High Luminosity LHC

Task2.2 HL-LHC Optics and Lattice Configurations

Bernhard Holzer

for the WP2, Task2.2 Team

B. Dalena, A. Bogomyagkov, R. Appleby, A. Fauss-Golfe, J. Payet, A. Chance', K. Hock, M. Korostelev, R. deMaria, J. Resta, C. Milardi, L. Thompson, M. Thomas, A. Wolski

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“ … and do not show too many of this strange

zig zag plots “

High Luminosity LHC

Luminosity & Beam Optics

The HL-LHC Lattice & Optics has to establish β* at IP1 & 5 to reach a "virtual luminosity"

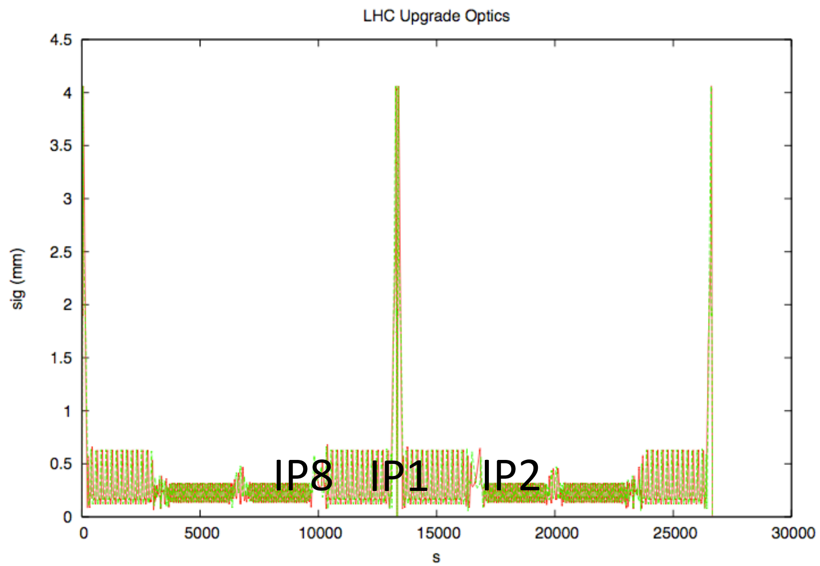
$$\hat{L}(25ns) = 24 * 10^{34} cm^{-2} s^{-1}$$

$$\hat{L}(50ns) = 26 * 10^{34} cm^{-2} s^{-1}$$

➔ ***to small for the IR1 / 5 matching section***

➔ ***squeeze starts at neighboring sectors ("ATS") .***

$$\beta_x^* = \beta_y^* \approx 15cm$$



-> gentle premonition:

the lattice modifications used to optimise for smallest β*

might not be adequate for β = 500...1000m

HL-LHC Parameter List

Parameter	nominal	25ns	50ns
N_b	1.15E+11	2.20E+11	3.50E+11
n_b	2808	2808	1404
N_{tot}	3.2E+14	6.2E+14	4.9E+14
beam current [A]	0.58	1.12	0.89
x-ing angle [mrad]	300	590	590
beam separation [σ]	9.9	12.5	11.4
β^* [m]	0.55	0.15	0.15
ε_n [μm]	3.75	2.50	3
ε_L [eVs]	2.51	2.51	2.51
energy spread	1.20E-04	1.20E-04	1.20E-04
bunch length [m]	7.50E-02	7.50E-02	7.50E-02
IBS horizontal [h]	80 -> 106	18.5	17.2
IBS longitudinal [h]	61 -> 60	20.4	16.1
Piwinski parameter	0.68	3.12	2.85
geom. Reduction factor 'R'	0.83	0.305	0.331
beam-beam / IP without Crab Cavity	3.10E-03	3.28E-03	4.72E-03
beam-beam / IP with Crab cavity	3.75E-03	1.08E-02	1.43E-02
Peak Luminosity without leveling [cm^{-2} s^{-1}]	1.0E+34	7.4E+34	8.5E+34
Virtual Luminosity: Lpeak/R [cm^{-2} s^{-1}]	1.2E+34	24E+34	26E+34
Events / crossing without leveling	19 -> 28	210	475
Levelled Luminosity [cm^{-2} s^{-1}]	-	5E+34	2.50E+34
Events / crossing with leveling	* 19 -> 28	140	140

x-angle

β^*

ε

L_0

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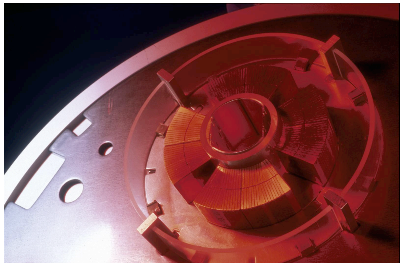
Lattice Modifications:

The Lattice has to be optimised to establish smallest β* values at IP1 & 5.

