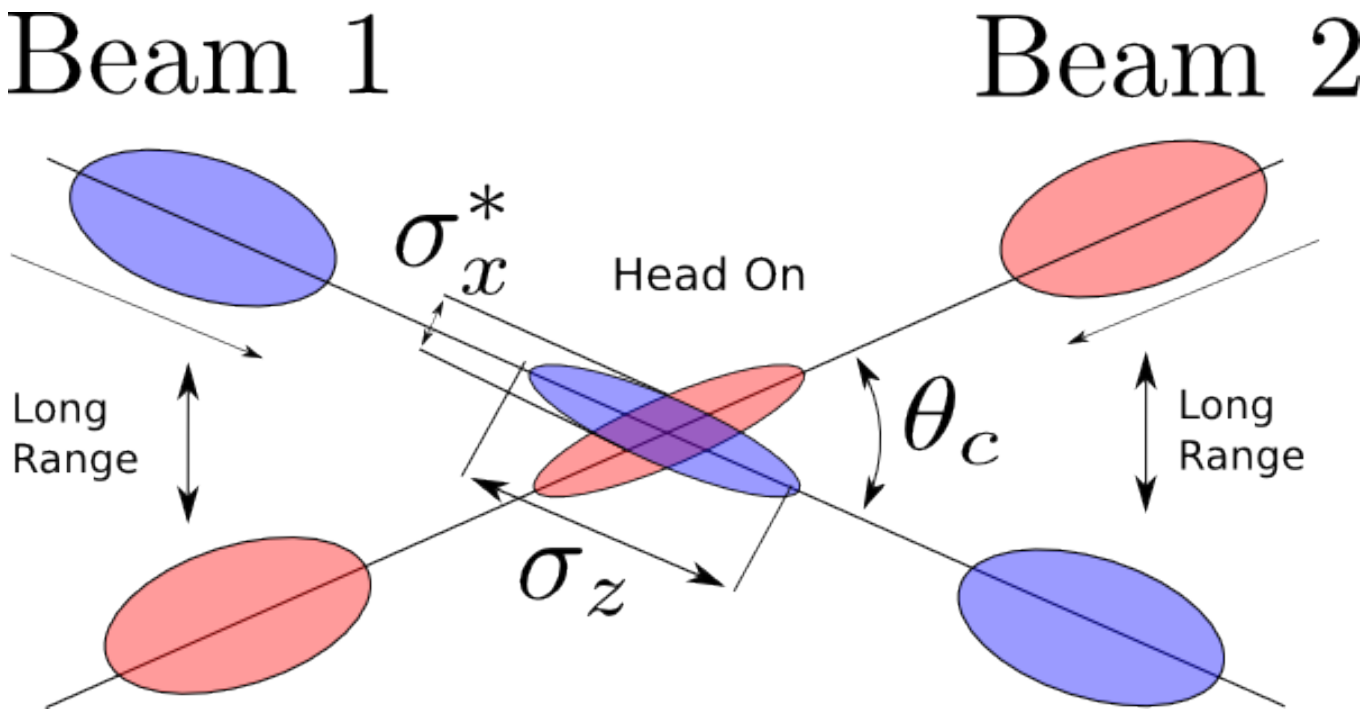
The has two performance goal for the peak luminosity: nominal ($L = 1\,10^{34}\,cm^{-2}\,s^{-1}$) and ultimate ($2.3\,10^{34}\,cm^{-2}\,s^{-1}$).
What is important is the integrated luminosity over time.

Peak luminosity: definition

$$L = \frac{N_b^2 f n_b}{4\pi\sigma_x^* \sigma_y^*} F(\theta_c, \sigma_x, \sigma_z)$$

Name	Symbol	Values
Revolution frequency	f	11245 kHz
Protons per bunch	N_b	$1.15\,10^{11}$
Number of bunches	n_b	2808
Transverse RMS beam size	σ_x	16.6 um
Crossing angle	θ_c	296 urad
Longitudinal RMS beam size	σ_z	7.5 cm
Geometric loss factor	F	0.829757
Initial beam beam separation	d_{sep}	9.8σ

Peak luminosity: geometric reduction factor



$$F = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma_x^*}\right)^2}}$$

$$\theta_c \propto \frac{1}{\sigma_x^*}$$

Peak luminosity: limitations

The limitations in LHC arising for an increase of the luminosity are:

- Bunch intensity: beam-beam interactions, beam current
- Number of bunches and bunch structure: beam current, multi-bunch instabilities, long range beam beam interactions (LRBB), e-cloud, collimation, stored beam energy
- Transverse beam size at the IP: interaction region layout, geometric reduction factor and LRBB (θ_c proportional to $1/\sigma_x^*$).

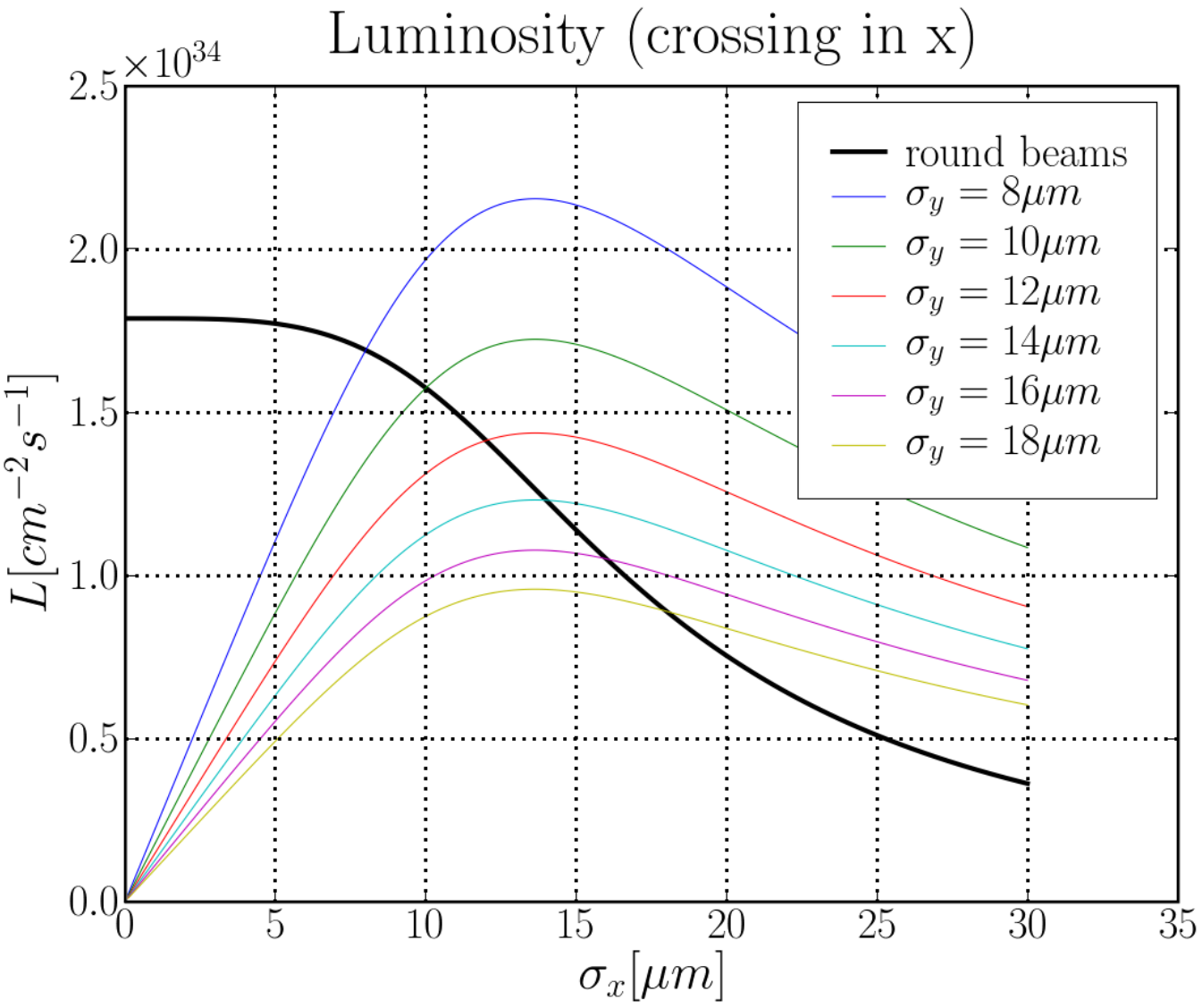
Upgrade strategies

Luminosity upgrade:

- increase bunch intensity (LPA, e-lens, wire compensation),
- increase number of bunches (RF),
- reduce the effect of the geometric reduction factor (crab crossing),
- rebeam beam effect (early separation schemes, wire compensation, e-lens),
- reduce the transverse beam size at the IP (IR upgrade).

For all the options refer to CARE-HHH-APD workshop proceedings.

Peak luminosity: IP beam size dependence



Outline

LHC performance and limitations

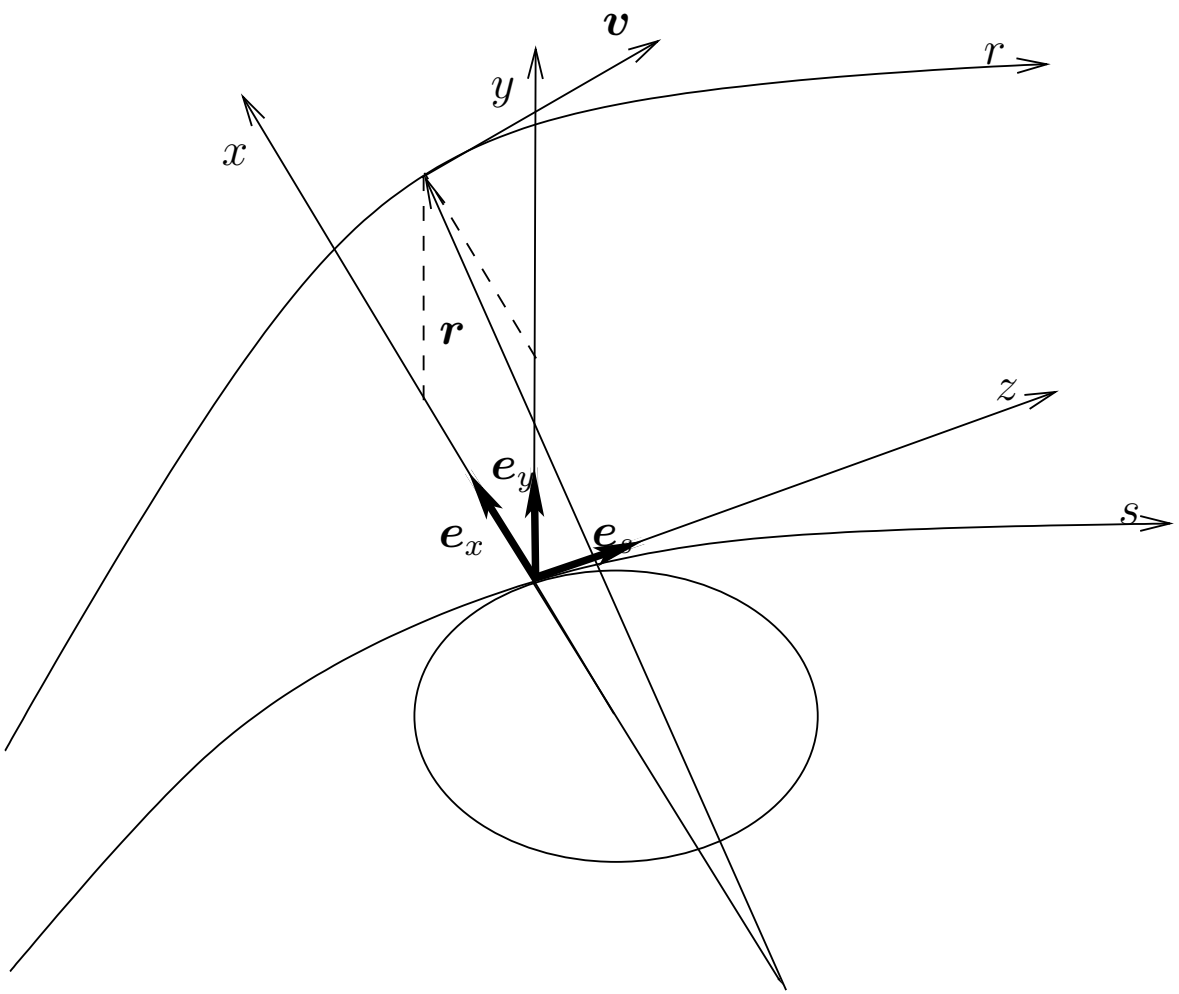
LHC Interaction region
- Accelerator reference frame
- Twiss parameters
- Interaction region layout
- Detector area
- TAS
- Triplets
- Separation Recombination
- Matching section and dispersion suppressor
- Nominal layout limitations
- Two options

Dipole first layouts

Quadrupole first layouts

Conclusion and future projects

Accelerator reference frame



Twiss parameters

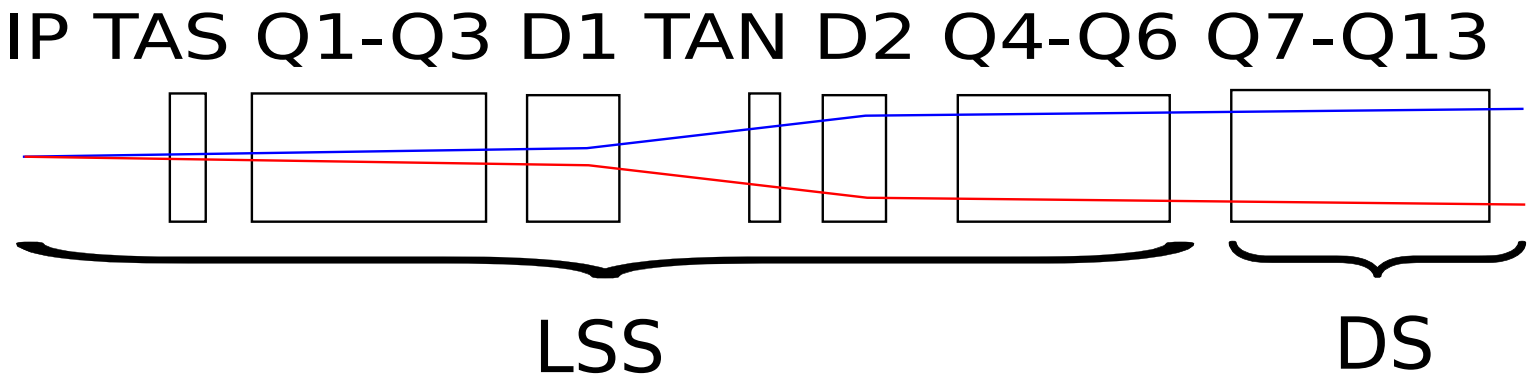
$$
\begin{aligned}
< I > &= \sqrt{< x^2 >< x'^2 > - < xx' > 2} = \varepsilon \\
< x^2 > &= \beta\varepsilon = \sigma^2 \\
< xx' > &= -\alpha\varepsilon \\
< x'^2 > &= \gamma\varepsilon,
\end{aligned}
$$

In case of linear unperturbed motion in a circular accelerator the Twiss parameters are invariant and periodic:

$$
\begin{aligned}
& x''(s) + k(s)x = 0 \\
& x(s) = \sqrt{2I\beta(s)}\cos(\phi(s) + \psi) \\
& \frac{1}{2}\beta(s)''\beta(s) - \frac{1}{4}\beta(s)'^2 + k(s)\beta(s)^2 = 1 \\
& \phi(s) = \int_{s_0}^{s} \frac{1}{\beta(t)} dt
\end{aligned}
$$

s longitudinal position, k focusing strengths.

Detector area

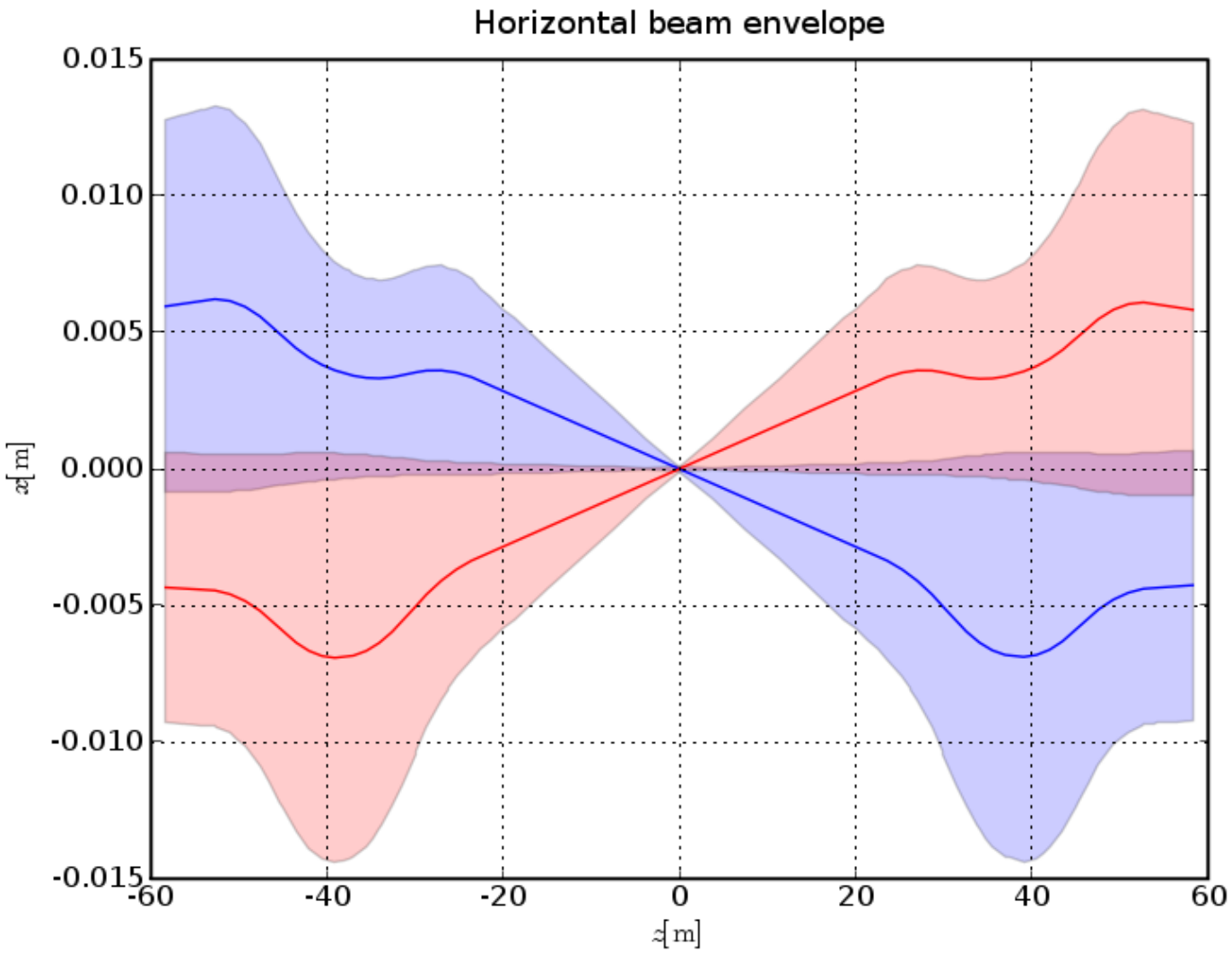


Region where the experiements take place. Approximately field free region of 19.45 m

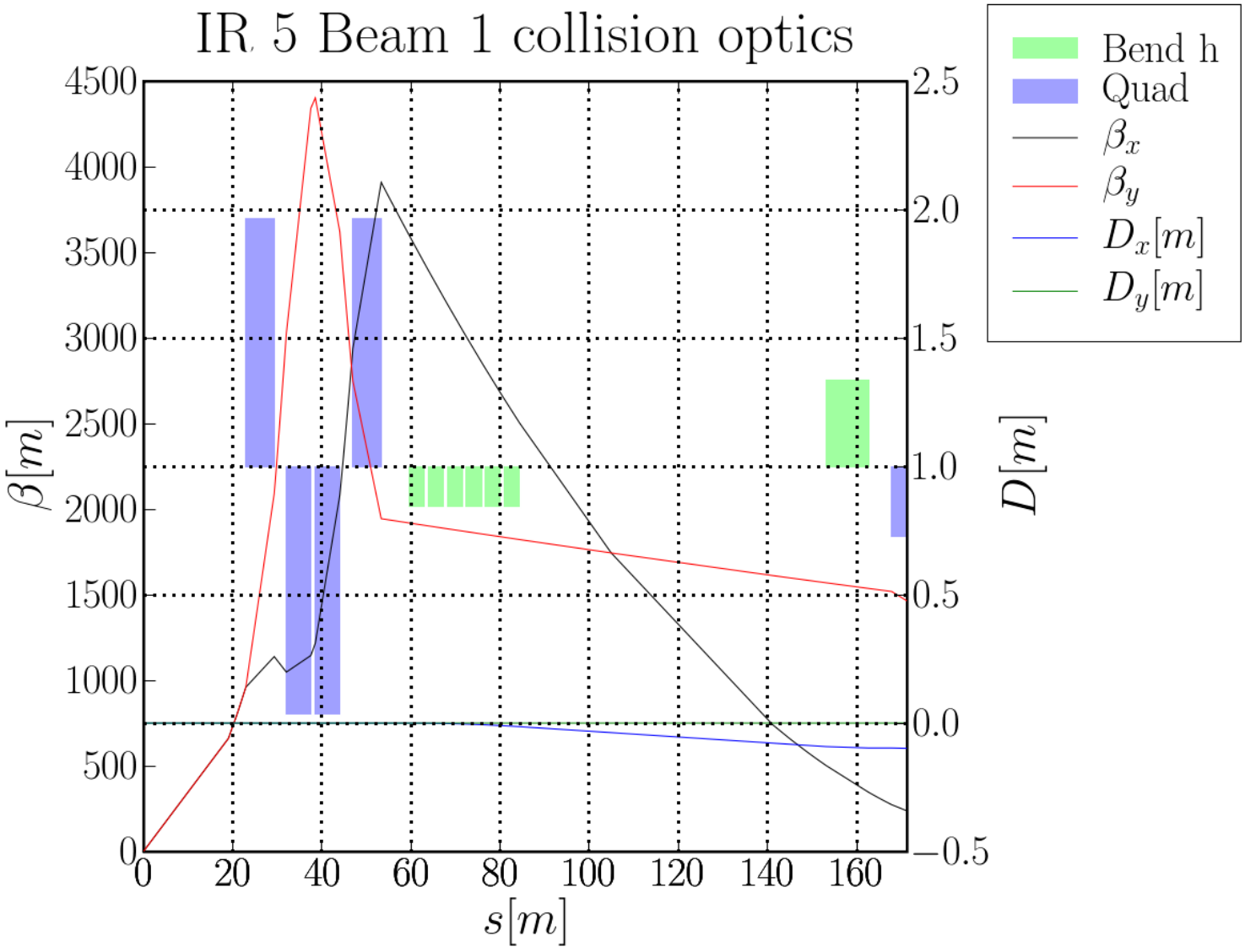
$$\beta(0) = \beta^* \qquad \beta'(0) = -2\alpha(0) = 0 \qquad \gamma(0) = 1/\beta^*$$

$$\beta(s) = \beta^* + s^2/\beta^* \qquad \sigma(s) = \sqrt{\varepsilon\beta(s)} \approx \varepsilon s/\sigma^*$$