present design goal: β* = 15 cm

larger triplet apertures (and D1, Q4, TAS / TAN etc)

$$g = \frac{2\mu_0 nI}{r^2}$$



re-optimise the position of matching quadrupoles

find space for orbit correctors / spool piece correctors

find space for crab cavities

establish a crossing scenario without changing the crab orbit

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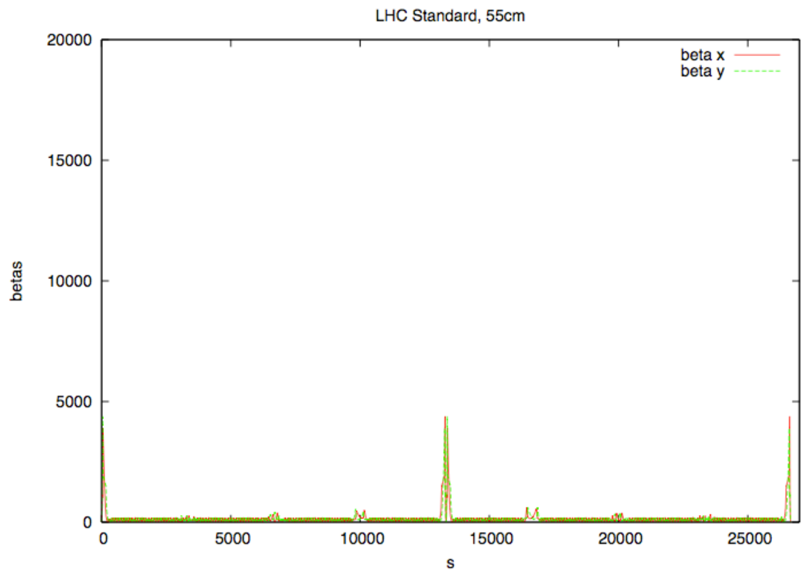
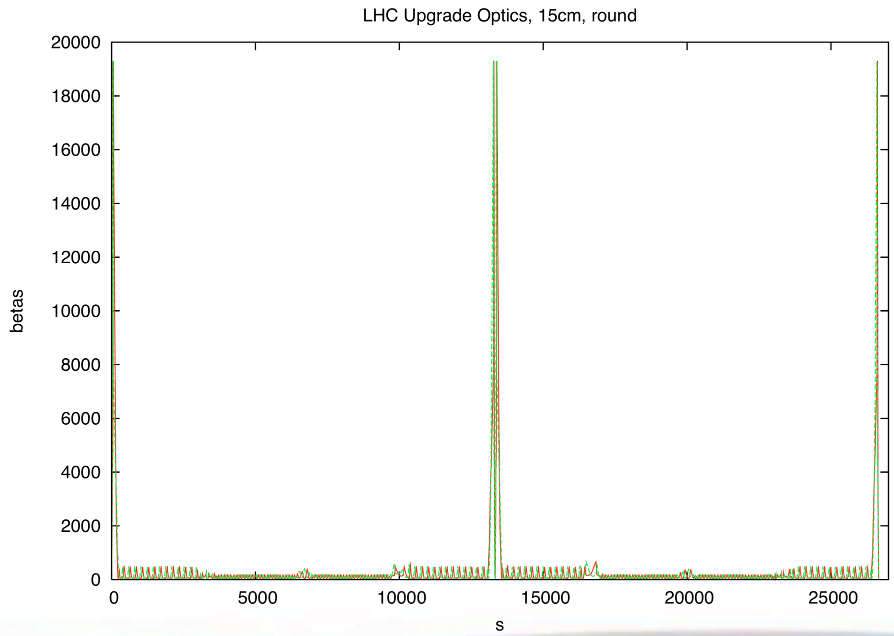
It is a long way to go:

LHC standard Optics, 55cm



HL-LHC Optics, 15cm



... my apologies for the zig-zags !

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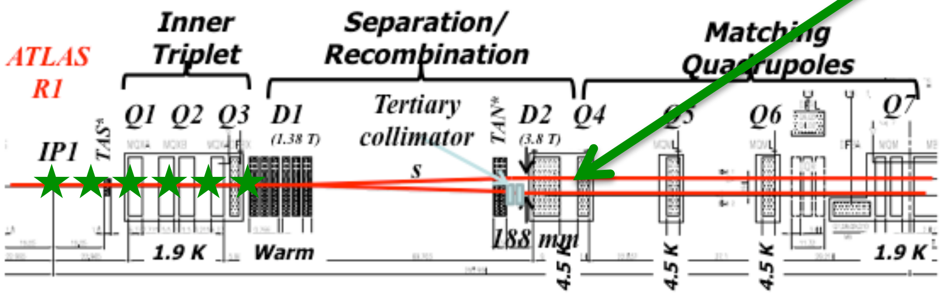
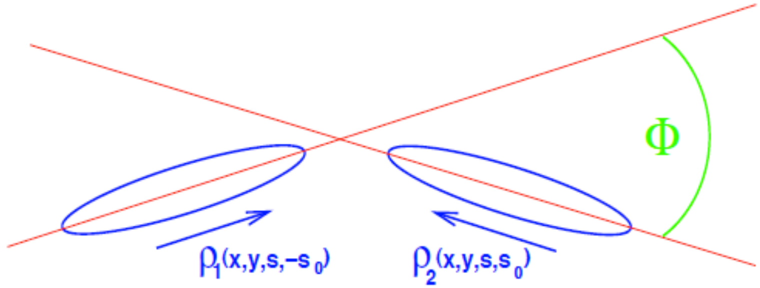
Luminosity, Loss Factor & Crab Cavities