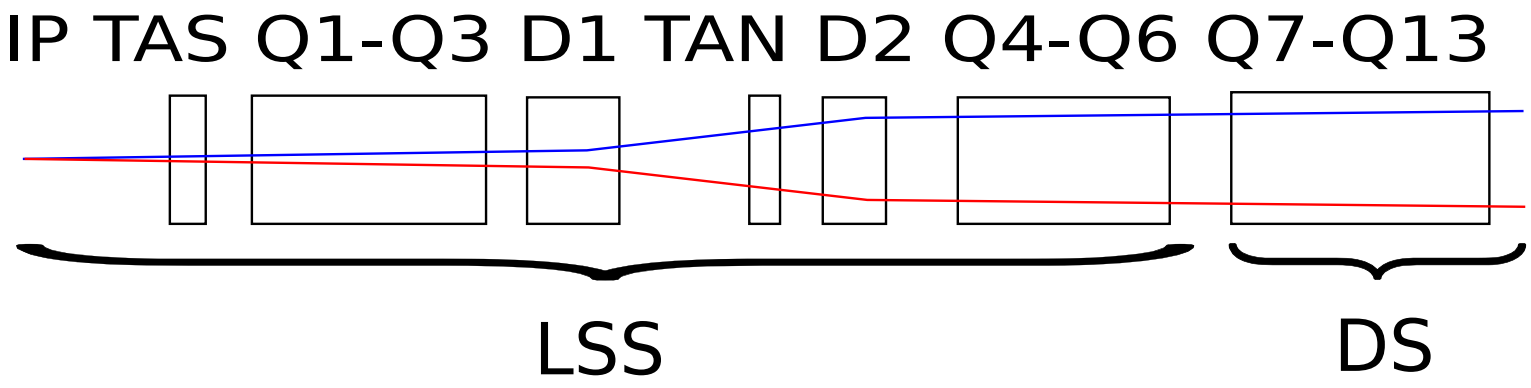
Detector area



Detector area

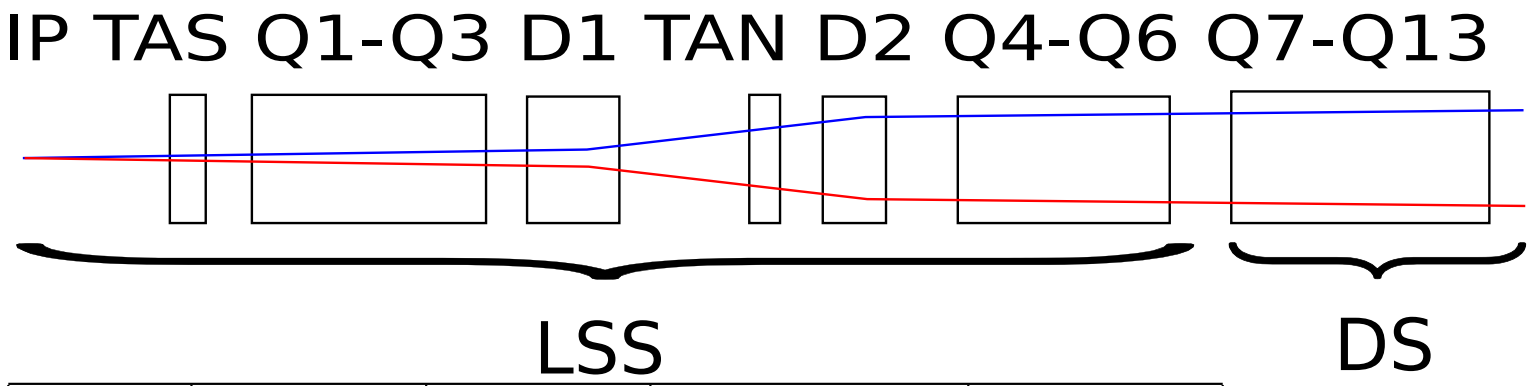


TAS



After the detector an absorber called TAS (Target Absorber Secondaries) is placed in order to shield the downstream magnets from the debris coming from the IP. It is a 1.8 m long copper cylinder with 34 mm aperture diameter.

Triplets

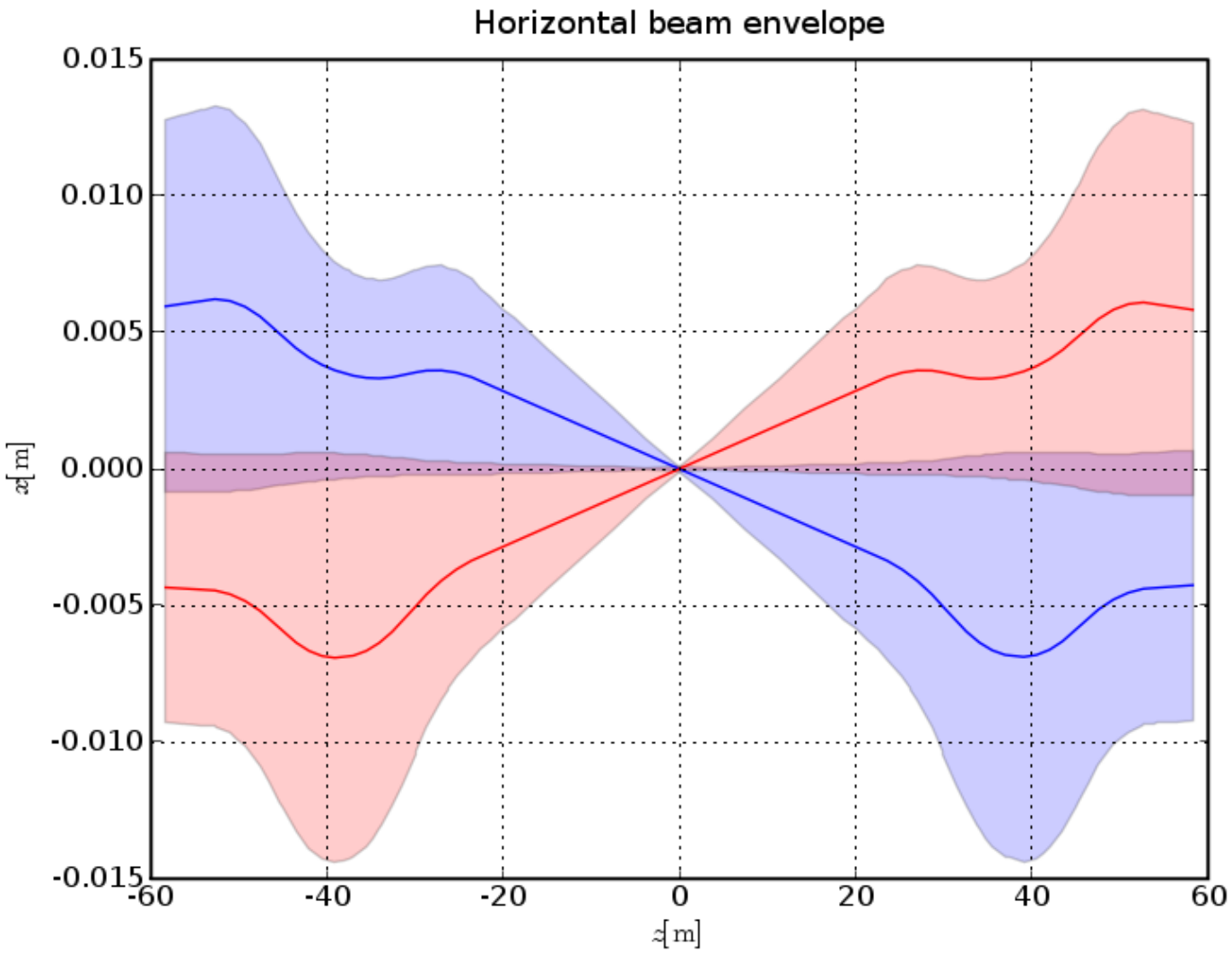


Mag.	Pos.	Length	Field	Inner D.
Q1	22.96m	6.37m	203.7T/m	0.070m
Q2A	32.05m	5.50m	-203.7T/m	0.070m
Q2B	38.55m	5.50m	-203.7T/m	0.070m
Q3	46.96m	6.37m	203.7T/m	0.070m

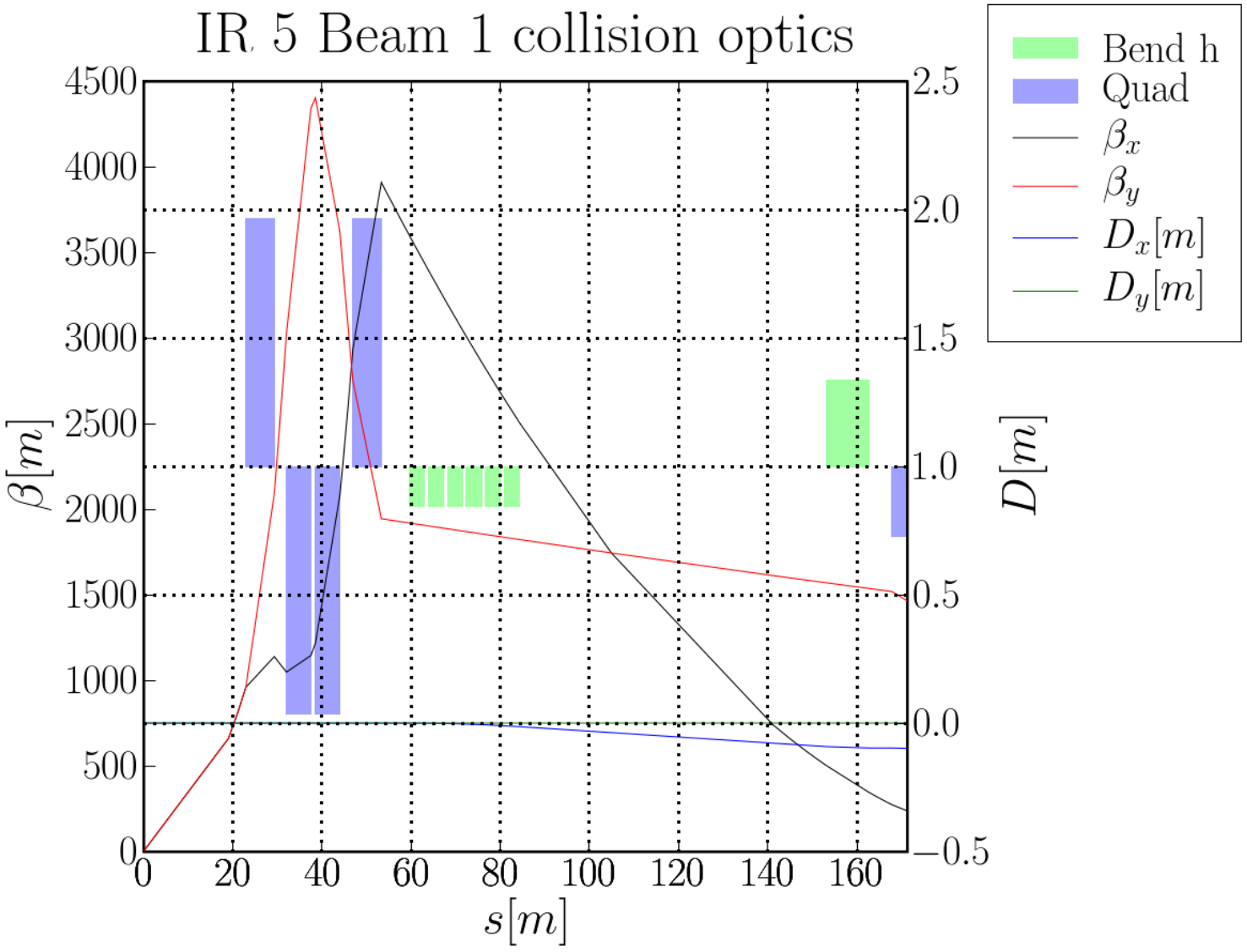
Single bore quadrupoles.

In the triplet assembly correctors, mask and absorbers are installed as well.

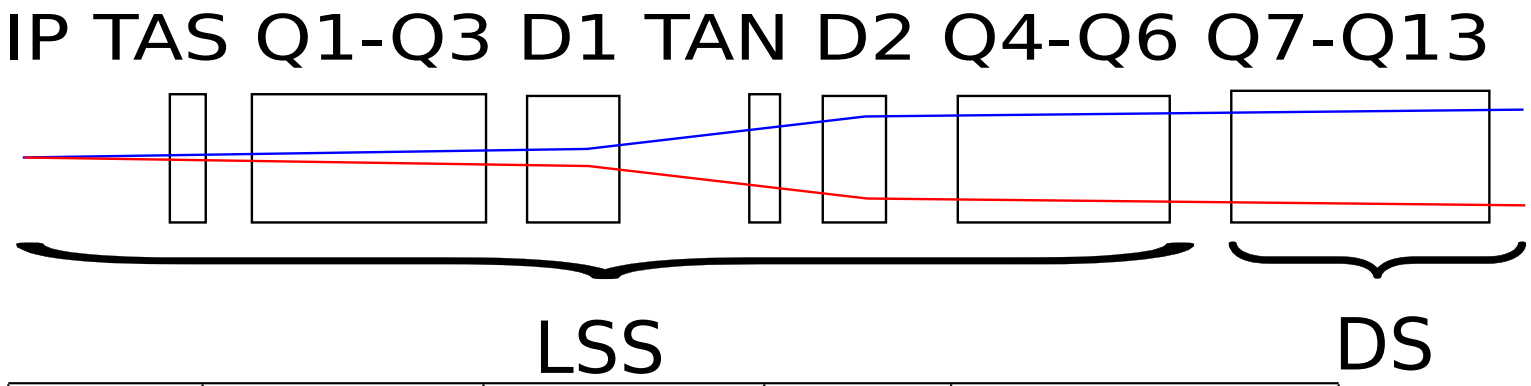
Triplets


Horizontal beam envelope
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
x[m]
-60
-40
-20
0
20
40
60
z[m]

Triplets


IR 5 Beam 1 collision optics
Bend h
Quad
β_x
β_y
$D_x[m]$
$D_y[m]$
$\beta[m]$
$D[m]$
$s[m]$
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
0
20
40
60
80
100
120
140
160

Separation recombination



Mag.	Pos.	Length	Field	Inner D.
D1	59.62m	6*3.40m	1.3T	0.063m(gap)
D2	153.17m	9.45m	2.8T	0.080m

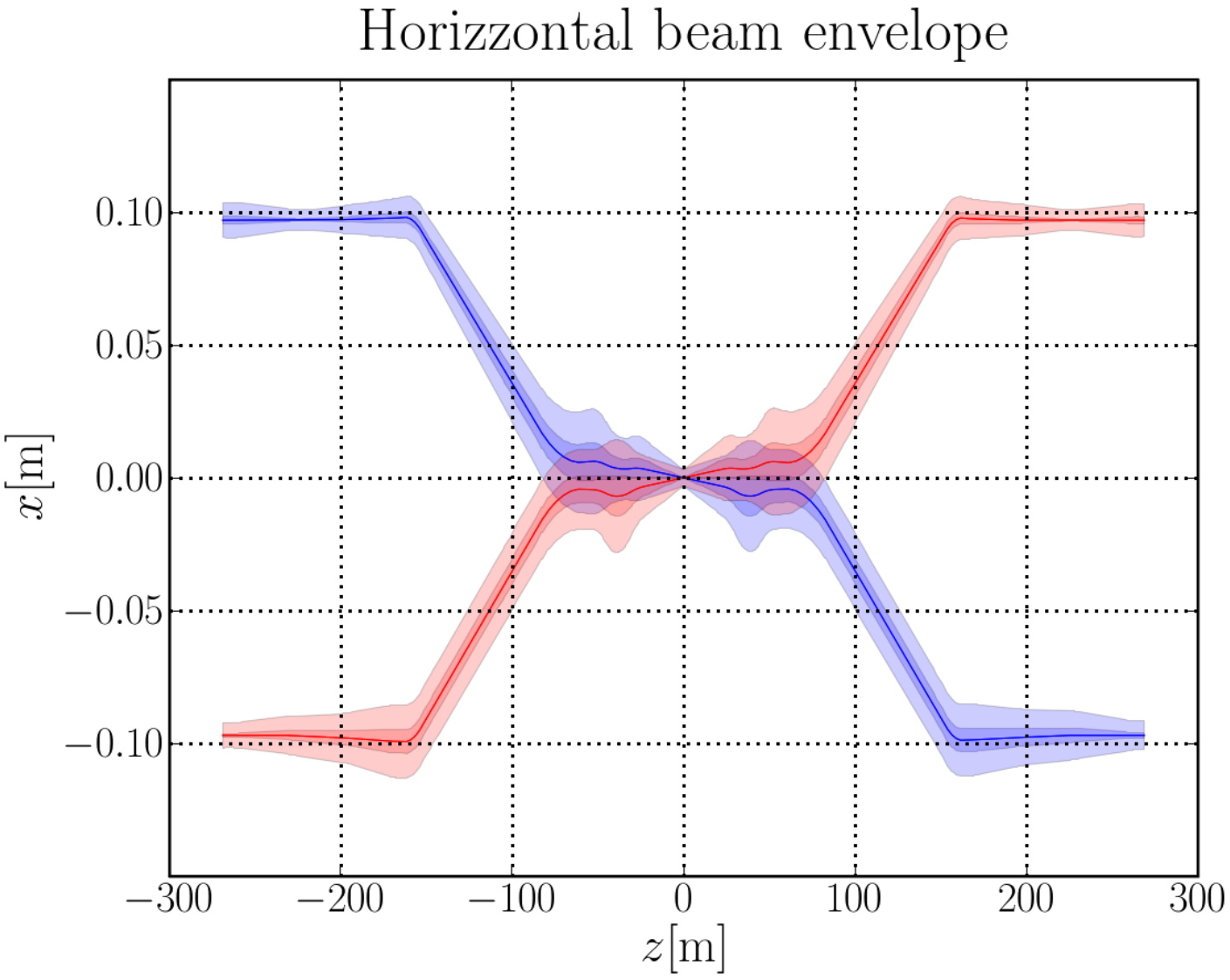
Beam must be separated by 194 mm.

D1: 6 single bore warm long dipole modules

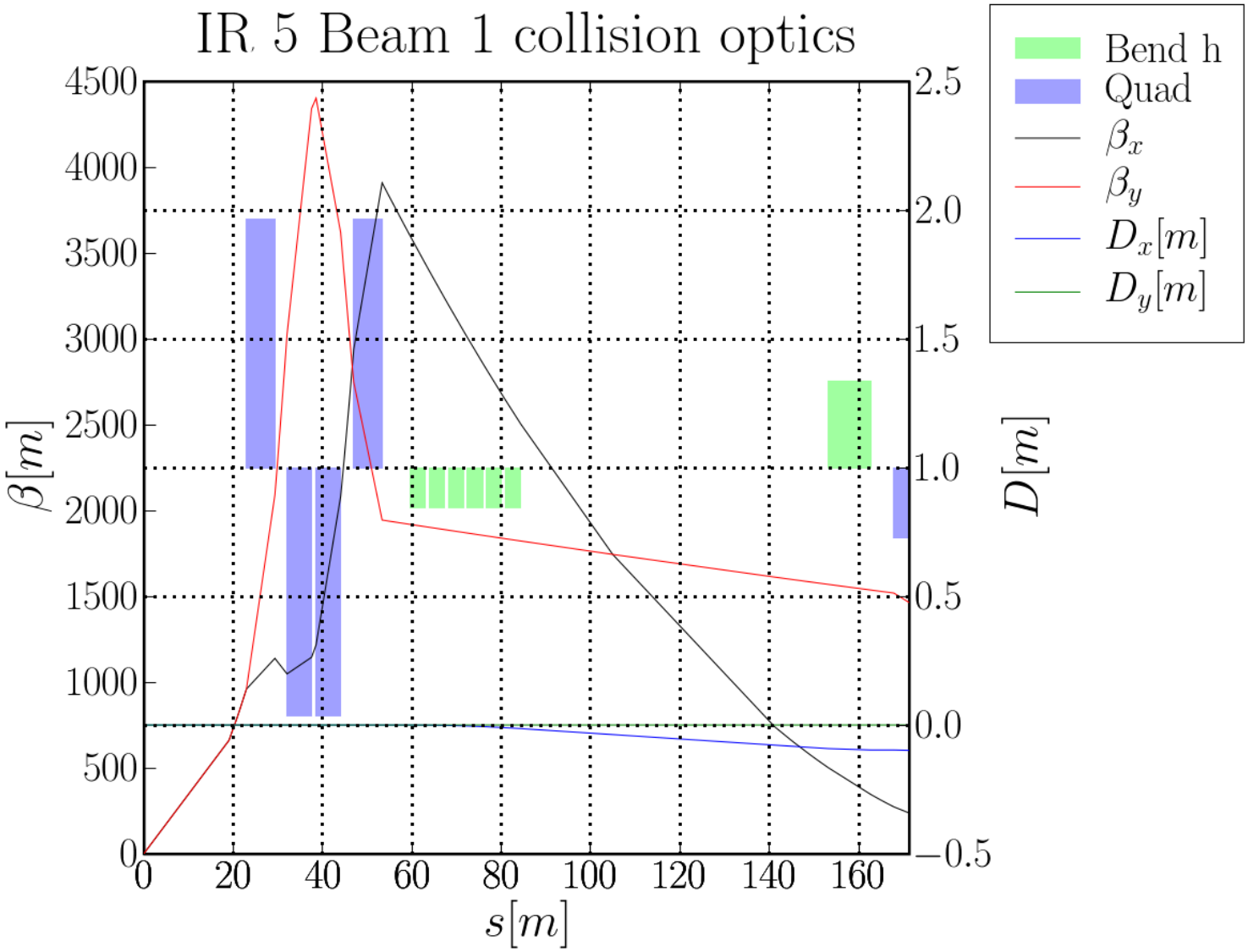
TAN: Target absorber neutral (3.5 m marble copper steel absorber)

D2: 2-in-1 cold dipole 9.4 m, 2.8 T

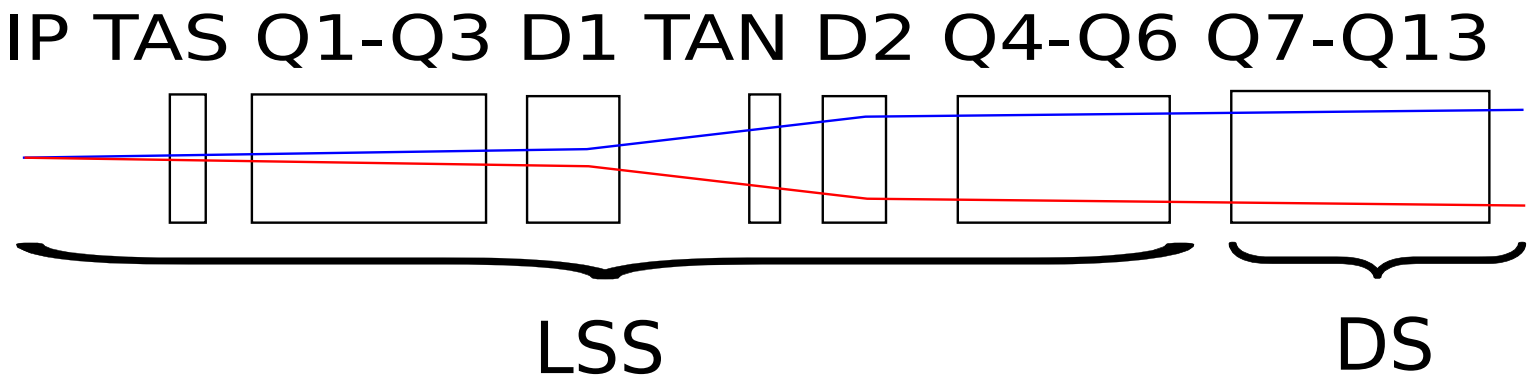
Separation recombination



Separation recombination



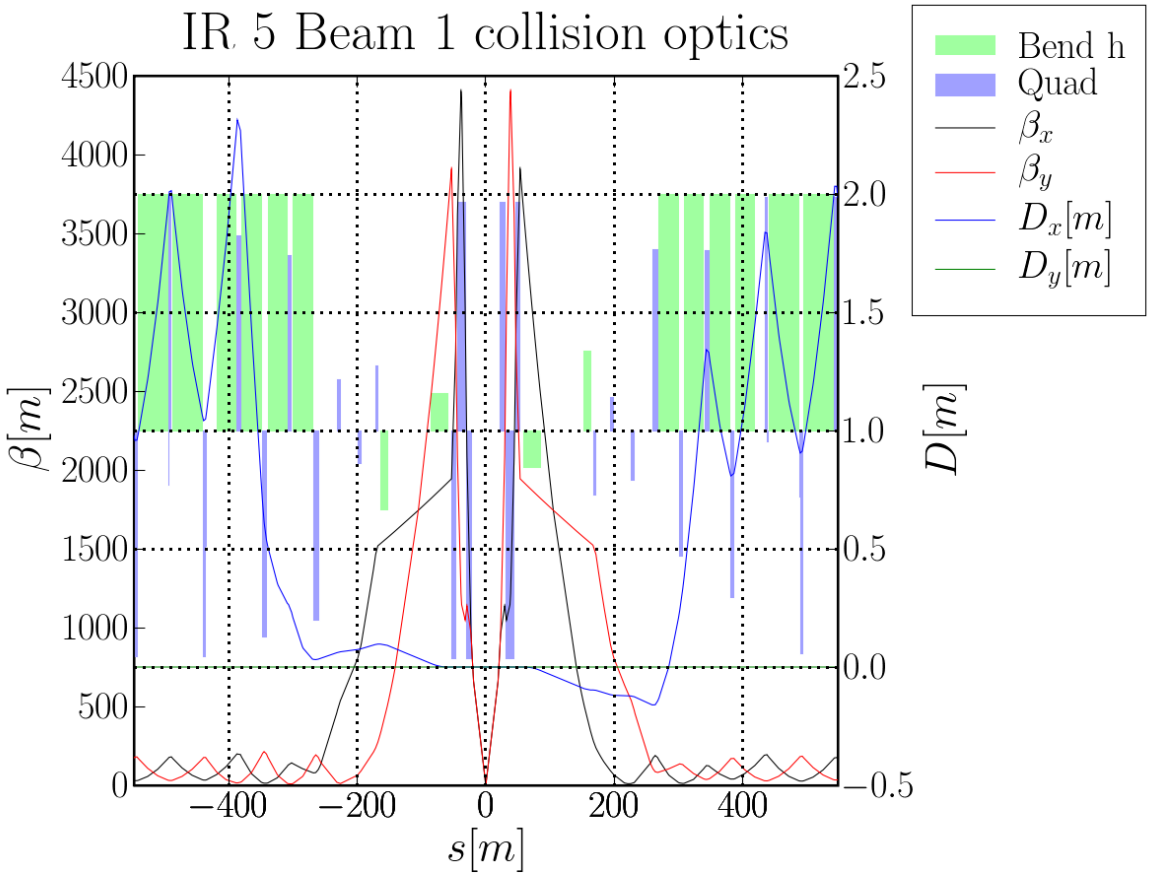
Matching section and dispersion suppressor



Suppress dispersion, provide optics tunability and transition.

7 2-in-1 quadrupoles and 3 trim quadrupoles individually powered.

Matching section and dispersion suppressor



Suppress dispersion, provide optics tunability and transition.

7 2-in-1 quadrupoles and 3 trim quadrupoles individually powered.

LHC performance and limitations

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- Separation Recombination
- Matching section and dispersion suppressor
- Nominal layout limitations
- Two options

Dipole first layouts

Quadrupole first layouts

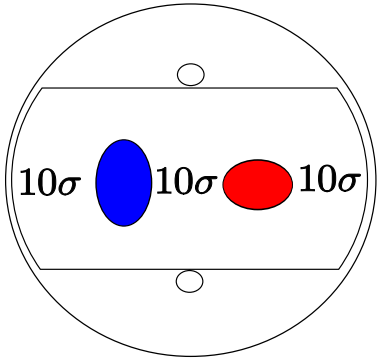
Nominal layout limitations

The limitations of the nominal layout when one tries to reduce the beam size are:

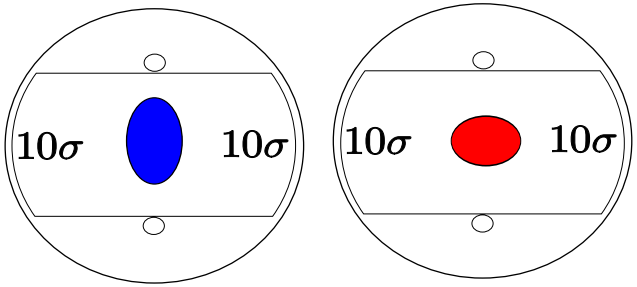
- Aperture
- Beam beam effect
- Field quality
- Heat deposition
- Radiation damage
- Chromatic aberrations
- Geometric reduction factor
- Matchability

Aperture

common bore



2-in-1 design



Aperture

Minimum required aperture in the triplet can be estimated using:

$$\mathrm{d} = 33\sigma + 22\,\mathrm{mm}$$

where beta beating, parasitic dispersion, closed orbit tolerances, alignment tolerances and beam screen are included.
The aperture in the triplet scales with $1/\sigma^*$.
Quadrupole gradient is limited by the peak field in the coil which is approximately proportional to the aperture. Peak field depends on the material, temperature, current, operational margin.
For LHC magnets field peak field are about NbTi 8 T, Nb3Sn 12 T.

Beam beam effect

Beam beam effect is difficult to quantify. It is responsible of strong non linear field acting on the beam at the collision point (head on) or when the other beam is closer (long range).
A measure of the effect is given by the linear tune shift for head on collisions:

$$\Delta Q_{\mathsf{ho}} = \frac{N_b r_p \beta^*}{4\pi\gamma\sigma_x^{*2}}$$

and for long range interaction

$$\Delta Q_{\mathsf{lr}} \propto \frac{N_b}{d_{\mathsf{sep}}^2}$$

Field quality and long term stability

$$B_y + iB_x = \sum_{n=0} (B_{n+1} + iA_{n+1}) \left(\frac{x+iy}{r_0} \right)^n$$

$$x''(s) = -\frac{q}{p} \frac{1}{1+\delta} B_y(s)$$

$$y''(s) = +\frac{q}{p} \frac{1}{1+\delta} B_x(s),$$

First order perturbation driving terms:

$$\Delta_x \propto \mathrm{Re}\left((B_n + iA_n) \beta_x^{p/2} \beta_y^{q/2} e^{i(p/2\Delta\phi + q/2\Delta\phi)} \right)$$

where p, q are integers and $p + q = n$ (resonances) or $p + q = n - 2r$ (sub resonances).
Field quality can be corrected local by multipole corrector magnets or improved by increasing precision in manufacturing or by increasing aperture.

Chromatic aberrations

As for the long term stability, an increase of the beta function increases the chromatic aberrations.

$$Q = Q_0 + Q_1\delta + \frac{Q_2}{2}\delta^2 + \dots$$

$$\beta(s) = \beta_0(s) + \beta_1(s)\delta + \frac{\beta_2(s)}{2}\delta^2 + \dots,$$

$$Q_0 = \frac{1}{2\pi}\oint \frac{1}{\beta(s)}ds \qquad Q_1 = -\frac{1}{4\pi}\oint k(s)\beta_0(s)ds$$

$$\beta_1(s) = -\oint k(s)\beta_0(s)\cos(2|\phi_0(s) - \phi_0(s')| - 2\pi Q_0)ds'$$

$$Q_2 = -\frac{1}{4\pi}\oint k(s)\beta_1(s)ds.$$

The linear part must be corrected by the lattice sextupoles. The non linear part is hard to correct and can drive instabilities and as well decrease the efficiency of the collimation.

Heat deposition

With an upgrade of the luminosity, the rate of debris generated by beam collision at IP increases accordingly.
The LHC absorber (TAN and TAS) are designed to reduce the heat load in the superconducting magnet for the maximum luminosity (1 kW at nominal luminosity).
In case of a luminosity upgrade either the absorber must be redesigned, or the superconducting must be able to sustain an higher heat load or the aperture of magnets must be increased to not intercept the debris.

Radiation damage

The debris generated at the IP are not only responsible for the heat load, but also for the radiation damage.
The LHC triplets lifetime is estimated to be $700\,\mathrm{fb}^{-1}$ of integrated luminosity which translates in 7 years of operation.
The radiation damage must be addressed in new triplet design in order to keep the lifetime of the magnets reasonably high.

Matchability

In order to create a small β^*, the beta function at the triplet must be large, but the arcs require a smaller beta.
The matching section and dispersion suppressor must therefore be able to transform a small beam with small divergence in the arc into beam with a large divergence in Q4 in order to assure a large beta in the triplet.
If too large beta are required, the LSS magnets may run in strength and aperture limitations.
The LSS must also be able to change the optics configuration smoothly between small β^* optics for collision to large β^* optics for injection and ramping at a constant phase advance.

Geometric reduction factor

In the nominal layout there are no directs means to compensate the effect of the geometric reduction factor. It becomes important when β^* is reduced.
A optimization can be done using flat beams but with some important limitations coming from imposed focusing anti-symmetry for single bore quadrupoles, aperture restrictions, matchability.

Two options

Limitations

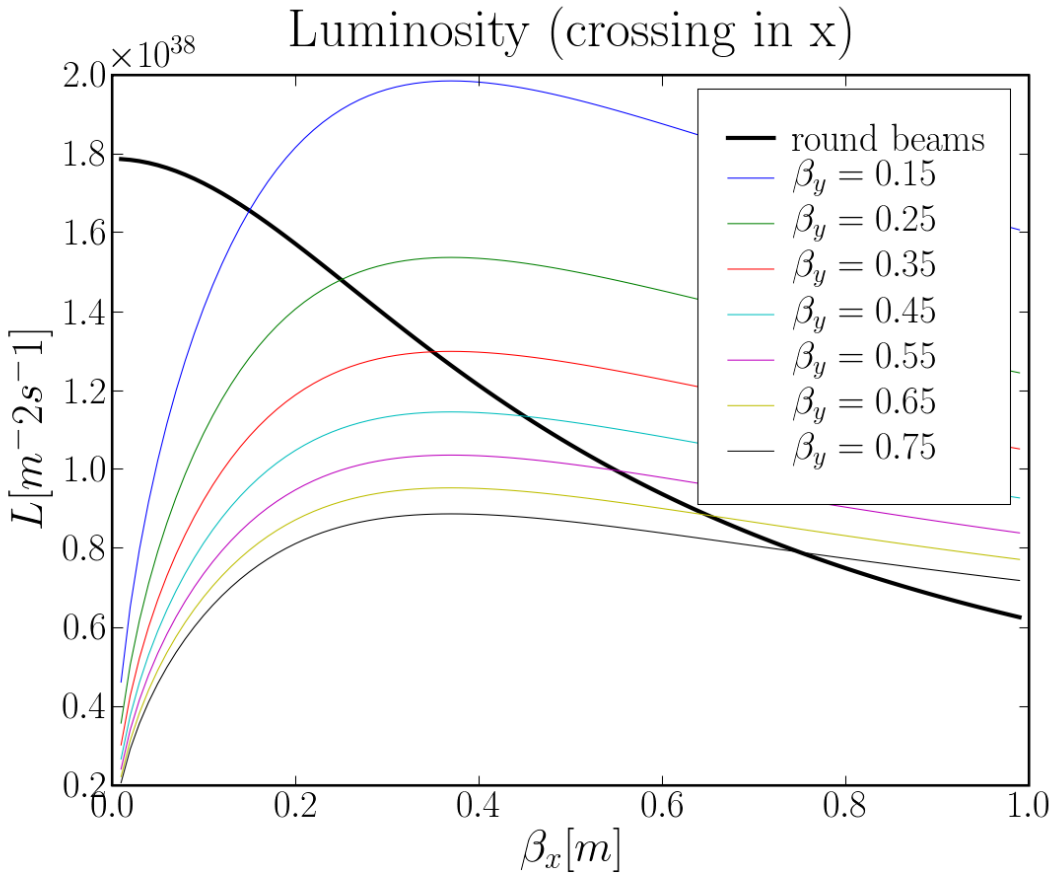
1. Aperture
2. Long range beam beam
3. Heat deposition
4. Radiation damage
5. Field quality
6. Chromatic aberrations
7. Geometric reduction factor
8. Matchability

There are a large number of dipole first and quadrupole first options studied (refer to CARE-HHH-APD proceedings). I'm going to talk about to options which aims at $\beta^* = 25\,\mathrm{cm}$:

- Dipole first option try to address (2,3,4,5 partially, 7 partially)
- Quadrupole first option (1,5,7 with limits)

Two options

The two options aim at $\beta^* = 25\,\mathrm{cm}$.



These options assume no change in the detector area.

Outline

LHC performance and limitations

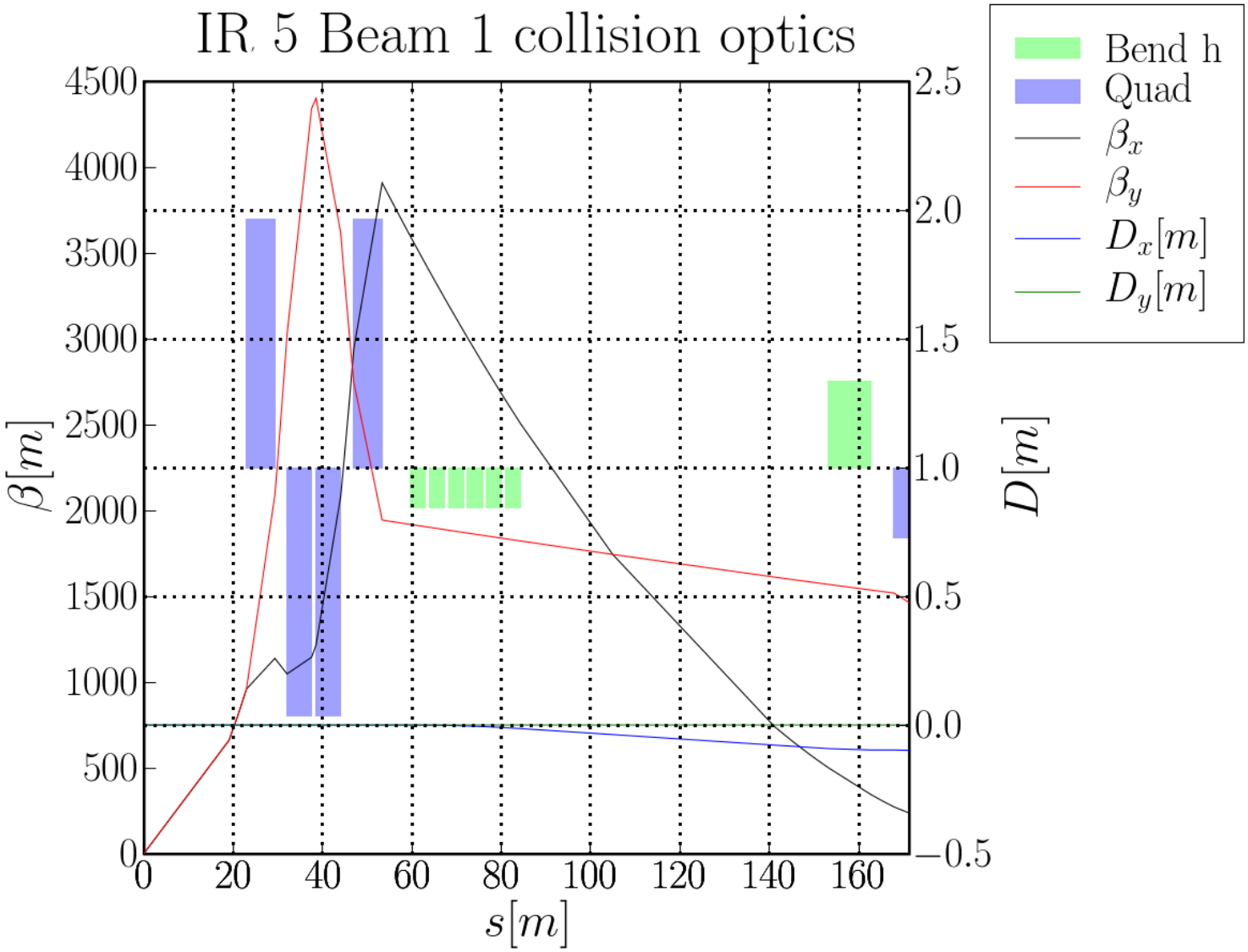
LHC Interaction region

Dipole first layouts
- Layout
- Crossing scheme
- Beam beam interaction
- Optics
- Aperture
- Chromaticity
- Dynamic Aperture
- Open questions

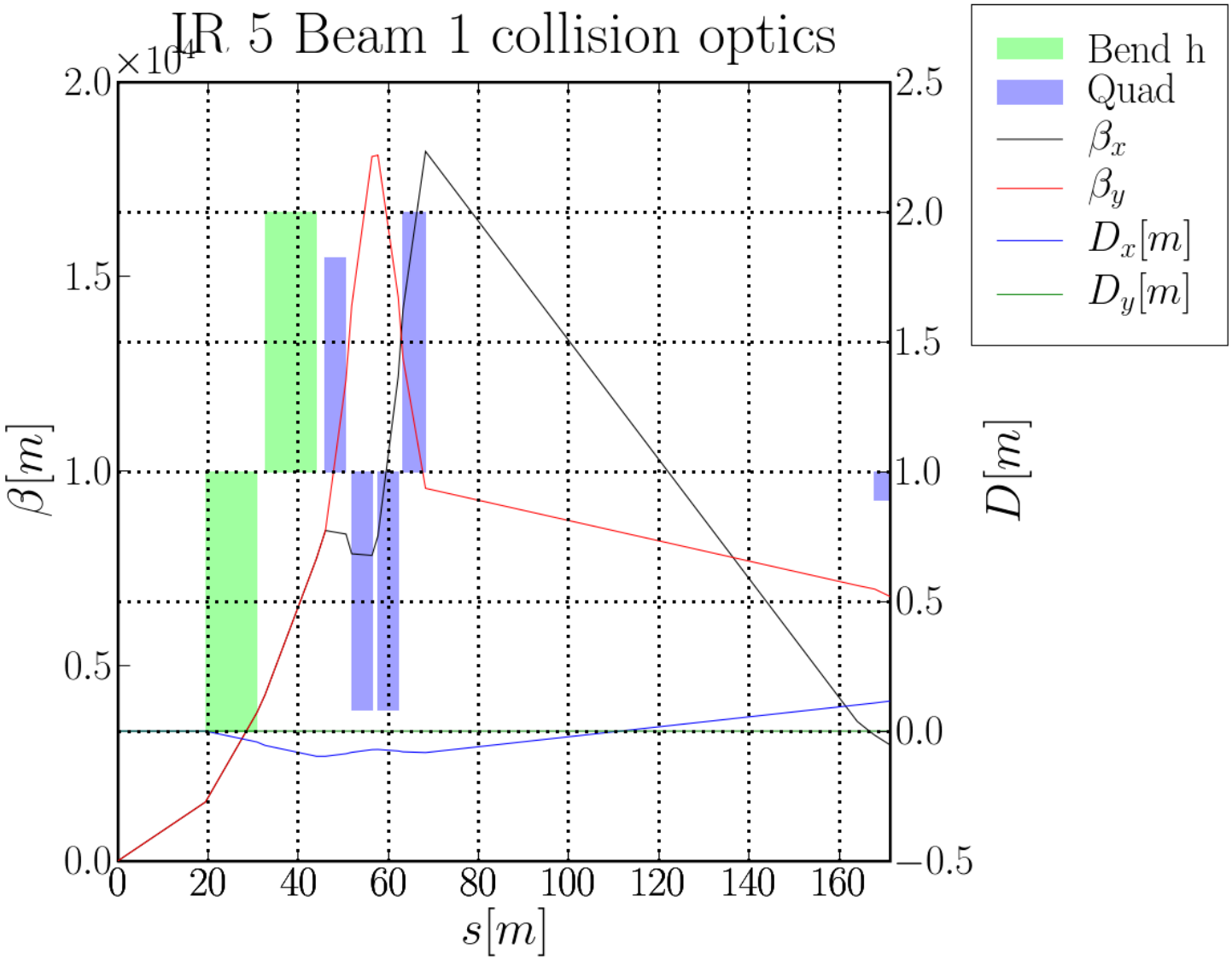
Quadrupole first layouts

Conclusion and future projects

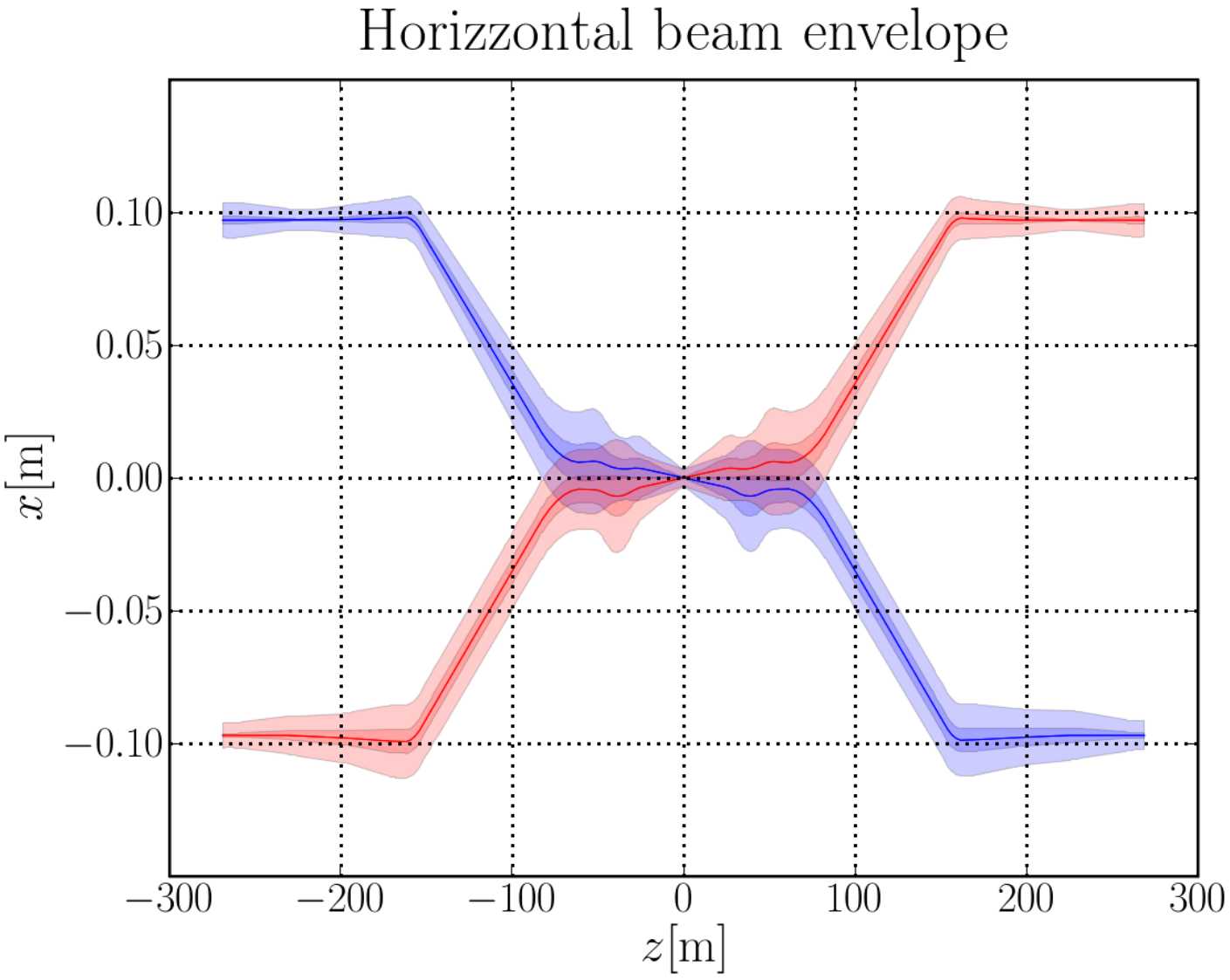
Nominal Layout



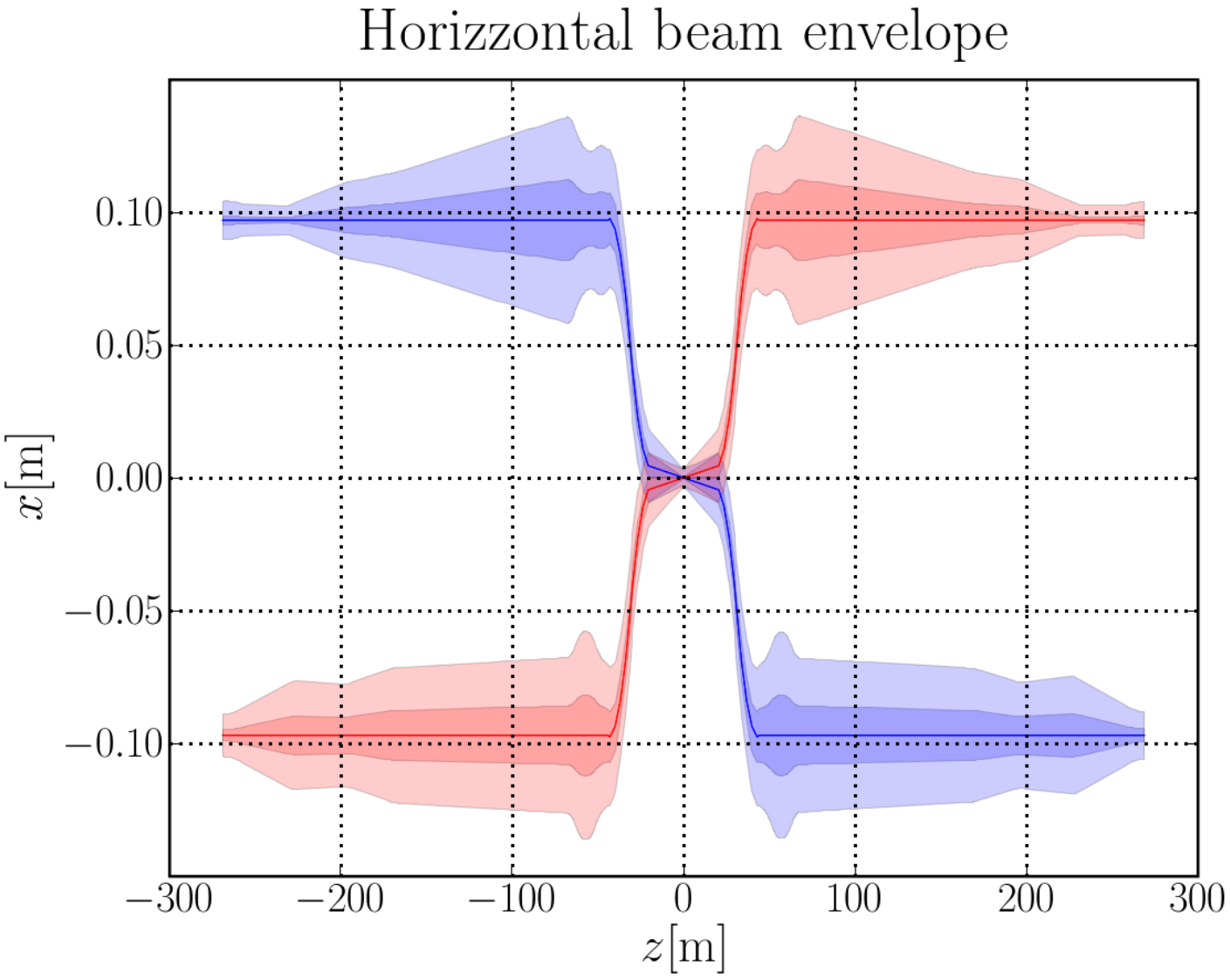
Upgraded Layout



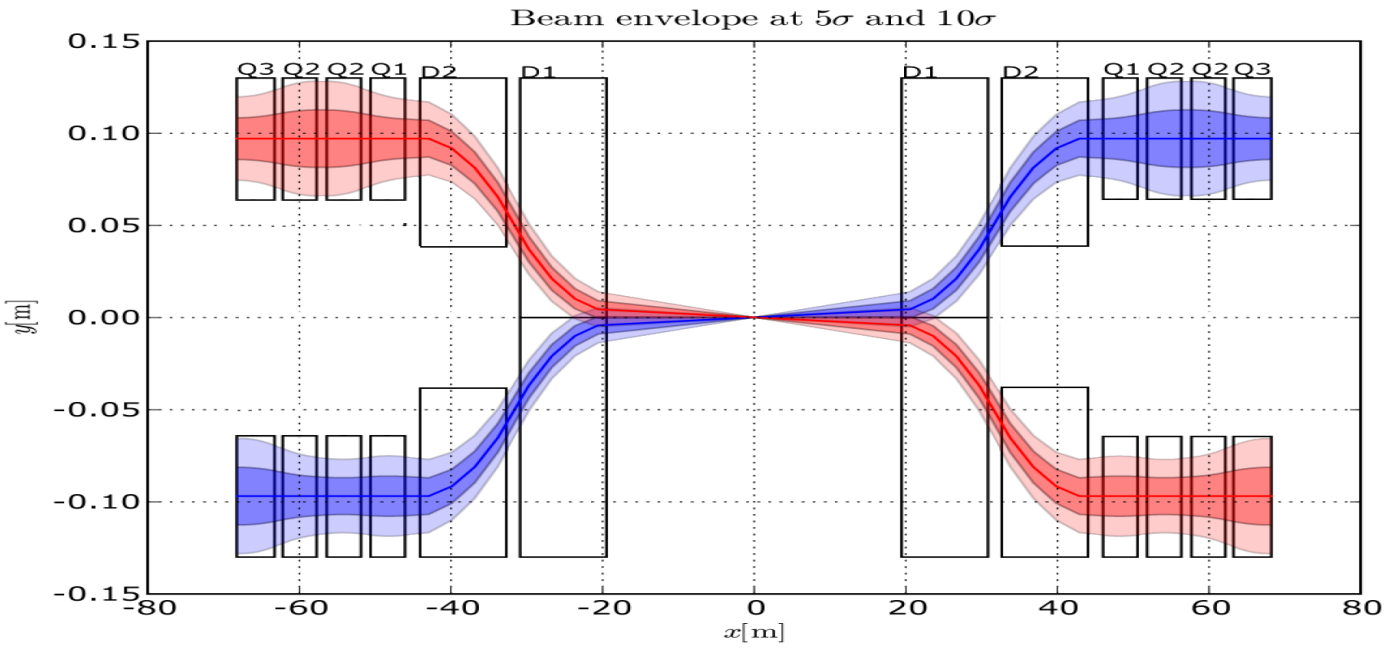
Nominal Layout



Upgraded Layout

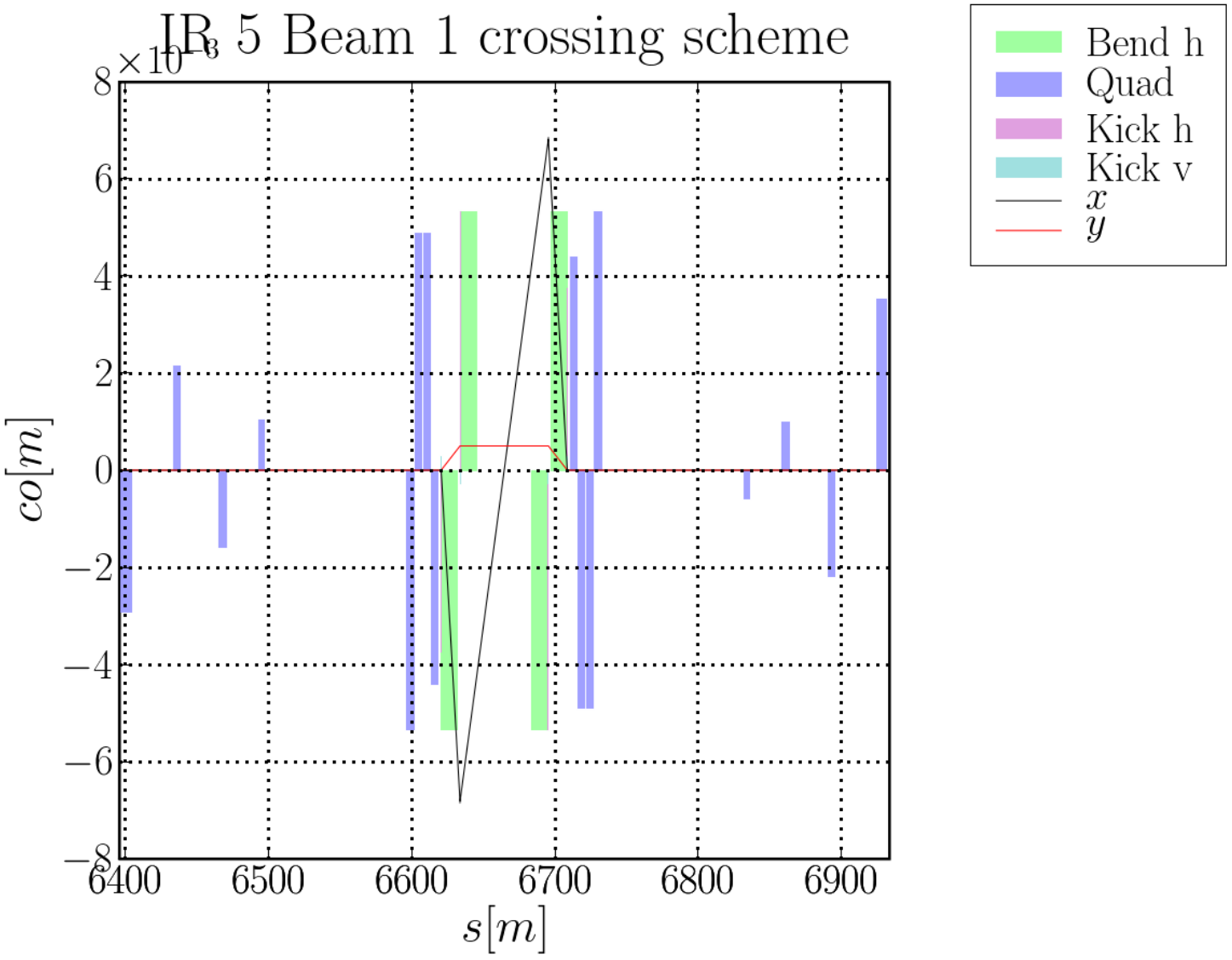


Layout specifications



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

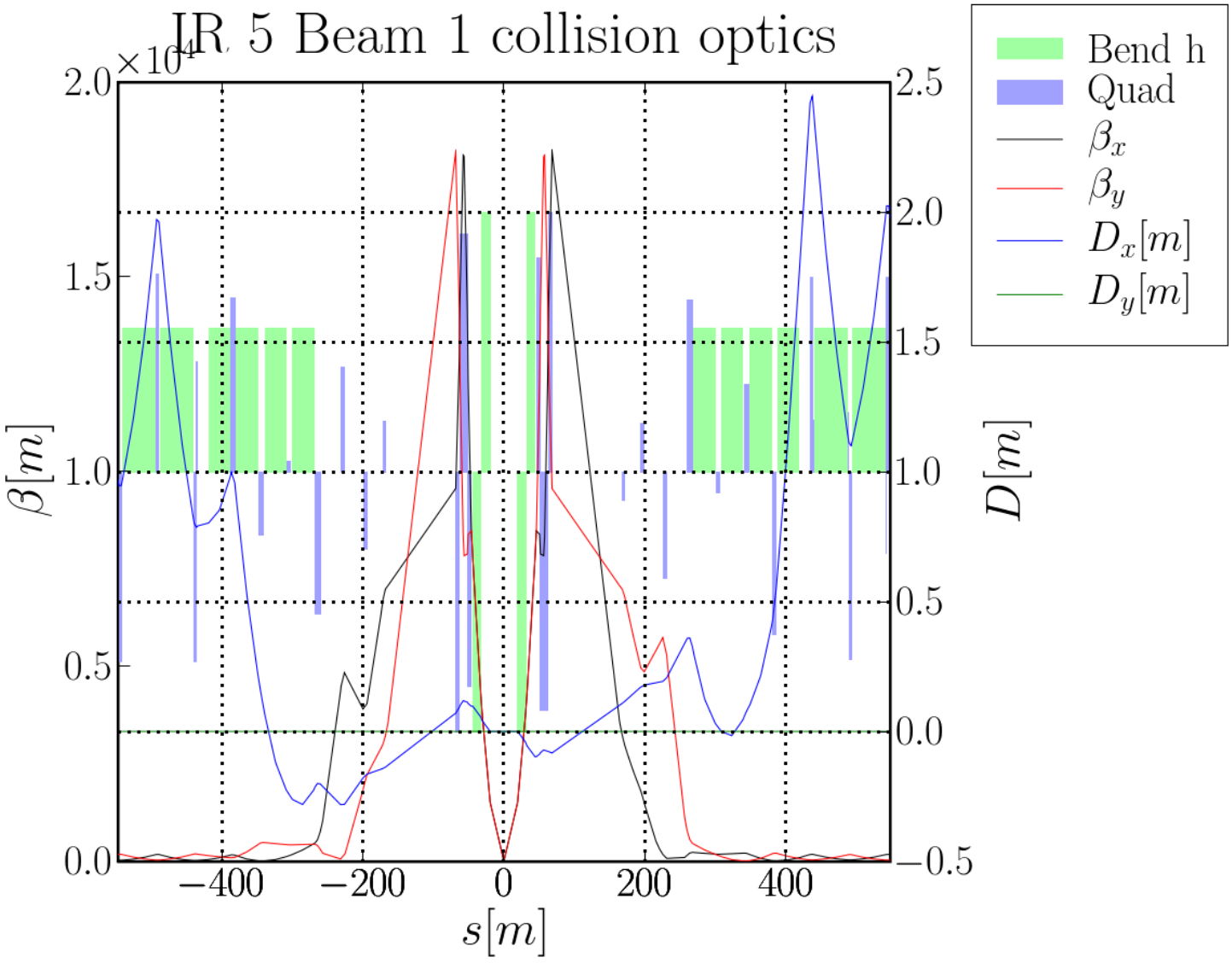
Crossing scheme



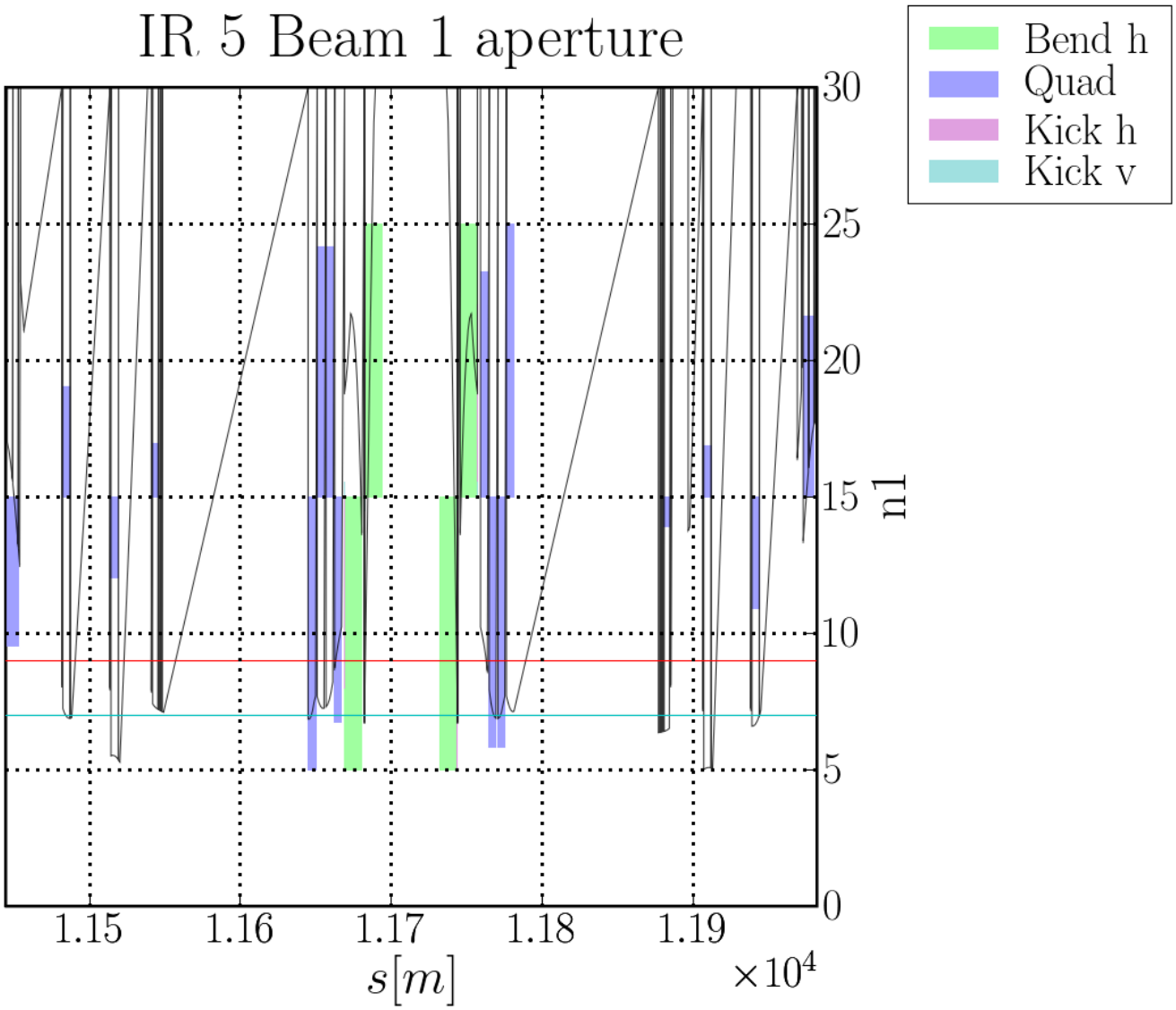
Beam beam interaction

Dipole first reduce the number of LRBB to 5 (LHC 15).

Optics

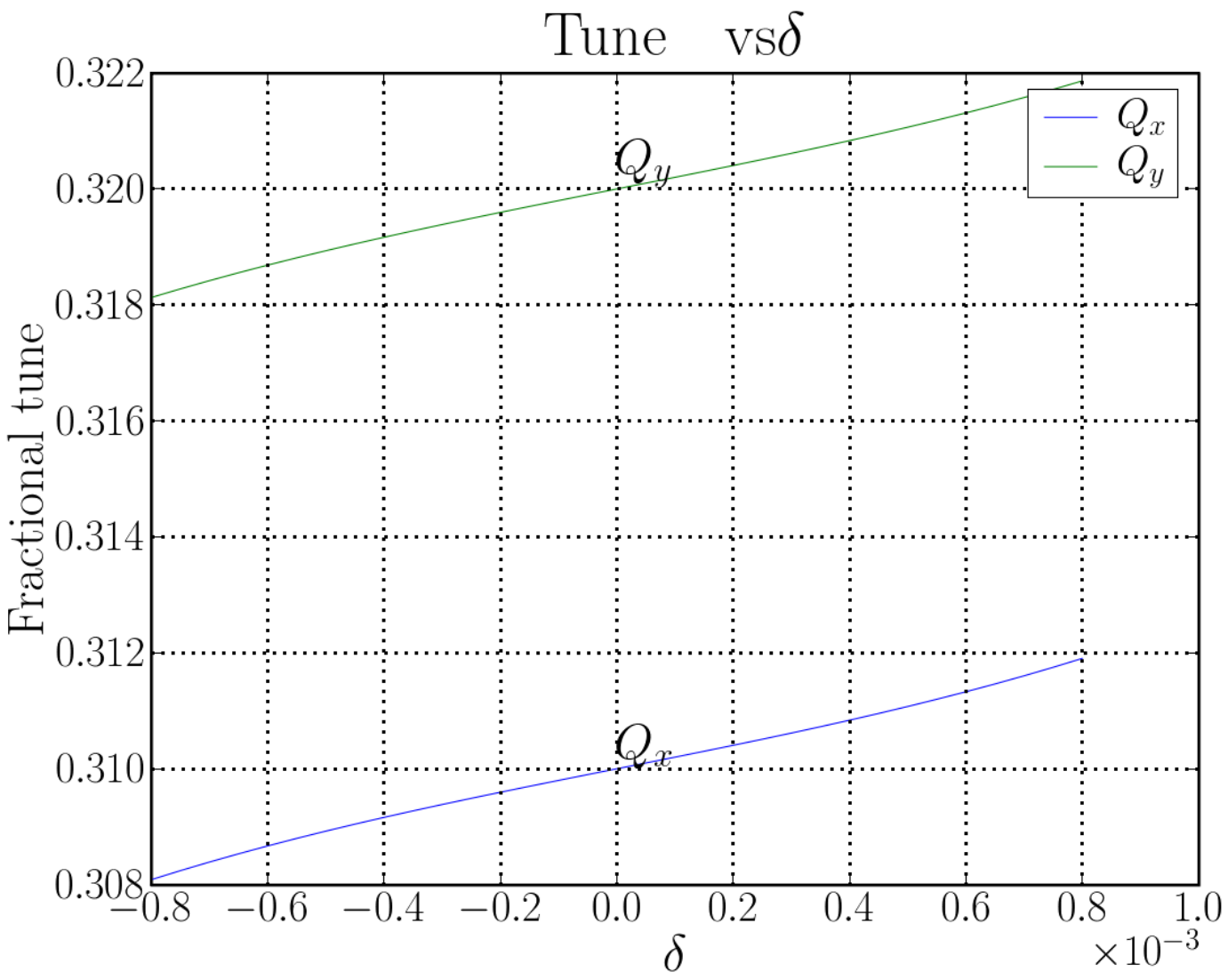

IR 5 Beam 1 collision optics
×10^4
2.0
1.5
1.0
0.5
0.0
β[m]
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
D[m]
−400
−200
0
200
400
s[m]
Bend h
Quad
β_x
β_y
$D_x[m]$
$D_y[m]$

Aperture



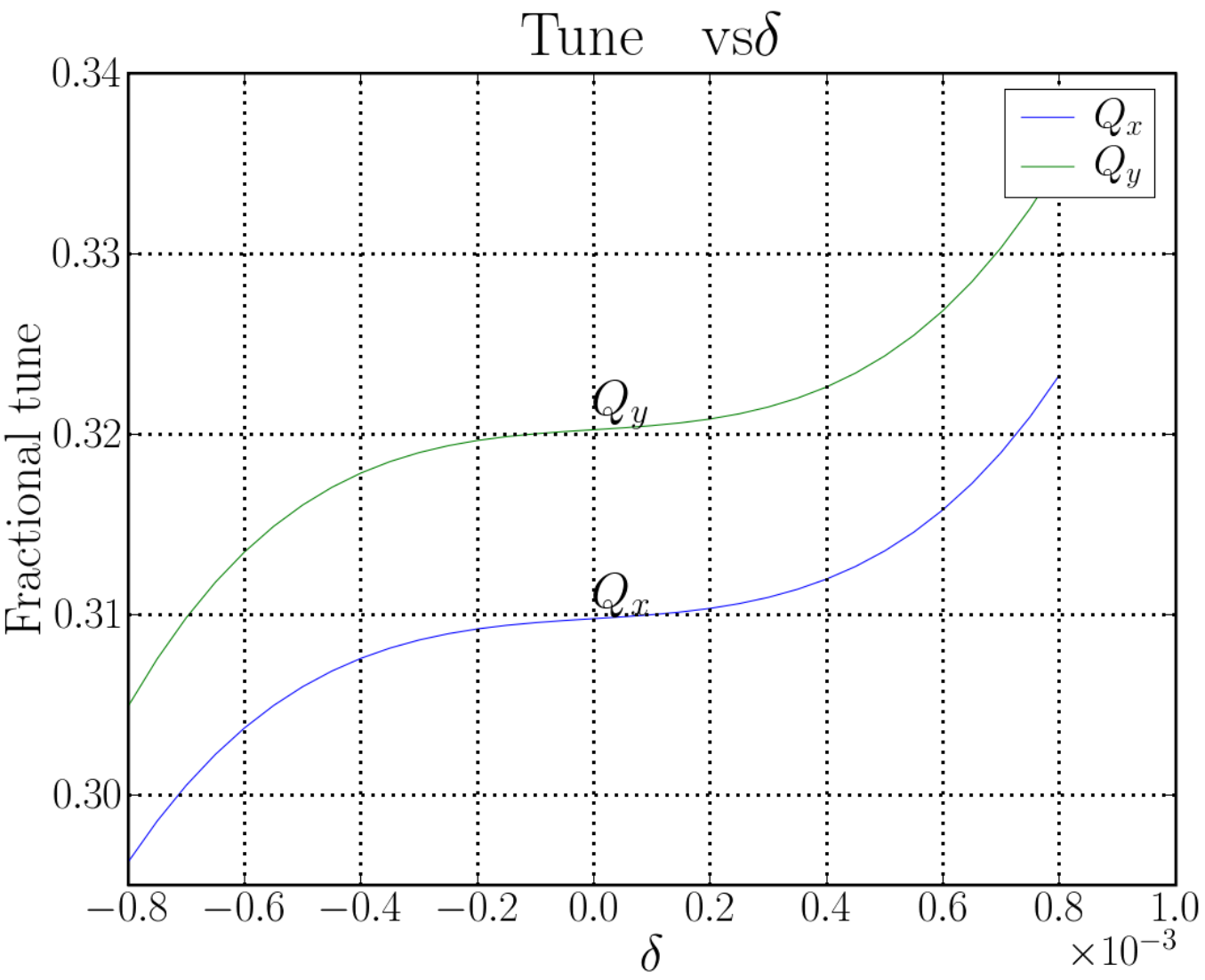
Apertures in terms of n_1: position in σ of a primary collimator which shield the vacuum chamber (beam screen).

Chromaticity



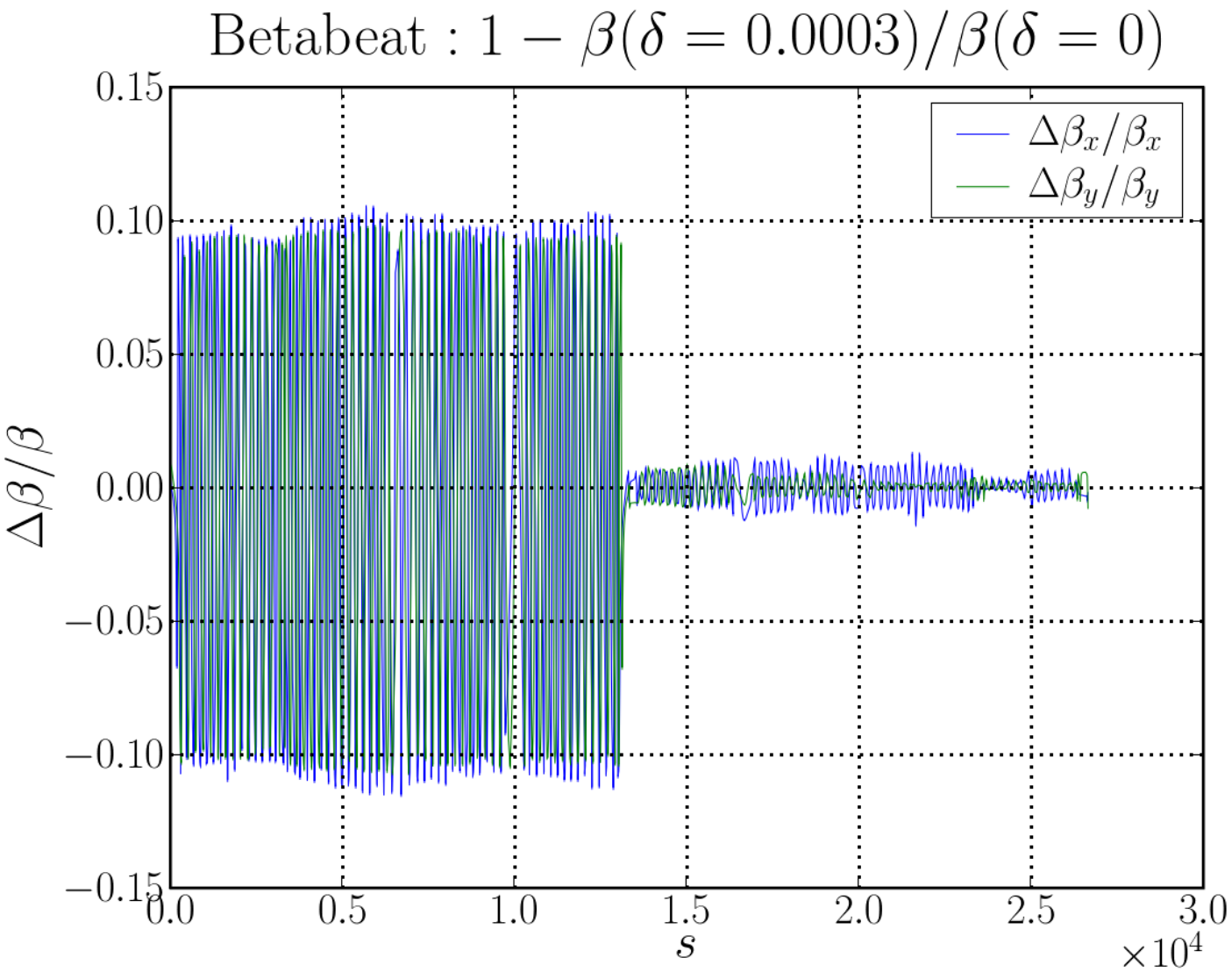
Requirements: 90%, 55% arc sextupoles. Local chromaticity correction still not demonstrated to be feasible.

Chromaticity



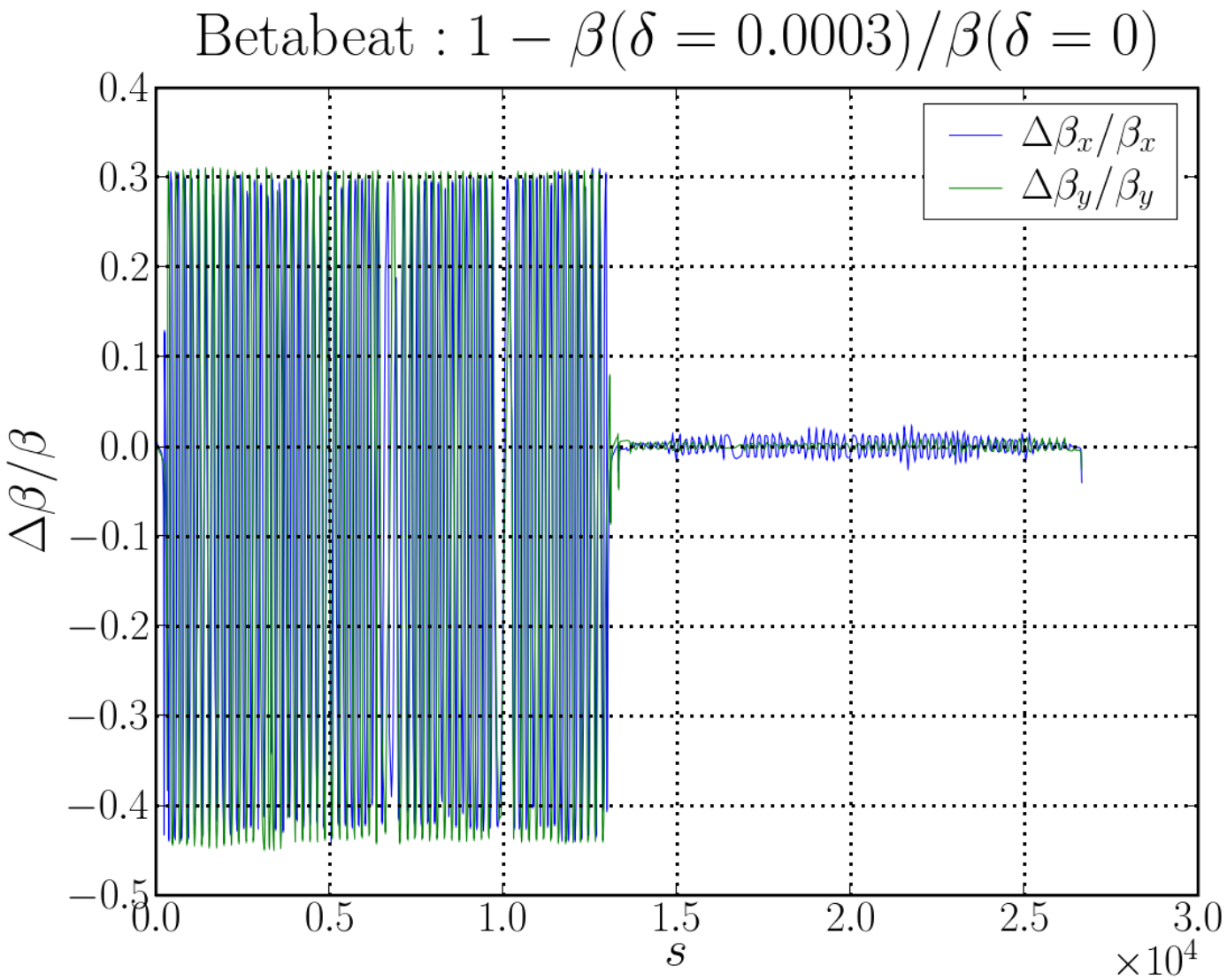
Requirements: 90%, 55% arc sextupoles. Local chromaticity correction still not demonstrated to be feasible.

Chromaticity



Requirements: 90%, 55% arc sextupoles. Local chromaticity correction still not demonstrated to be feasible.

Chromaticity



Requirements: 90%, 55% arc sextupoles. Local chromaticity correction still not demonstrated to be feasible.

Dynamic Aperture

Size of the transverse region where particles survives after many turns (can be expressed in number of σ.)
The parameter space has been probed by:

- using the field quality of existing magnets, DA=3σ,
- using different scaling laws DA=8.3σ,
- using a multipole by multipole scan ($B_n/B_2 < 1\,10^{-4}$ at $r_0 = 34\,\mathrm{mm}$).

Open questions and challenges

- Design of D1, D2 TAS and TAN
- Improve the DA
- Optimize the luminosity gain (symmetric doublet solution)
- Solve chromaticity issues

Outline

LHC performance and limitations

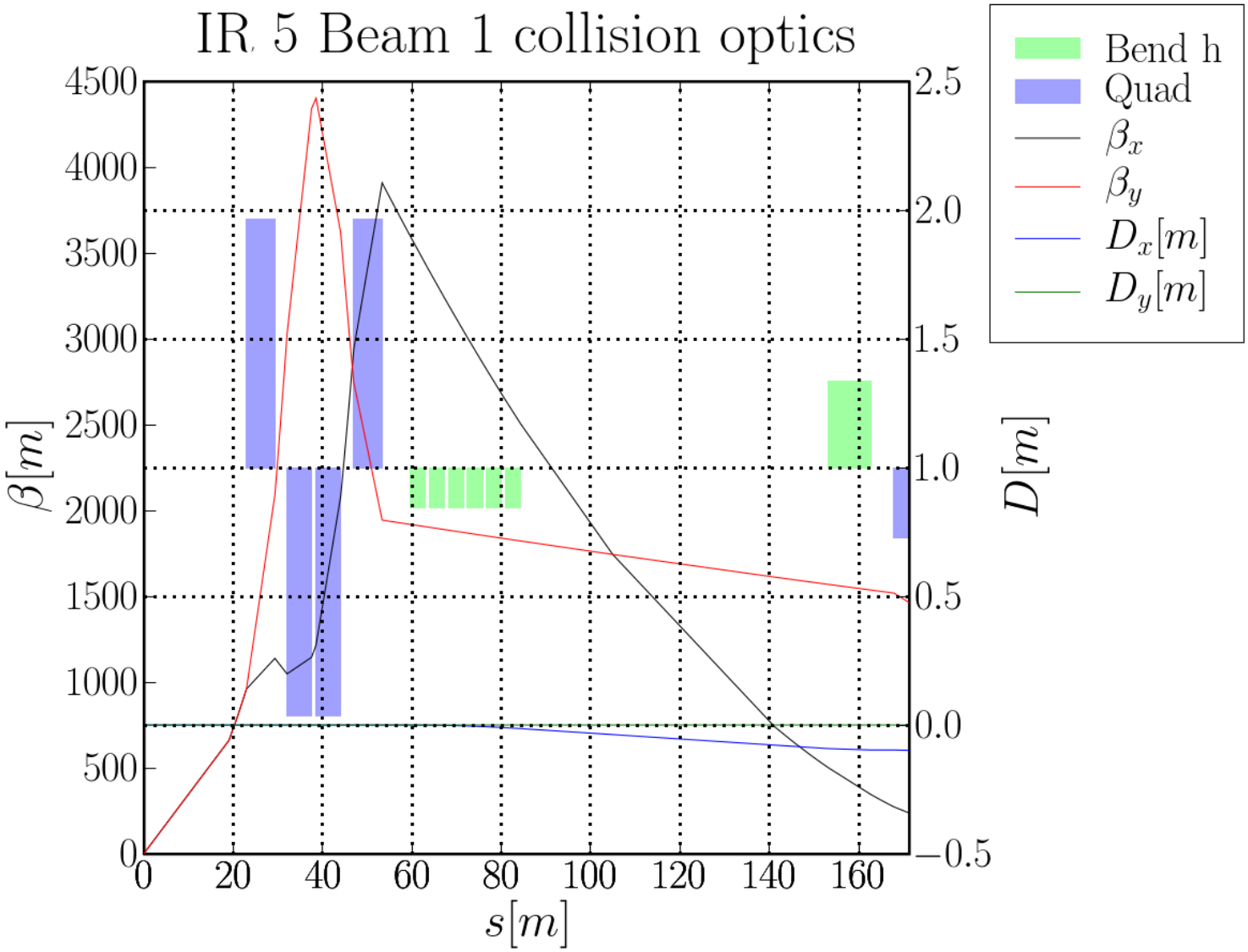
LHC Interaction region

Dipole first layouts

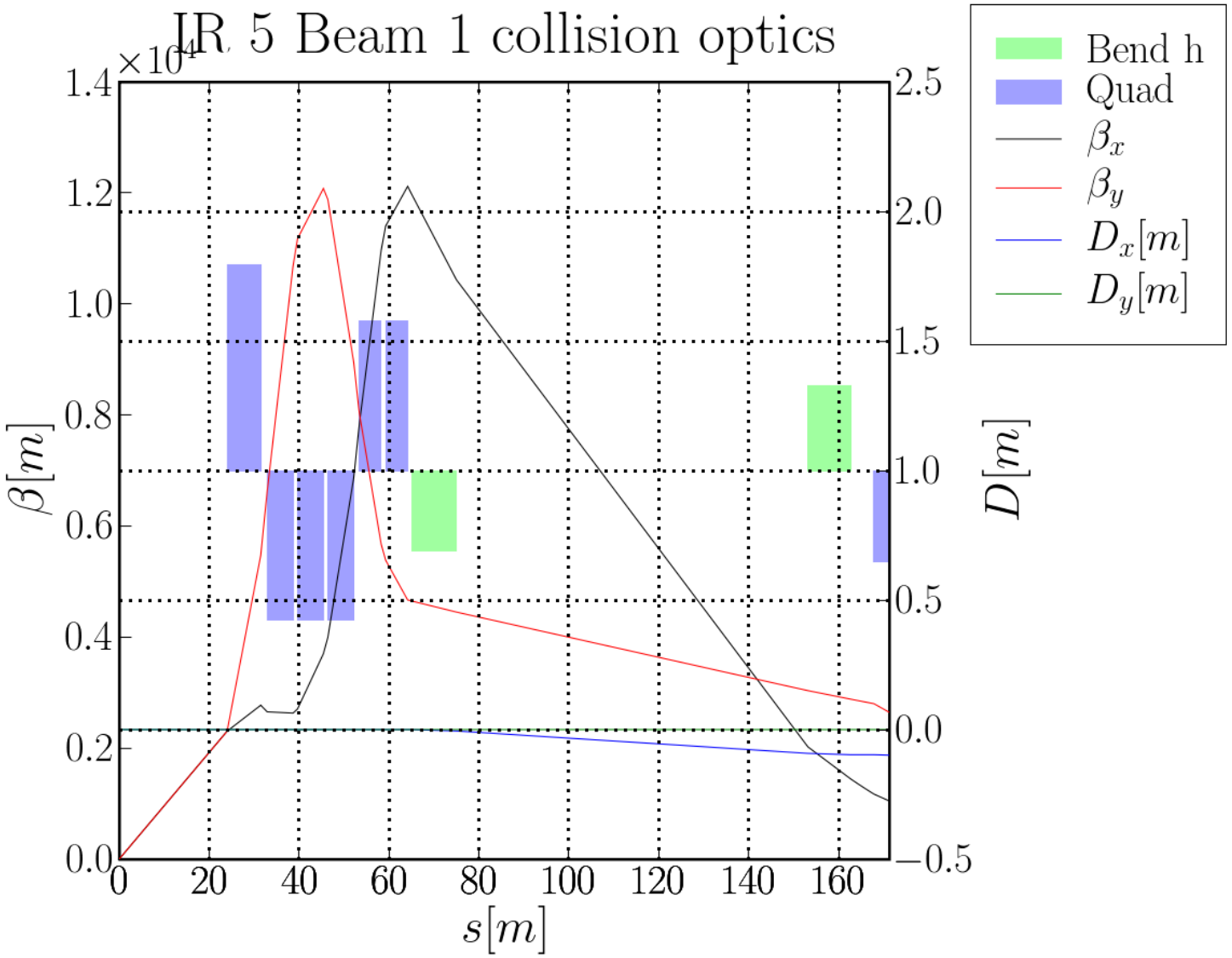
Quadrupole first layouts
- Layout
- Triplet optimizations
- Realistic implementation
- Layouts
- Aperture bottlenecks
- Dynamic aperture
- Chromatic aberrations
- Conclusions
- Open questions

Conclusion and future projects

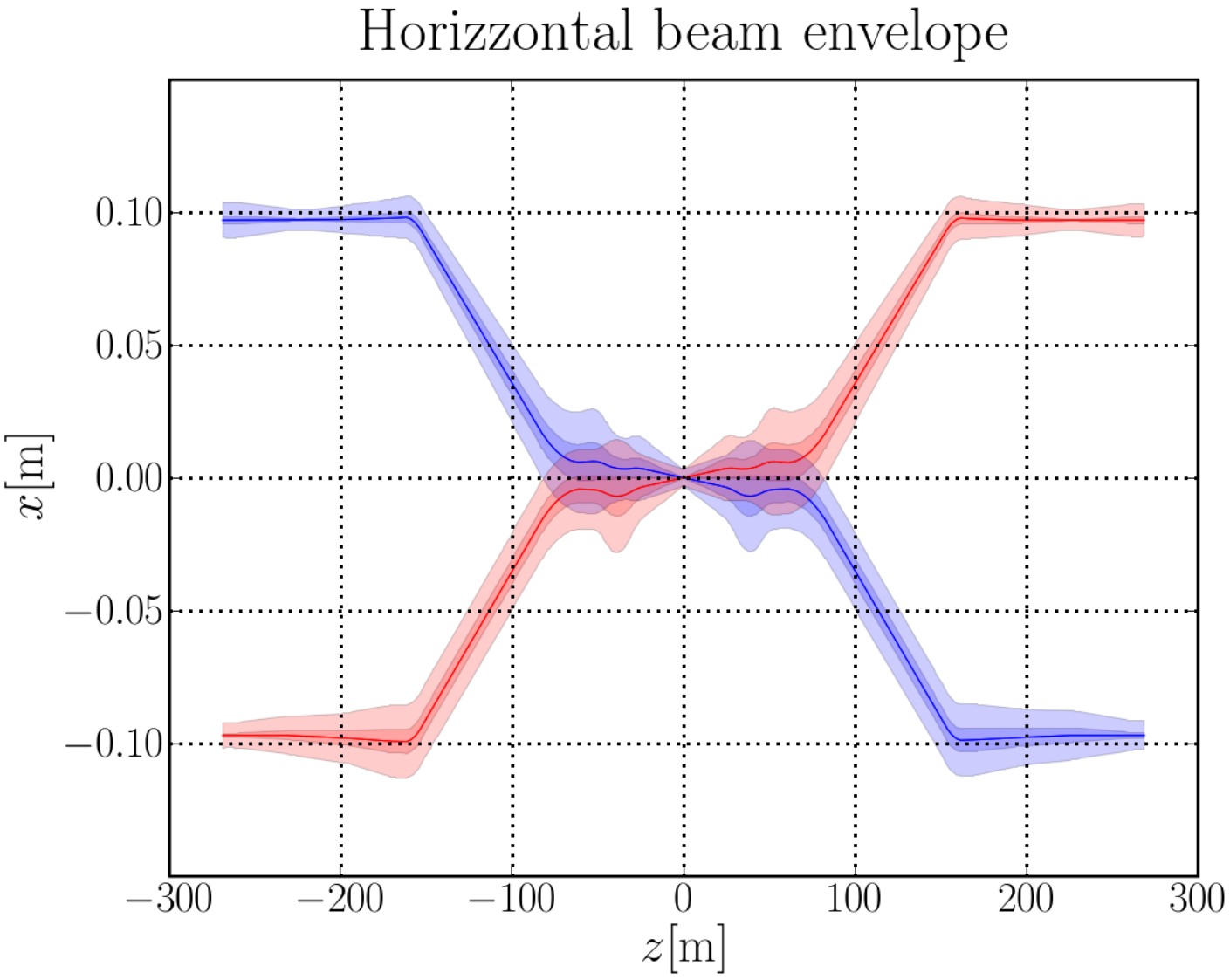
Nominal Layout



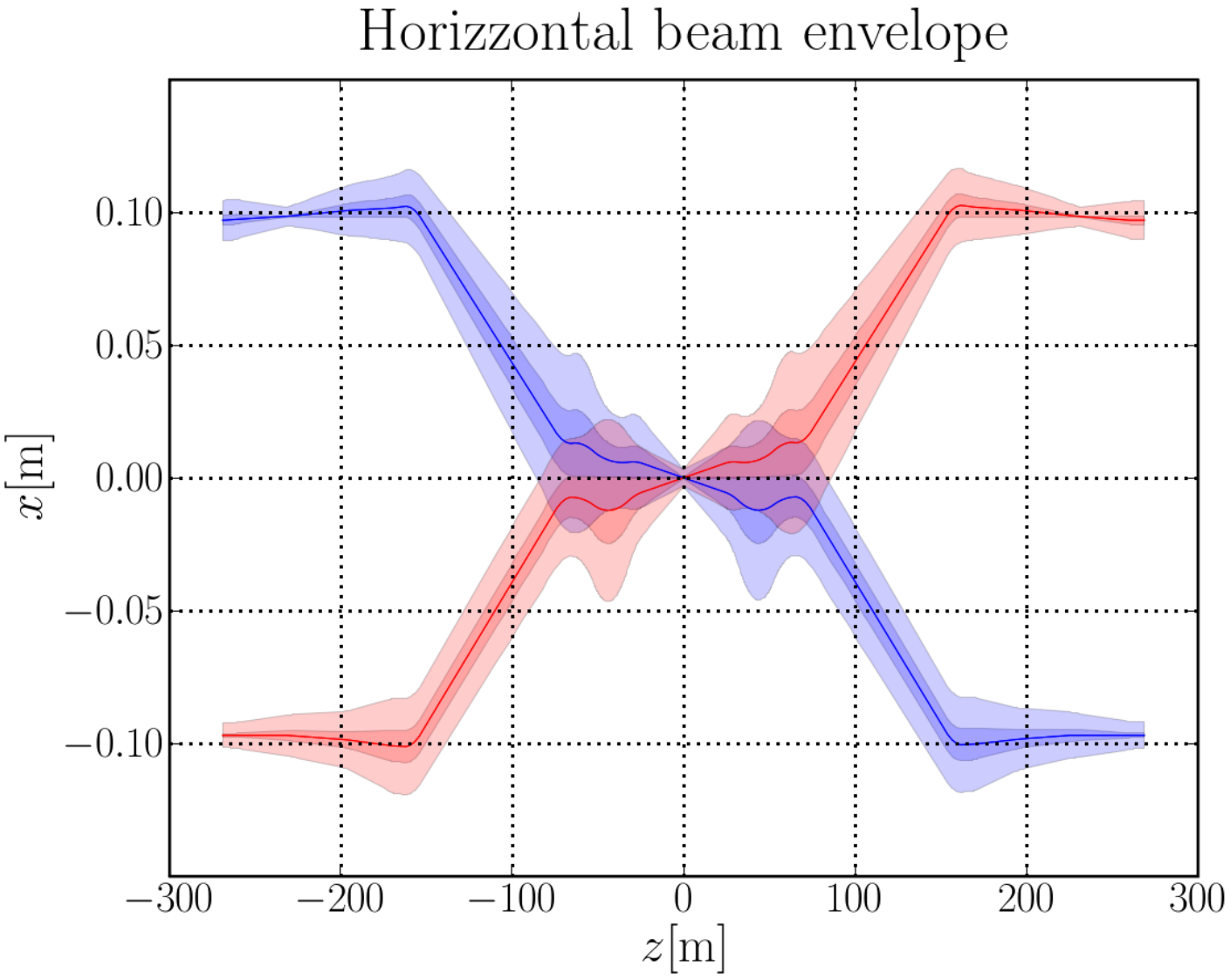
Upgraded Layout



Nominal Layout

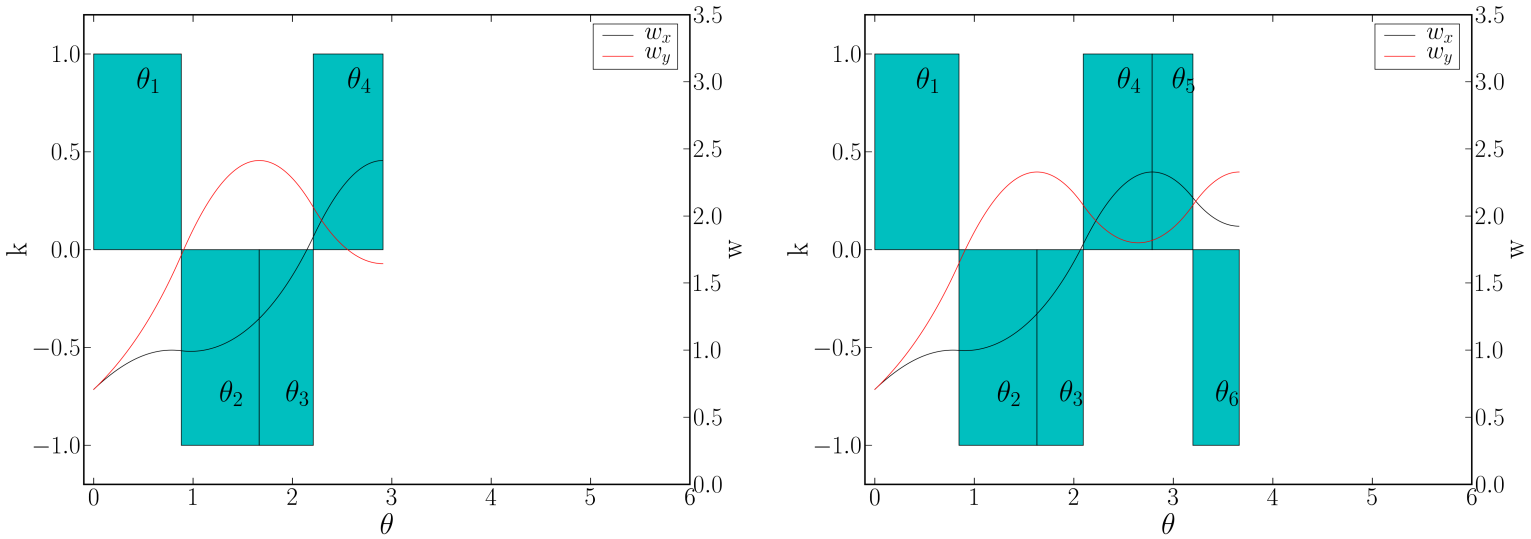


Upgraded Layout



Parameter space via simplified triplet and quadruplet

The design of quadrupole first layouts requires a careful optimization of the focusing system assembly.
I use 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 beam size (beta peak) possible in the triplet or quadruplet.

Normalization

Let $w = \sqrt{\beta}$, then

$$w''(s) \pm k(s)w(s) - \frac{1}{w^3(s)} = 0$$

In the triplet the high order term can be neglected, therefore

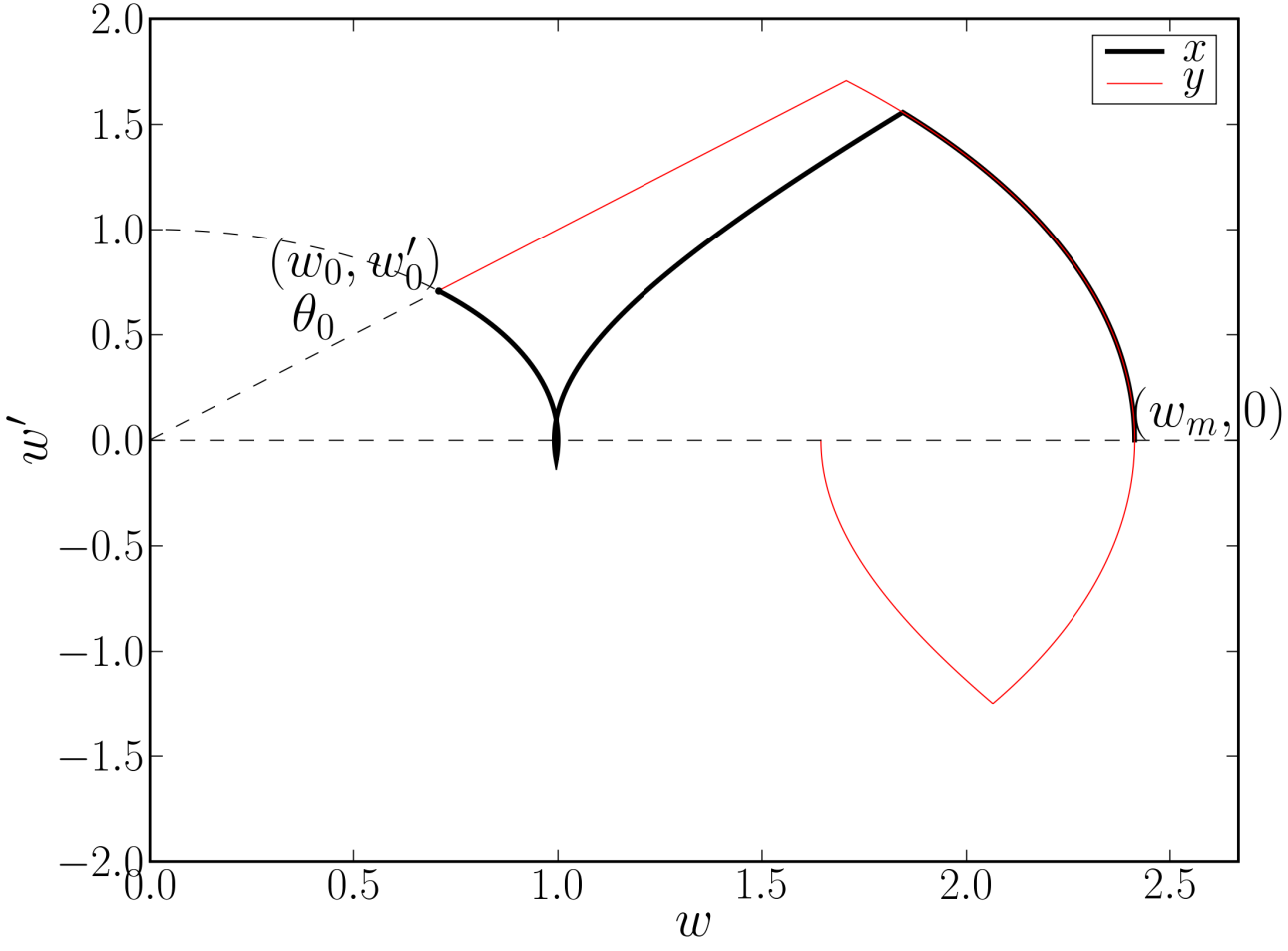
$$w''(s) \pm k(s)w(s) = 0$$

and if k is piecewise constant

$$w(s) = w_0 \cos(s\sqrt{k}) + \frac{w_0'}{\sqrt{k}} \sin(s\sqrt{k})$$

A solution for a round beam focus system depends on three paramaters: $w(L^*)$, $w'(L^*)$ and k.
By using the normalization $\theta \to s\sqrt{k}$, the solution are just circular or hyperbolic rotation. The diff.eq is homogeneous and linear then the solutions depends only on the ratio of the initial condition.
From three parameters we end up with one:
$\sqrt{k}w(L^*)/w'(L^*) \simeq L^*\sqrt{k}$.

Triplet layout



Triplet problem

Using normalization we have a diff.eq:

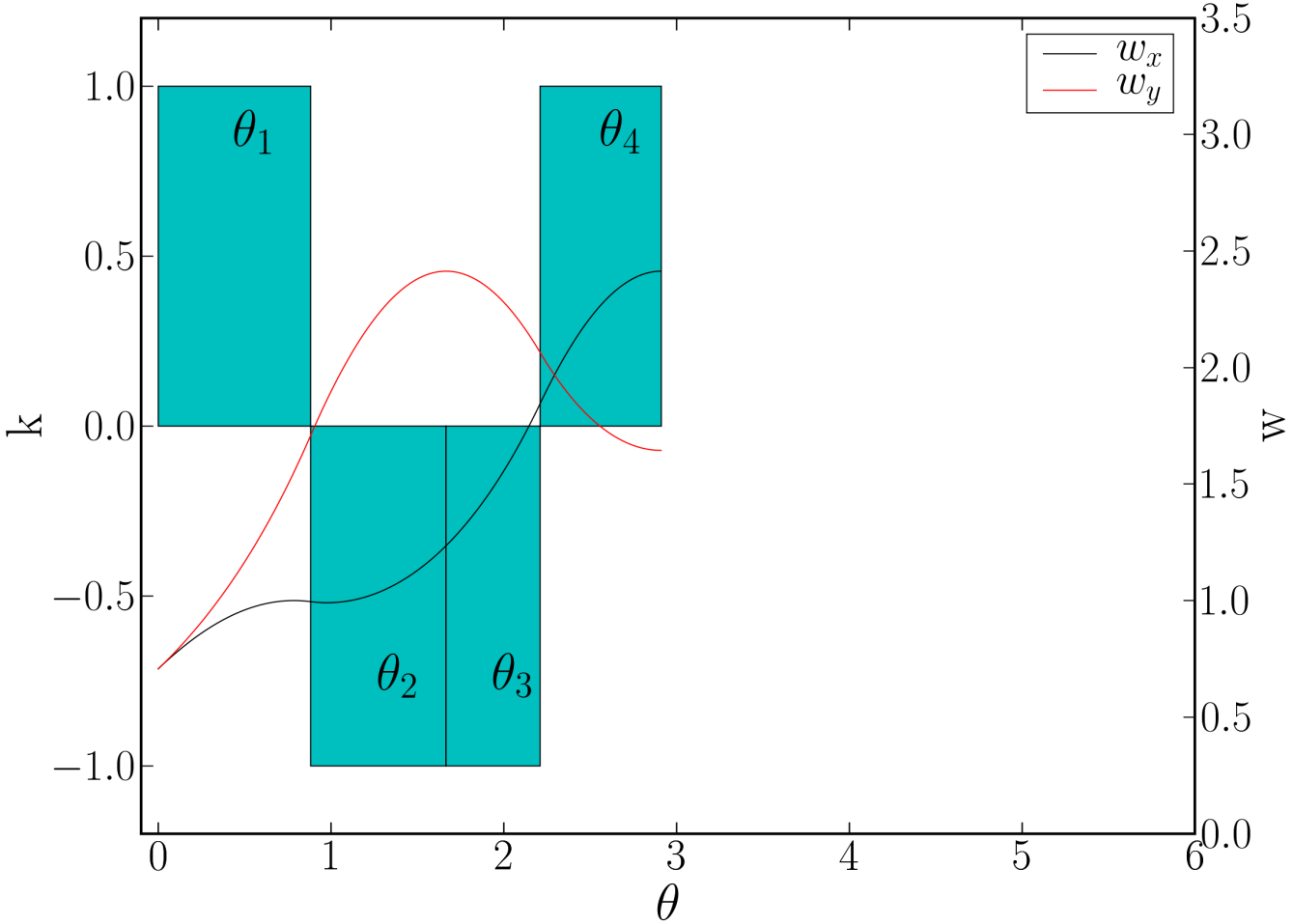
$$\bar{w}''(\theta) \pm \bar{w}(\theta) = 0 \qquad\qquad \theta = s\sqrt{k}$$

Aming to a parallel to point final focus system which optimize the aperture for round beams (same β, same ε) we need two fit for a triplet four conditions:

$$\bar{w}'_x(\theta_4) = 0 \quad \bar{w}'_y(\theta_4) = 0 \quad \bar{w}_y(\theta_2) = \bar{w}_x(\theta_4) \quad \bar{w}'_x(\theta_2) = 0$$

in four parameters (the norm. legnths of the quads) $\theta_i = l_i\sqrt{k}$.

Triplet layout



General triplet solution

The initial condition for the triplet problem are:

$$w(s = L^*) = L^*/\sqrt{\beta^*} \qquad w'(s = L^*) = 1/\sqrt{\beta^*}$$

Knowing that:

$$\theta = s\sqrt{k} \qquad \bar{w}(\theta) = w(s) \qquad \bar{w}'(\theta) = \sqrt{k}w(s)$$

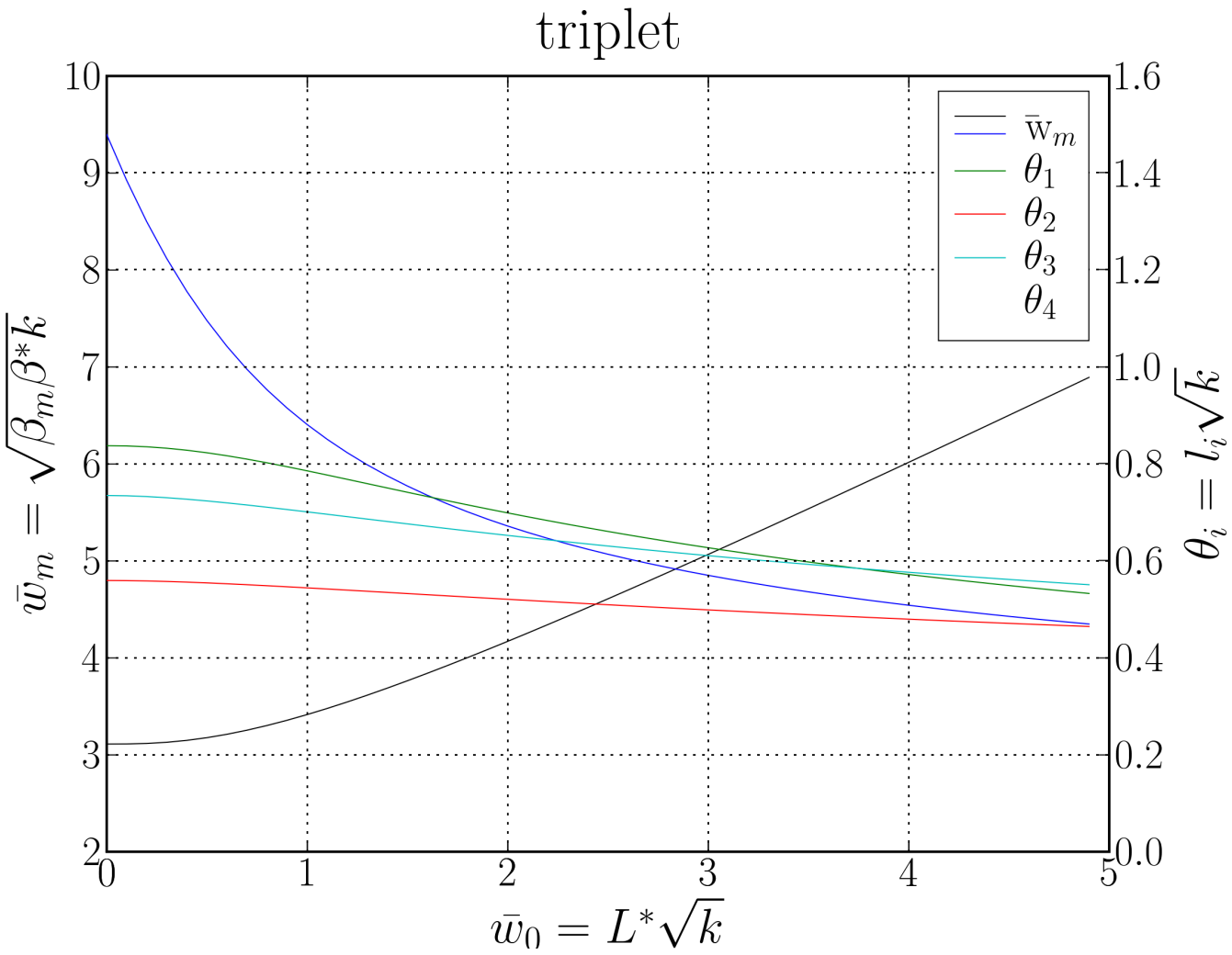
The initial conditions:

$$\bar{w}_0 = L^*\sqrt{k} \qquad \bar{w}_0' = 1$$

gives the scalings

$$\bar{w}_{\mathsf{max}} = w_{\mathsf{max}}\sqrt{\beta^* k} \qquad \theta_i = \sqrt{k}l_i$$

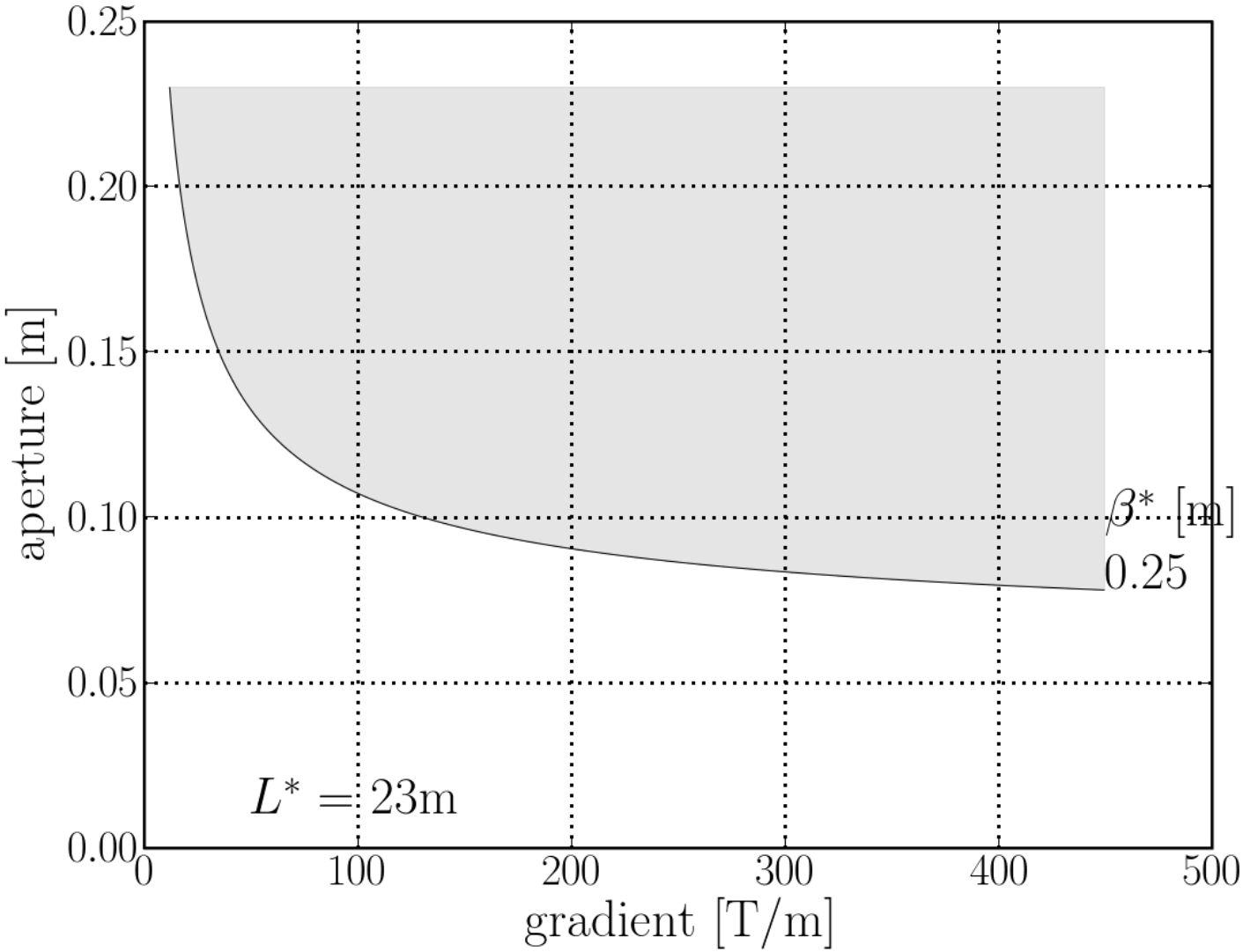
Triplet solution



More detail in LHC project report 1051.

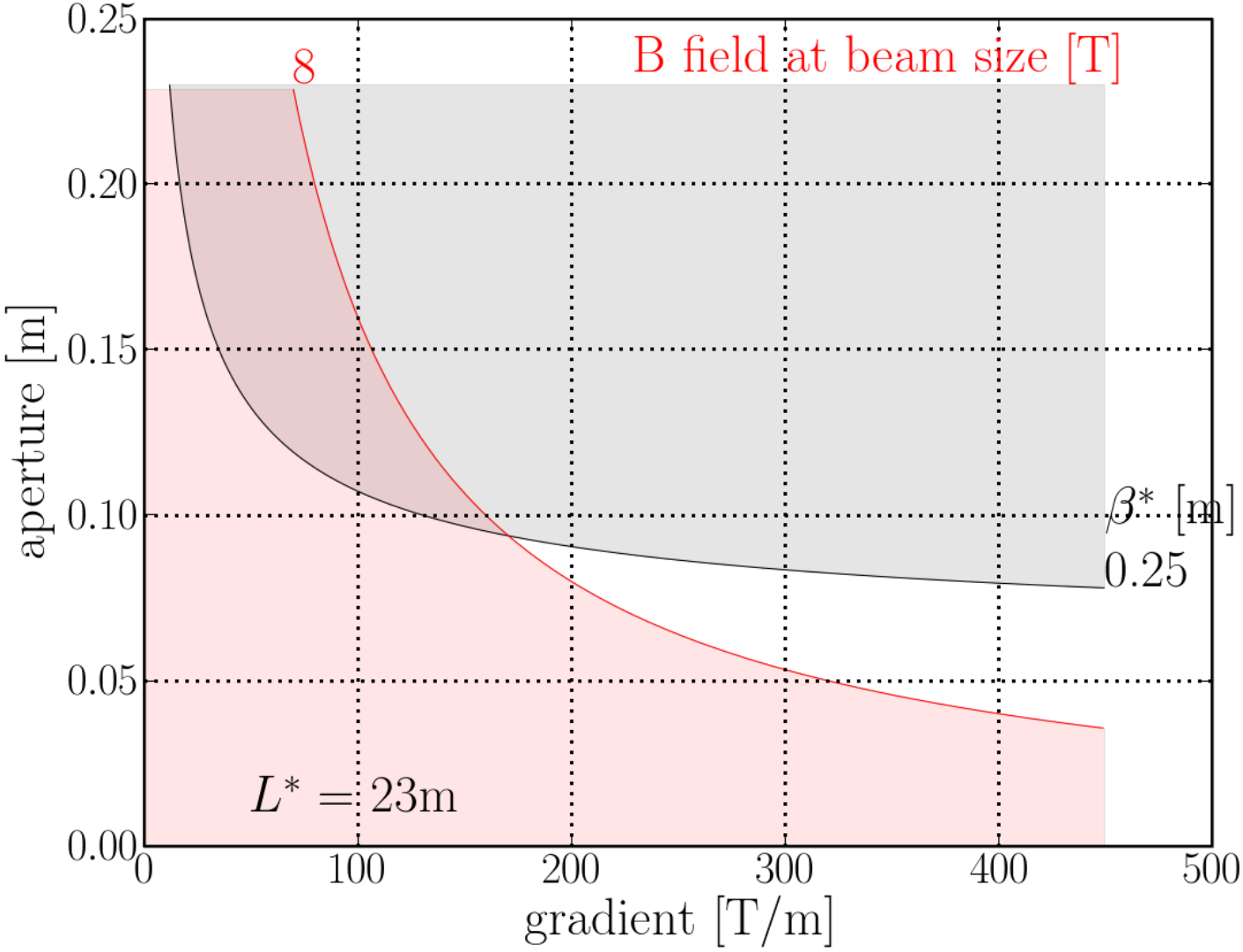
Beam size vs gradient

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



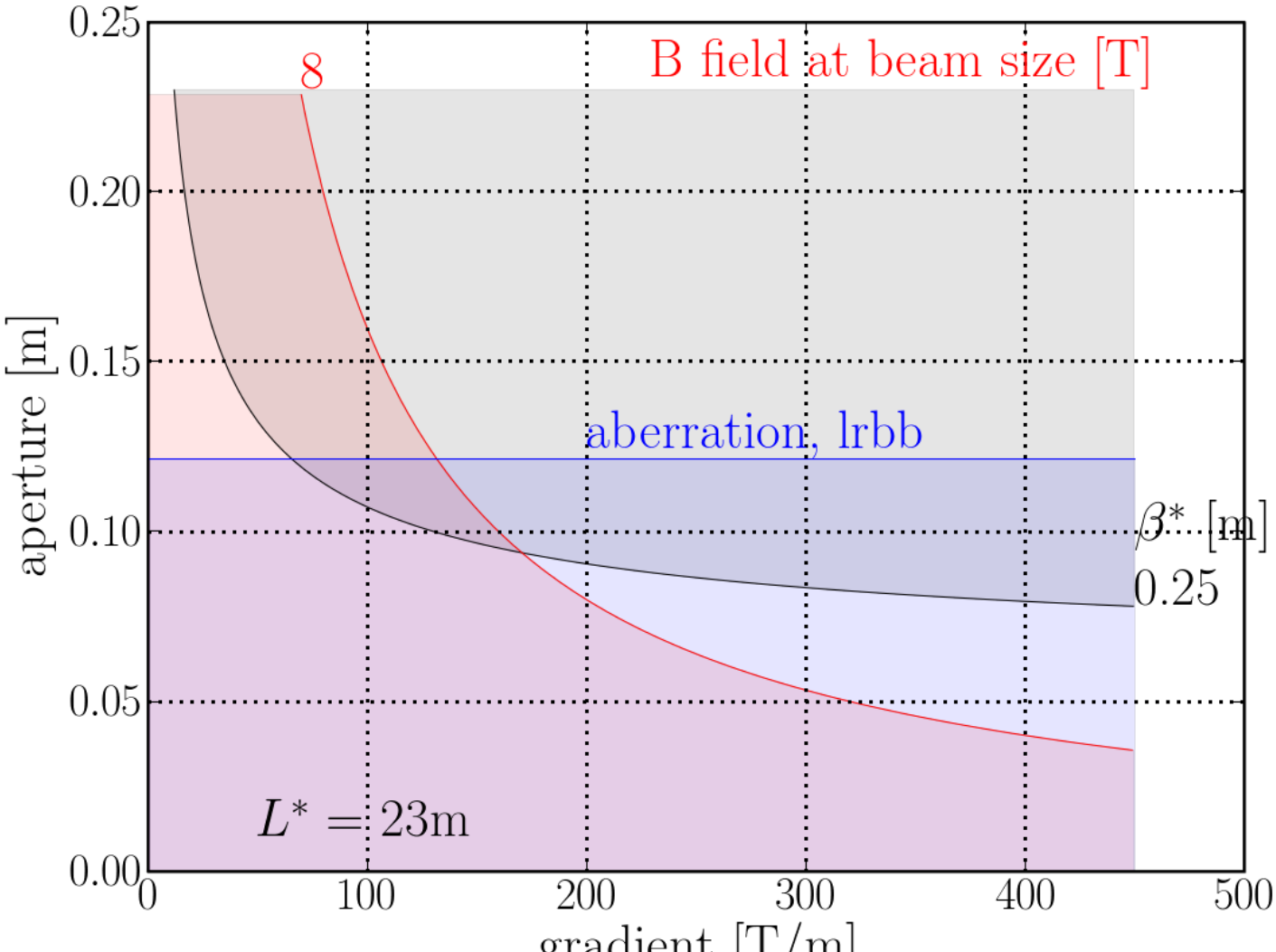
Beam size vs gradient

Magnet max aperture: $a_{max} = \frac{2B_{peak}}{kp/q}$.



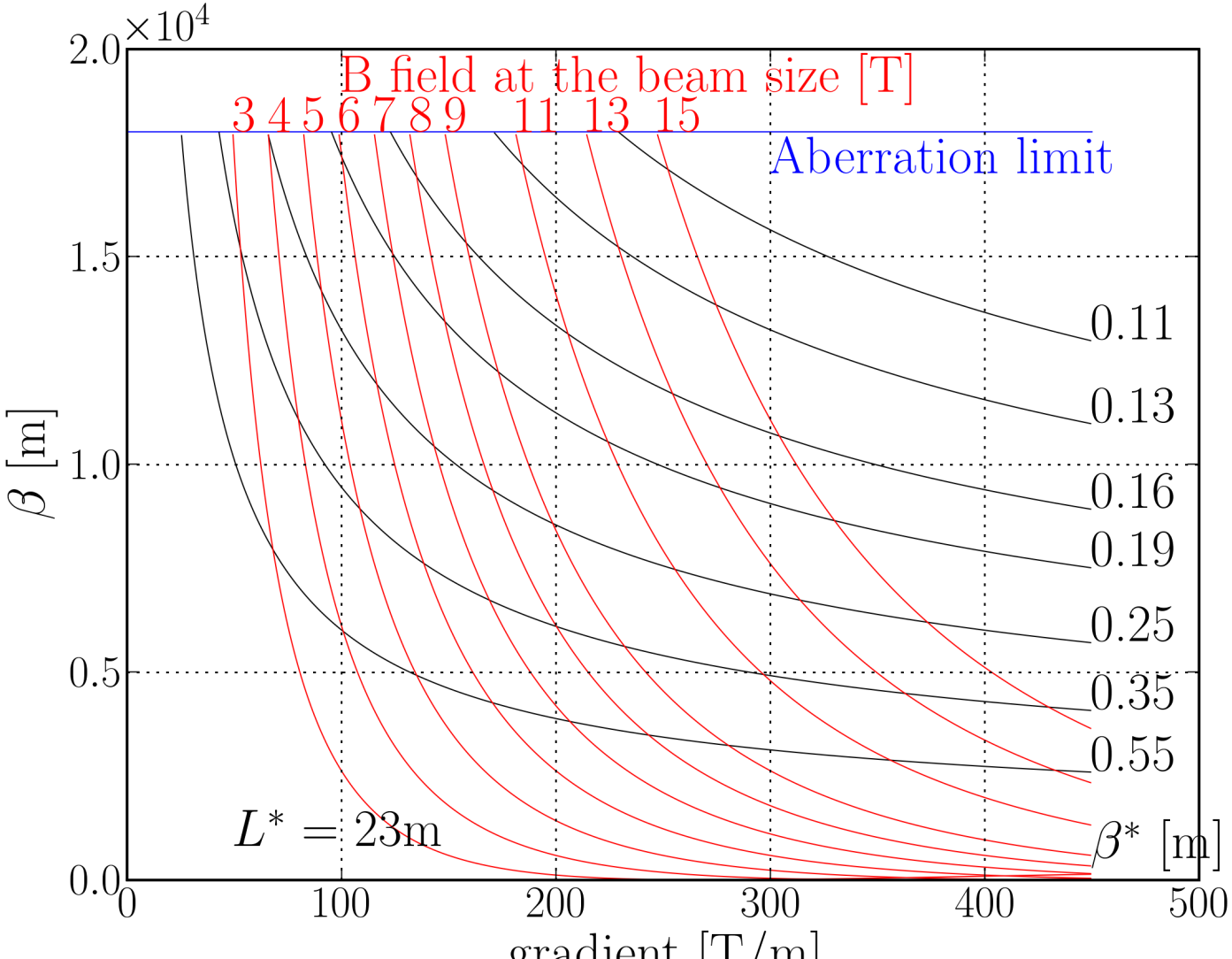
Beam size vs gradient

When the gradient decrease the aperture required by the beam increase slower w.r.t. the aperture compatible with a given peak field.



Beam size vs gradient

When the gradient decrease the aperture required by the beam increase slower w.r.t. the aperture compatible with a given peak field.

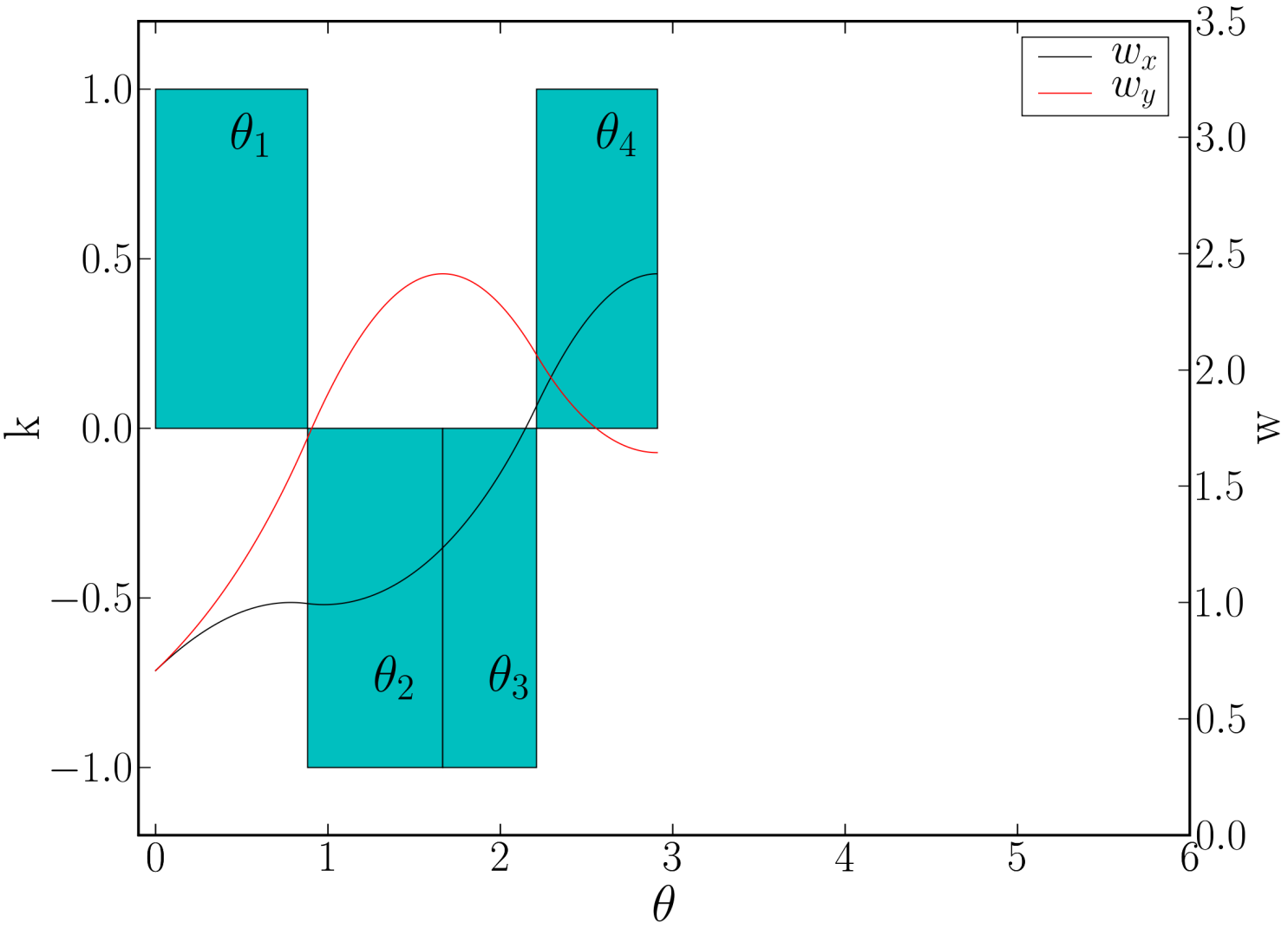


Beam size vs gradient

When the gradient decrease the aperture required by the beam increase slower w.r.t. the aperture compatible with a given peak field. It implies that smaller is the gradient, larger will be the aperture margins.
The clear advantage of low gradient quadrupole magnets is limited by the fact that the quadrupoles needs to be longer, the beta functions get larger and the chromatic aberrations increase.
Another disadvantage is that the number of LLRB increase as well.

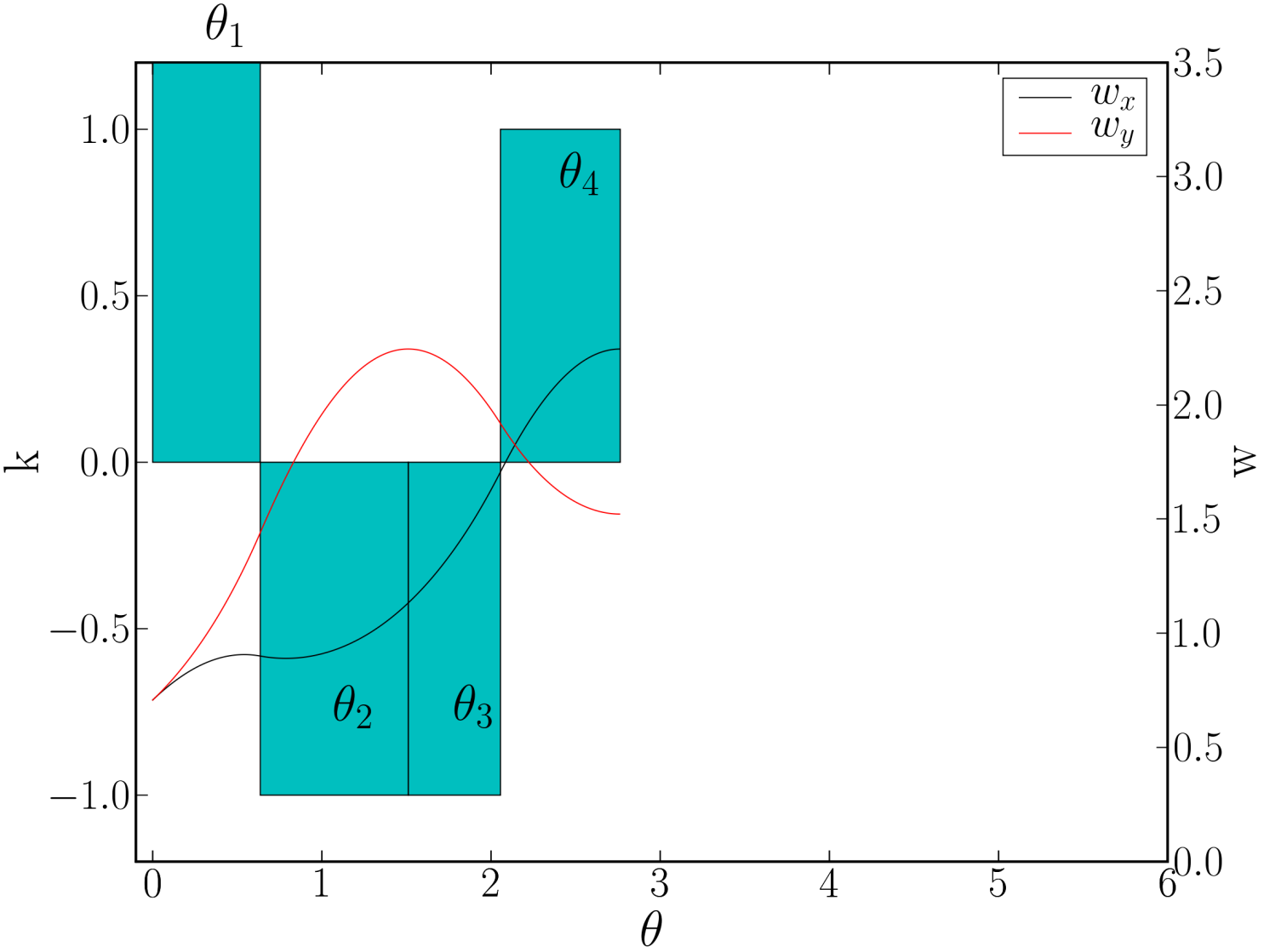
Realistic implementation

Starting from the ideal case



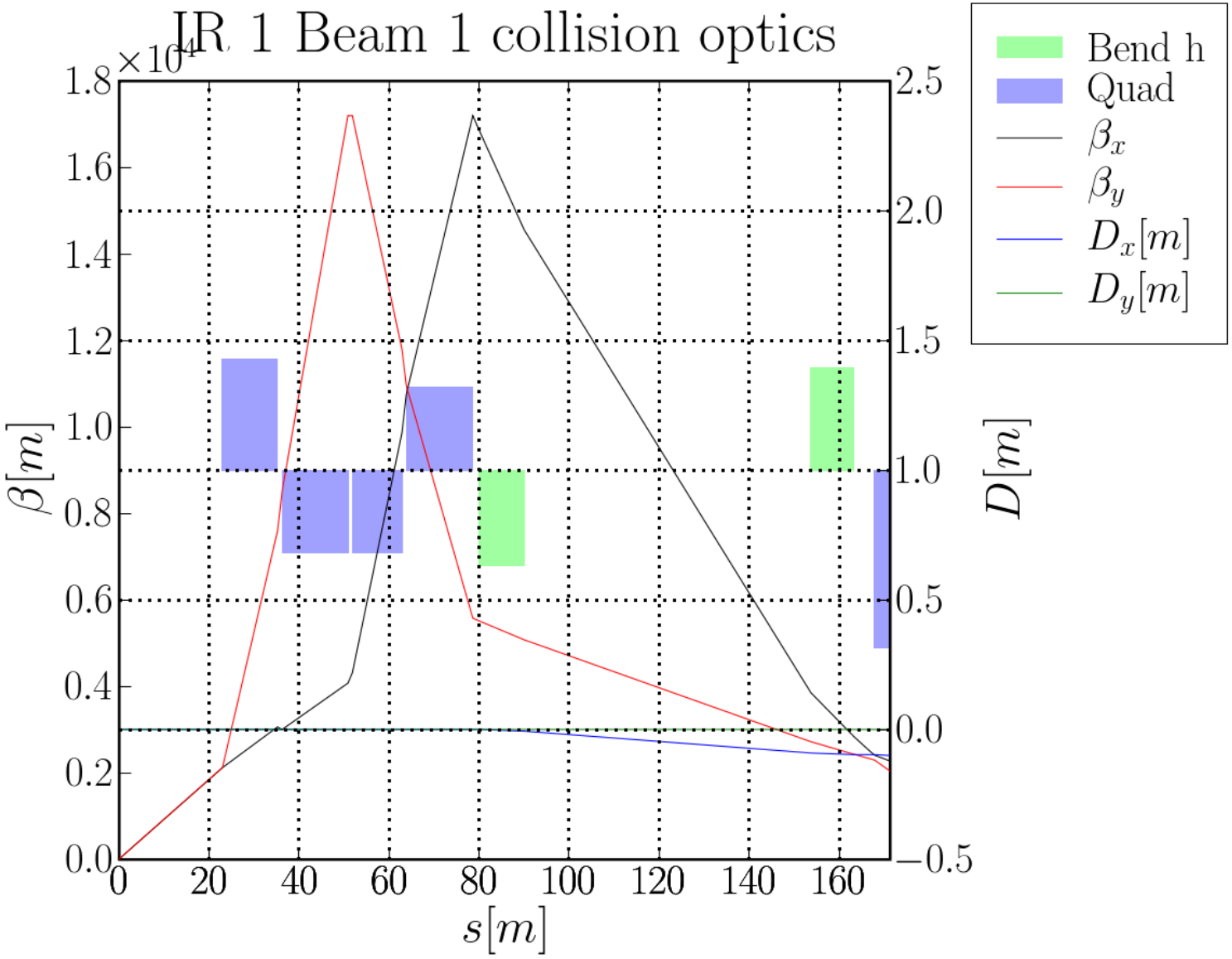
Realistic implementation

Optimize Q1



Then split and focus to match to the arc.

Compact



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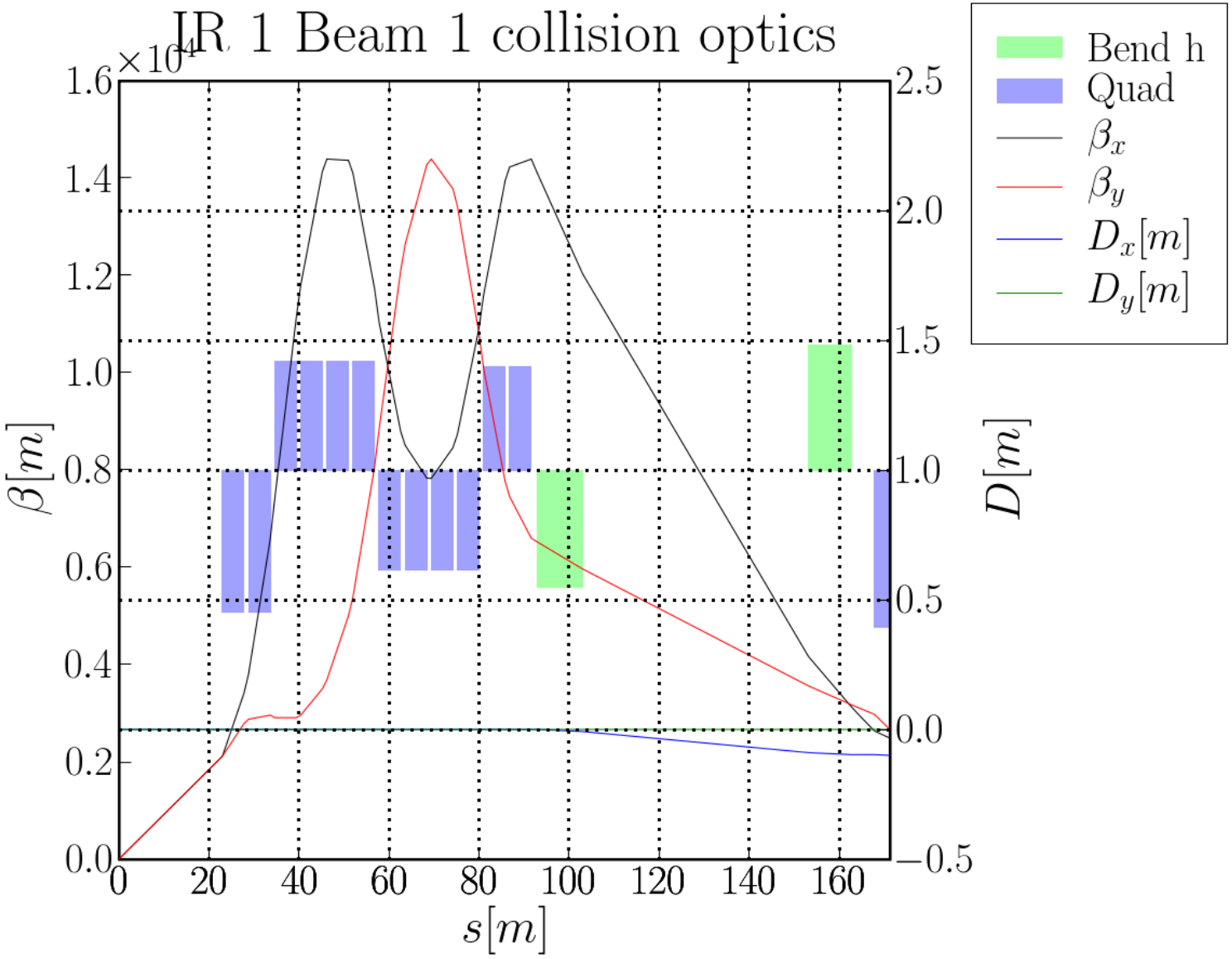
Modular



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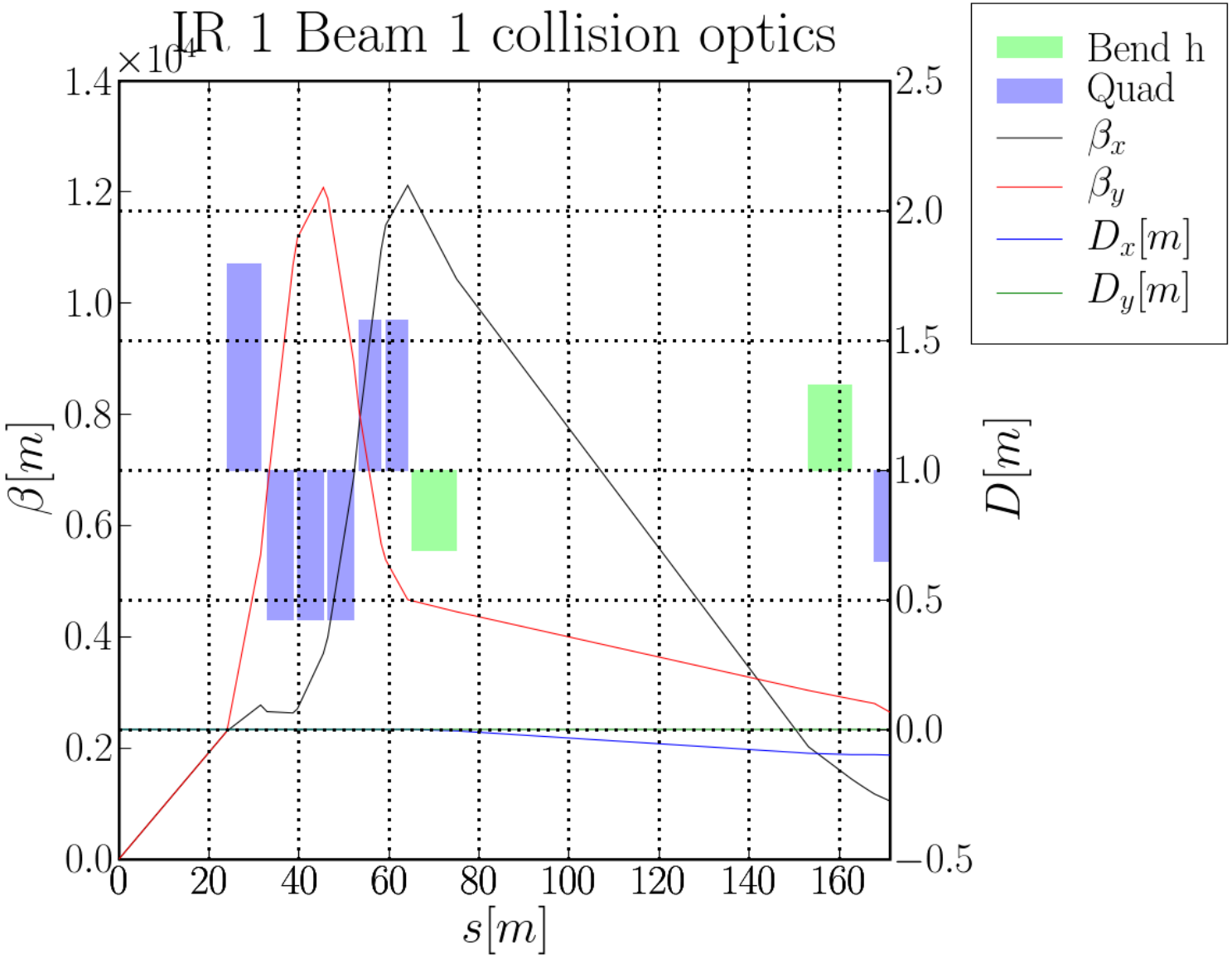
Lowbetamax



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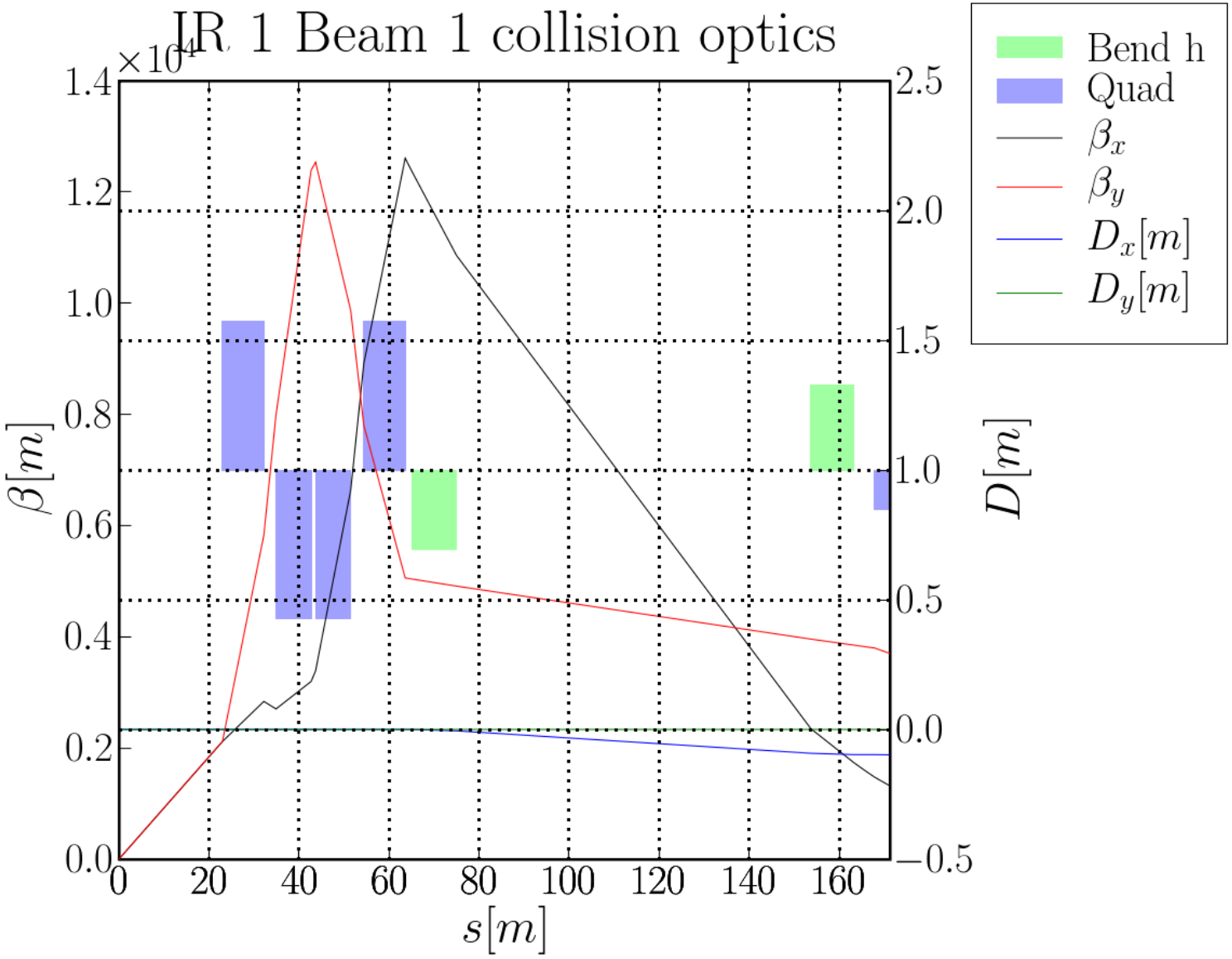
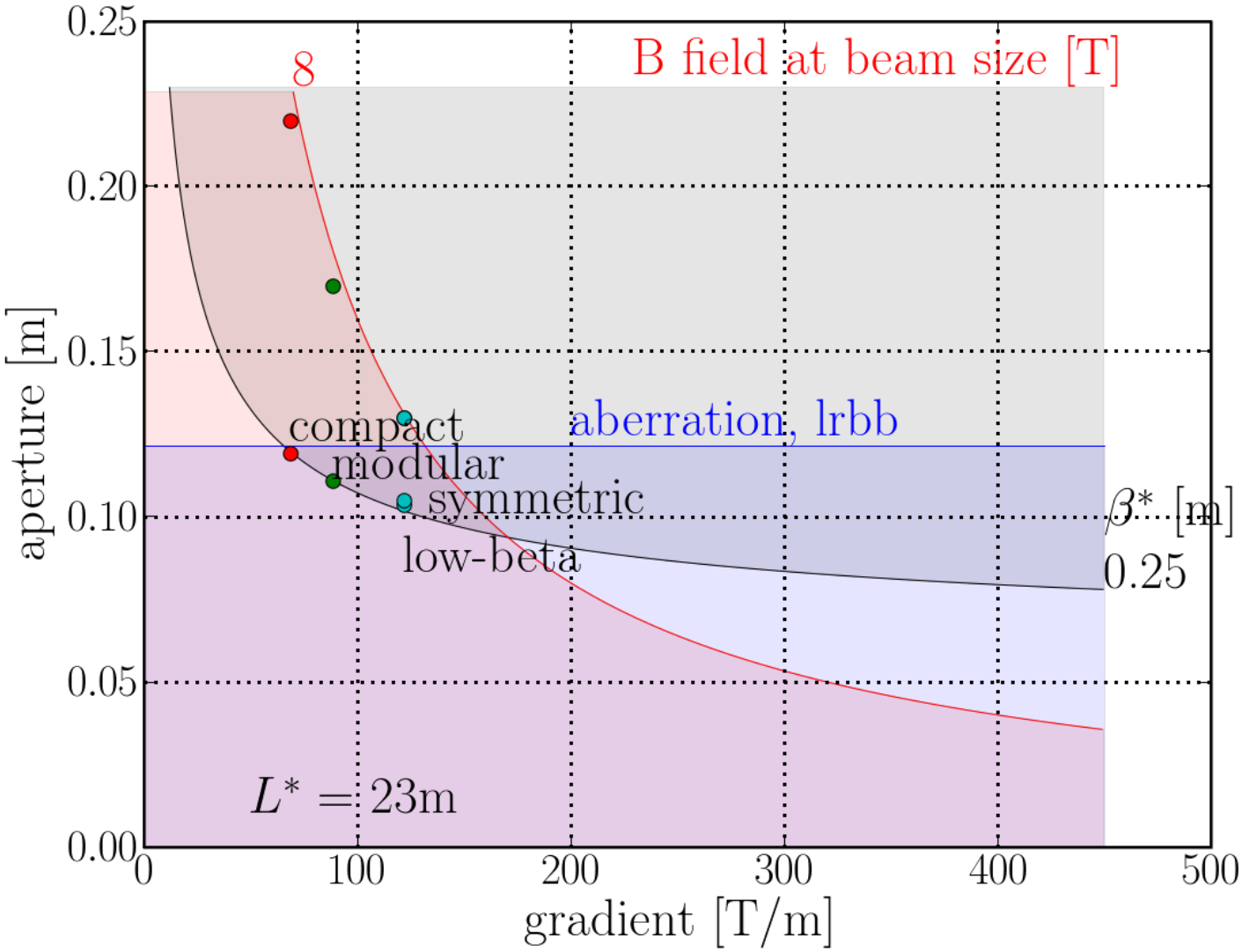
Symmetric



LHC Project Report 1000

Choice of the gradient



Layouts

	Compact	Modular	Lowbeta	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

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

Data in terms on n1. Lowbetamax and symmetric provide a better balance between apertures in triplets- and LSS than compact and modular.

Dynamic aperture

	Compact	Modular	Lowbeta	Symmetric	LHC
Full	16	11	14	12	12
Triplet only	22	17	14	12	
Triplet escluded	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 lowbeta, 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 E. 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.

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

The off momentum beta beat may reduce the collimation efficiency.

Conclusions

Quadrupole first options show that weaker and longer quadrupole allow a reduction of $\beta*$ requiring a smaller peak field in the coil. The weaker they are, more aperture margins and better dynamics can achieved.
The drawbacks are an increase of chromatic aberrations, an increase of LRBB interaction, limitation of aperture in the MS.
MS quadrupoles are requested to provide more divergence at smaller aperture: stronger 2-in-1 quadrupoles, with standard aperture (70-60mm) and field quality, would be beneficial.

Open questions and challenges

Solution studied are close to be realistic but many refinements are still needed for a final solution:

- check whether the larger off momentum beta beat affects the operation or the protection of the machine.
- 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, while keeping the IR tunable
- 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.

Outline

LHC performance and limitations

LHC Interaction region

Dipole first layouts

Quadrupole first layouts

Conclusion and future projects

Conclusions

The LHC is a collider designed to reach unprecedented performance. Still an upgrade R&D program has been launched to push the performance limit. An analysis of the performance limitations lead to identify in the IR an area whose upgrade can increase the performance or the operational margin.
Two IR upgrade options aiming to $\beta^* = 25\,\mathrm{cm}$ has been identified and studied.

- Dipole first: allow a larger luminosity increase potential, but the implementation is still challenging.
- Quadrupole first: conservative upgrade with smaller luminosity increase potential. The implementation is feasible.

Future plans

CERN management has identified two upgrade paths:

- Phase I upgrade: 2012, quadrupole first IR upgrade aim to ultimate performance and larger operational margin
- Phase II upgrade: $>$2015, aim to a factor 10 from nominal performance. The are two main line path (large Piwinsky angle and early separation scheme). Both take advantage of a reduction of β^*.

LHC luminosity upgrade is not only interaction region upgrade, there are a wealth of proposals and ideas (among them crab cavities, wire compensation, e-lens).

Acknowledgment

Thanks for the continuous support and inspiration to: Aurelio Bay, Oliver Brüning, Ulrich Dorda, Massimo Giovannozzi, Stéphane Fartoukh, Tom Kroyer, Frank Schmidt, Rogelio Tomas, Thys Risselada, Leonid Rivkin, Albin Wrulich.
Many thanks for the helpful discussions and ideas to: Chiara Bracco, Roderik Bruce, Helmut Burkhardt, Rama Calaga, Werner Herr, Jean Pierre Kouchuck, Simine Gilardoni, Ramesh Gubta, Jean Bernard Jeanneret, John Johnstone, John Jowet, Emanuale Laface, Daniela Macina, Nicola Mokhov, Steve Peggs, Tanaji Sen, Vladimir Shiltsev, Guido Sterbini, Walter Scandale, Ezio Todesco, Frank Zimmermann.