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{2\pi\sqrt{\sigma_{1x}^2+\sigma_{2x}^2}\sqrt{\sigma_{1y}^2+\sigma_{2y}^2}} \; * R$$

ideal luminosity formula



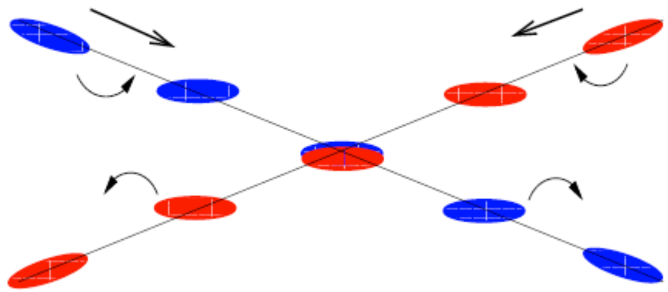


loss factor due to crossing with an angle
(pure geometric effect ... but large)

$$R = \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})^2}} \approx \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}} \; * H$$

≈ 0.33

"crab" crossing scheme



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what we are talking about:

four baseline optics
based on assumptions on
aperture & magnet technique

ap. [9] [mm]	grad [10] [T/m]	lengths [11] [m]	β^* [cm]	N1 [12] [ppb]	N2 [13] [ppb]	t [14] [h]
150	144(83%Sn)	8.2 , 7.0	13.0	1.99E11	1.21E11	6.06
150	96(83%Ti)	10.8 , 9.0	17.0	2.03E11	1.36E11	5.24
140	150(80%Sn)	8.00, 6.8	15.0	2.01E11	1.29E11	5.64
140	100(80%Ti)	10.5, 8.8	19.0	2.05E11	1.42E11	4.89
120	170(83%Sn)	7.1 , 6.1	18.6	2.05E11	1.42E11	4.96
120	120(83%Ti)	9.3, 7.8	24.0	2.11E11	1.58E11	4.14
85	160(78%Ti)	7.7, 6.6	44.0	2.41E11	2.11E11	2.33
80	257(80%Sn)	4.8, 5.5	39.0	2.33E11	1.99E11	2.65

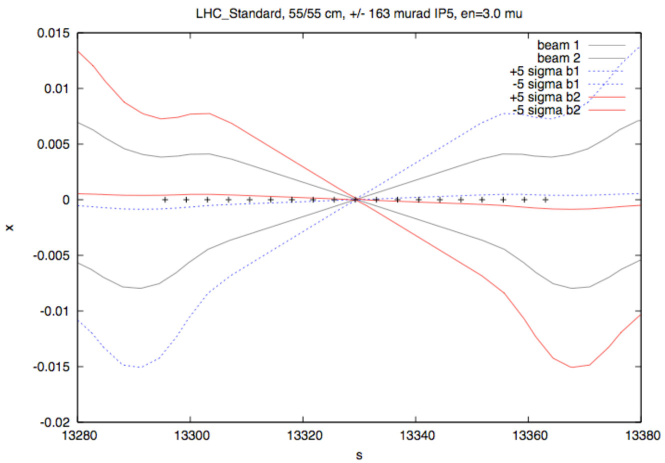
and the latest version, based on 150mm aperture - 140T/m gradient ...
... being finalised at the moment

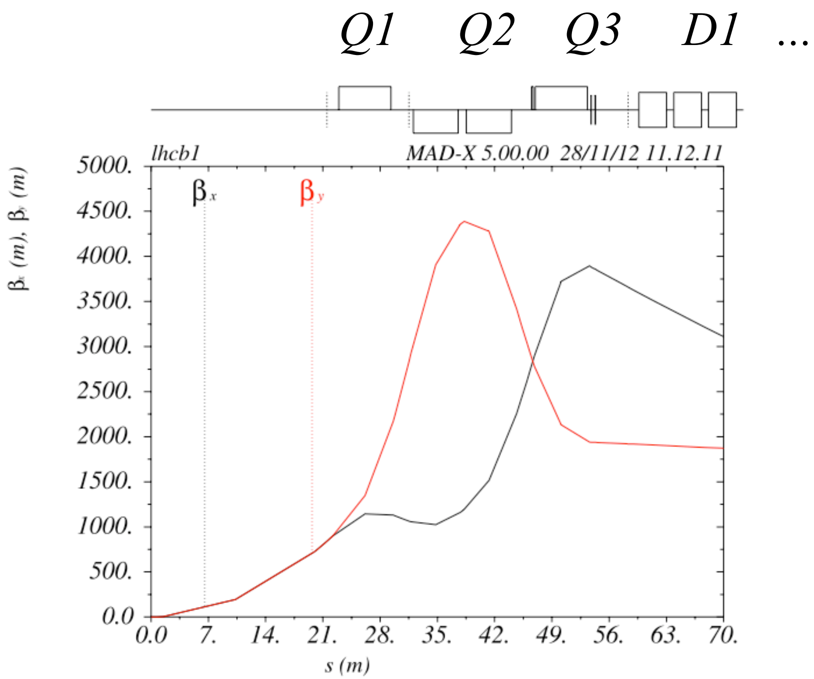
Standard LHC

Beam Envelopes:

Standard LHC, β*= 55cm, ε = 3.0

crossing angle = +/- 145 μrad

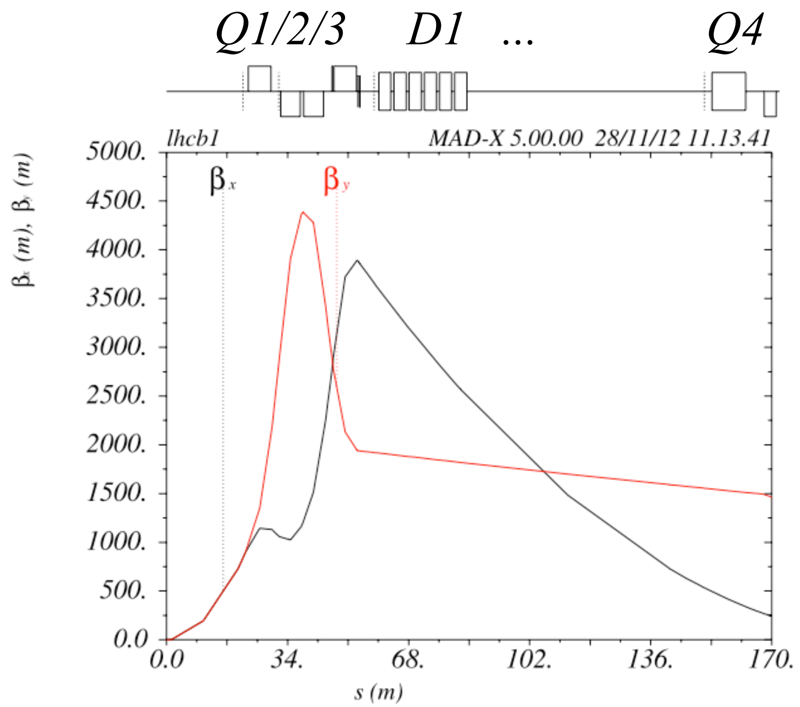


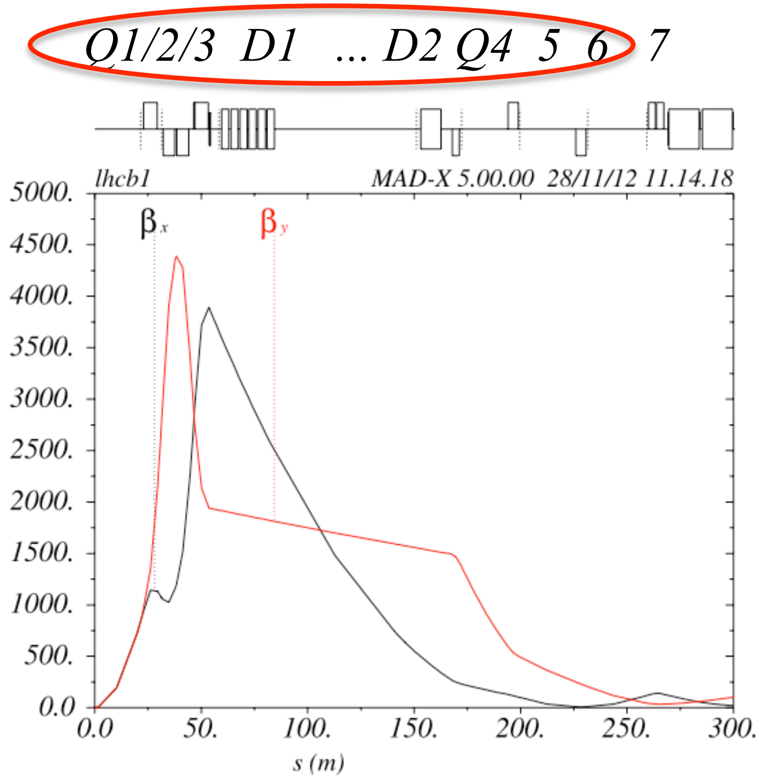


Lattice & Optics for LHC Standard

Standard LHC

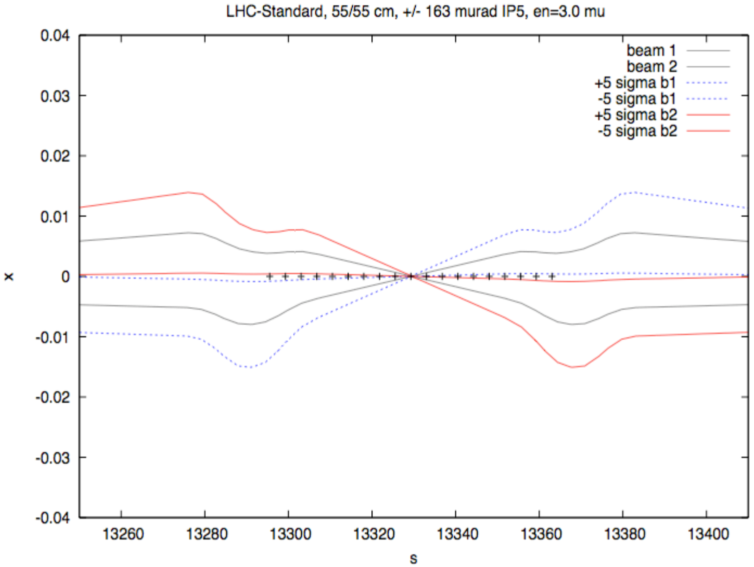
Lattice:



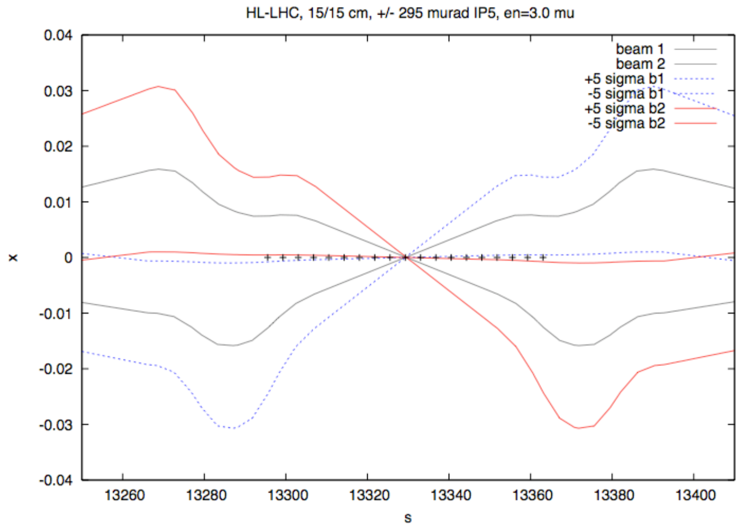


Upgrade Lattice: SLHC_V3.1b
150 T/m, 140mm

Beam Envelopes: HL-LHC, **β*= 15cm**, ε = 3.0
crossing angle = **+/- 295 μrad**



Standard LHC, 55cm



HL-LHC, 15cm

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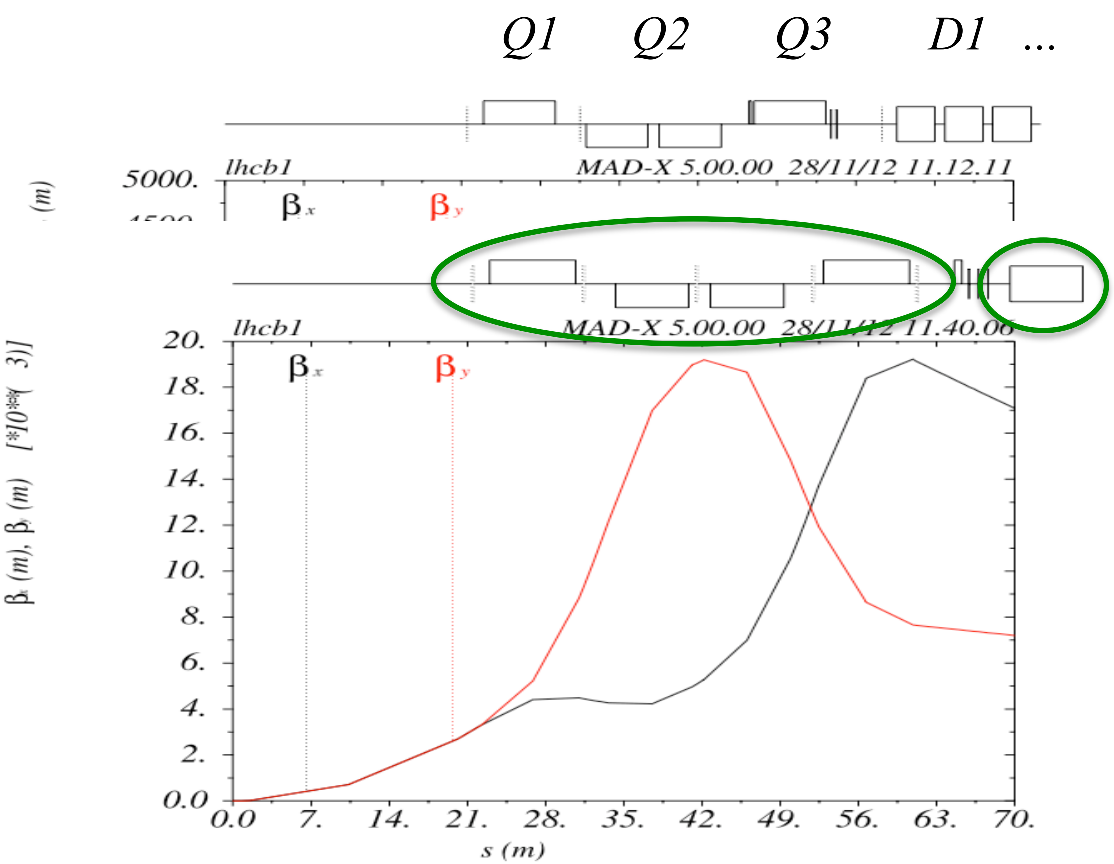
Upgrade Lattice: SLHC_V3.1b
150 T/m, 140mm

Lattice:



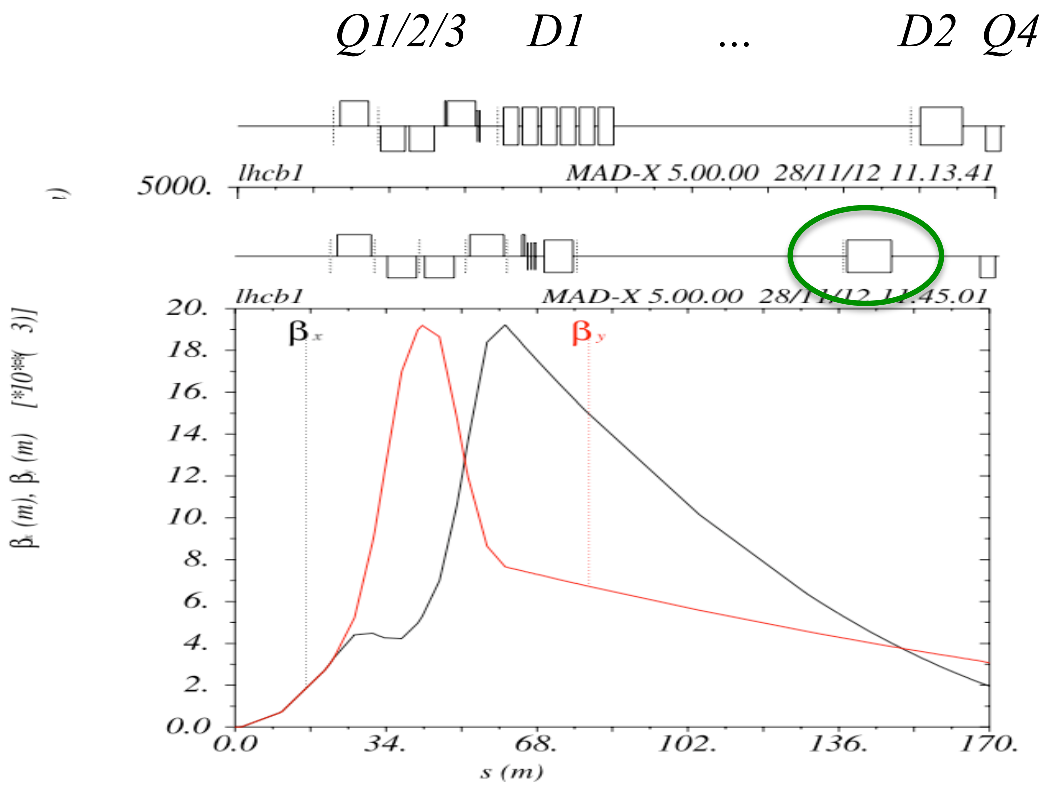
LHC Standard Lattice

SLHC Lattice V3.1b

longer triplet quadrupoles
D1 shifted away from IP
D1 sc and only 1 magnet

Upgrade Lattice: SLHC_V3.1b
150 T/m, 140mm

Lattice:



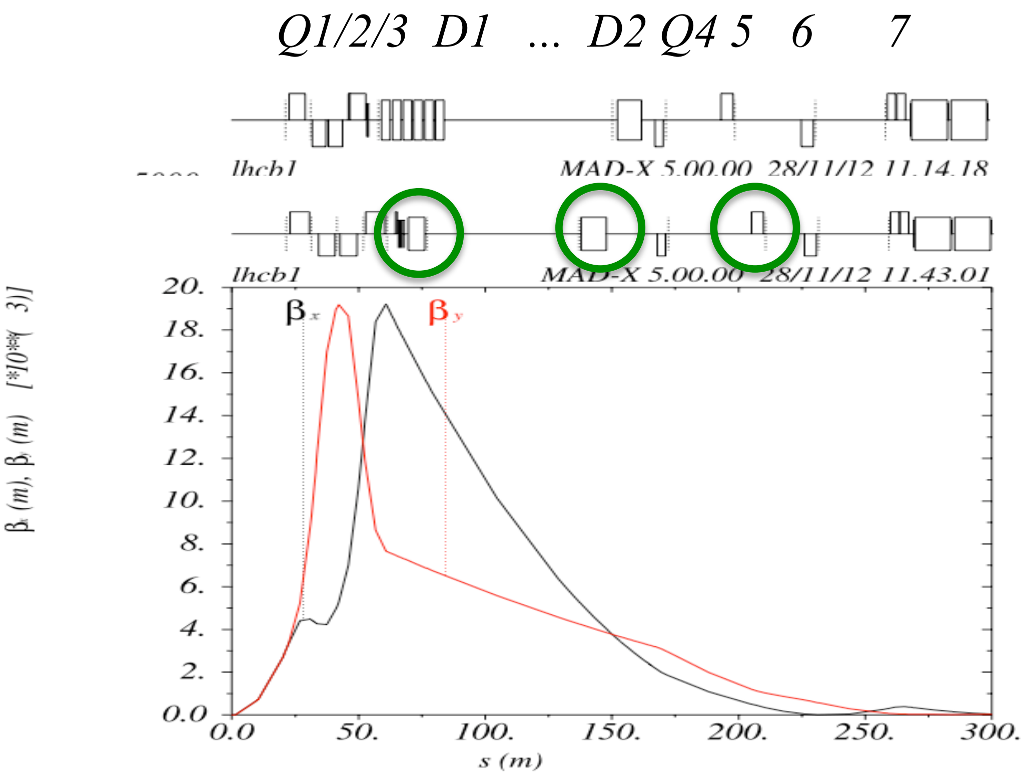
LHC Standard Lattice

SLHC Lattice V3.1b

longer triplet quadrupoles
D1 shifted away from IP
D1 sc and only 1 magnet
D2 shifted towards IP for
crab cavities Δs = -15m

Upgrade Lattice: SLHC_V3.1b
150 T/m, 140mm

Lattice:



LHC Standard Lattice

HL-LHC Lattice V3.1b

longer triplet quadrupoles
D1 shifted away from IP
D1 sc and only 1 magnet
D2 shifted towards IP for
crab cavities Δs = -15m

Q5 shifted away from IP
Δs = +11m

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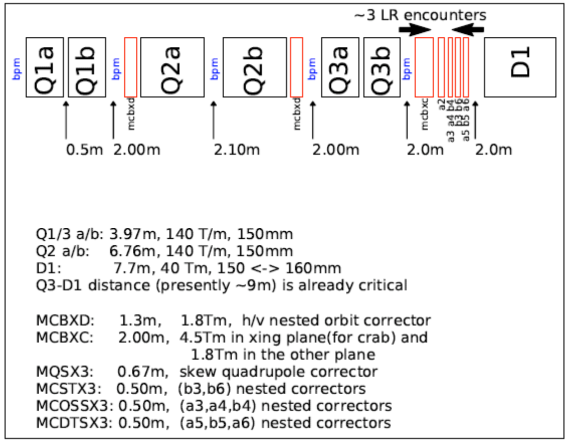
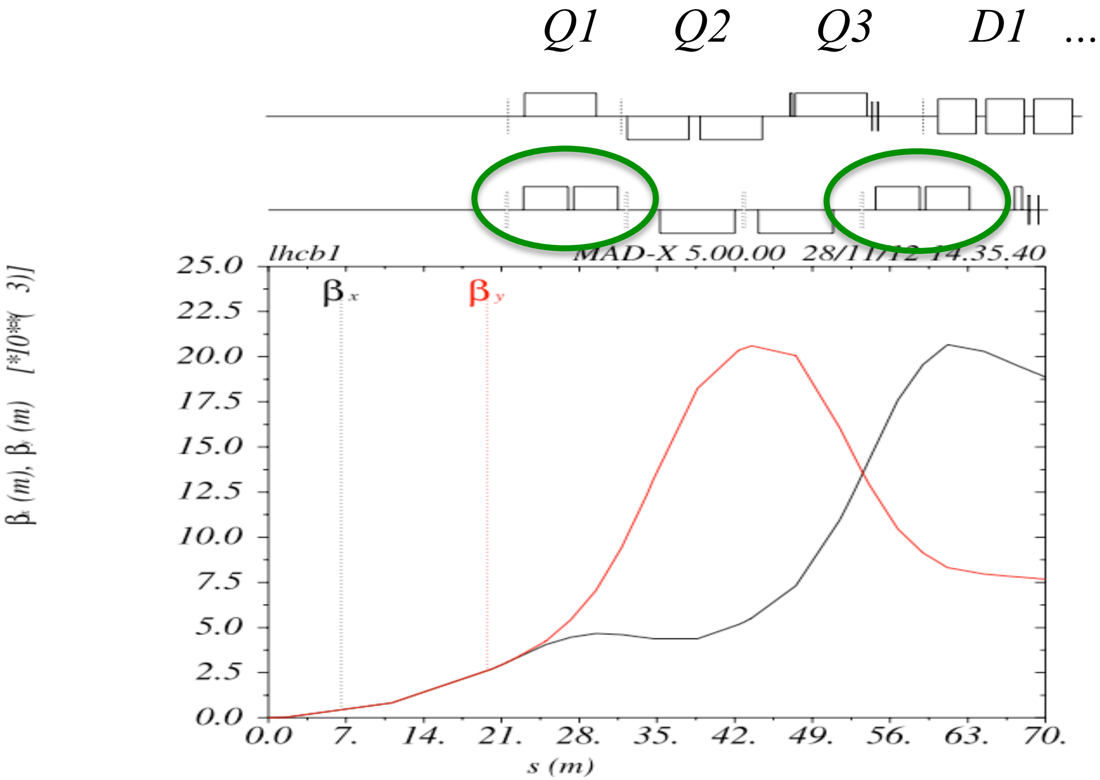
Upgrade Lattice: HL-LHC_V1.0
140 T/m, 150mm

Lattice:





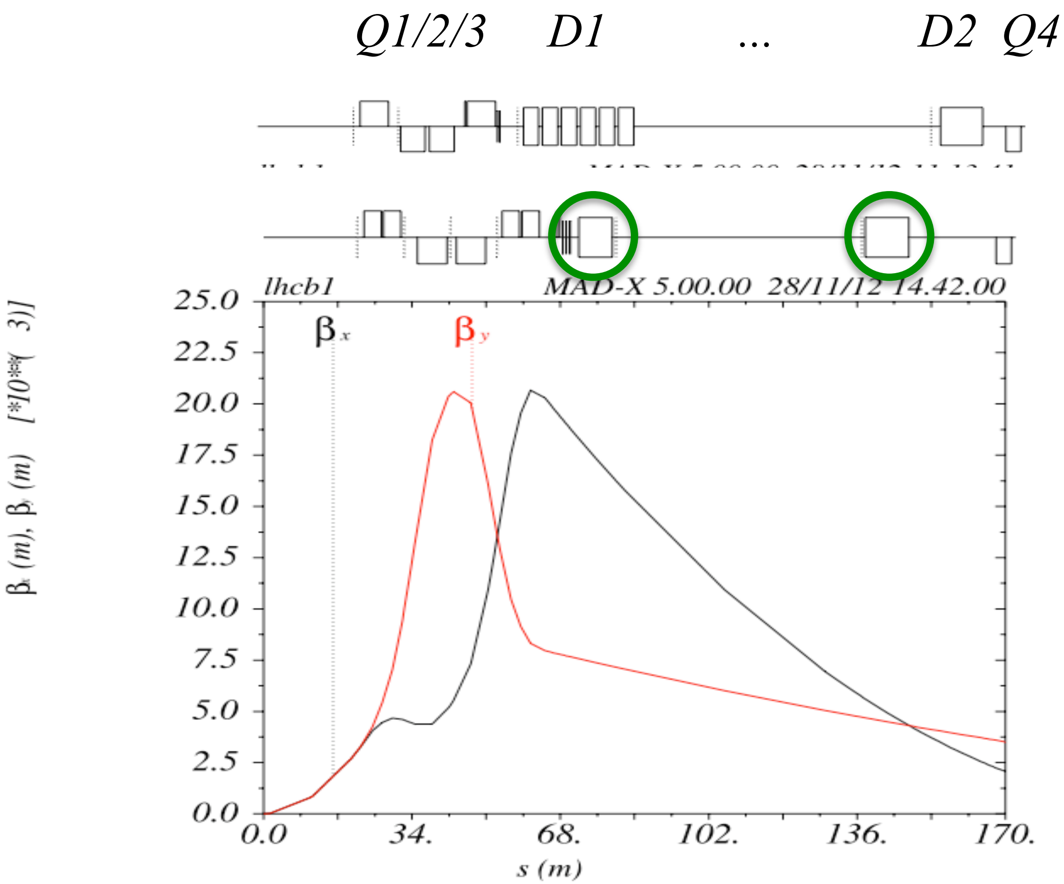
LHC Standard Lattice

HL-LHC Lattice V1.0

even longer triplet quadrupoles
Q1 and Q3 split in two magnets

Upgrade Lattice: HL-LHC_V1.0
140 T/m, 150mm

Lattice:



LHC Standard Lattice

LHC Lattice V1.0

longer triplet quadrupoles

Q1 and Q3 split in two magnets

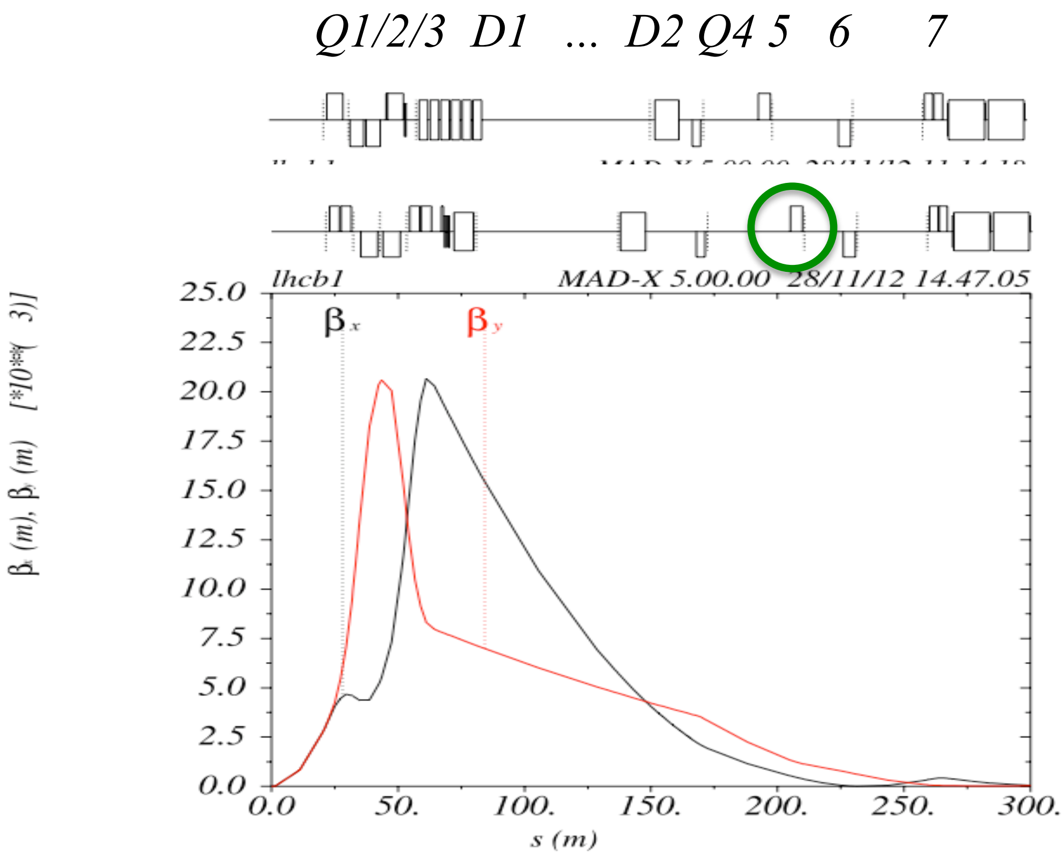
D1 shifted away from IP

D1 sc and only 1 magnet

D2 shifted towards IP for crab cavities $\Delta s = -15$m

Upgrade Lattice: HL-LHC_V1.0
140 T/m, 150mm

Lattice:



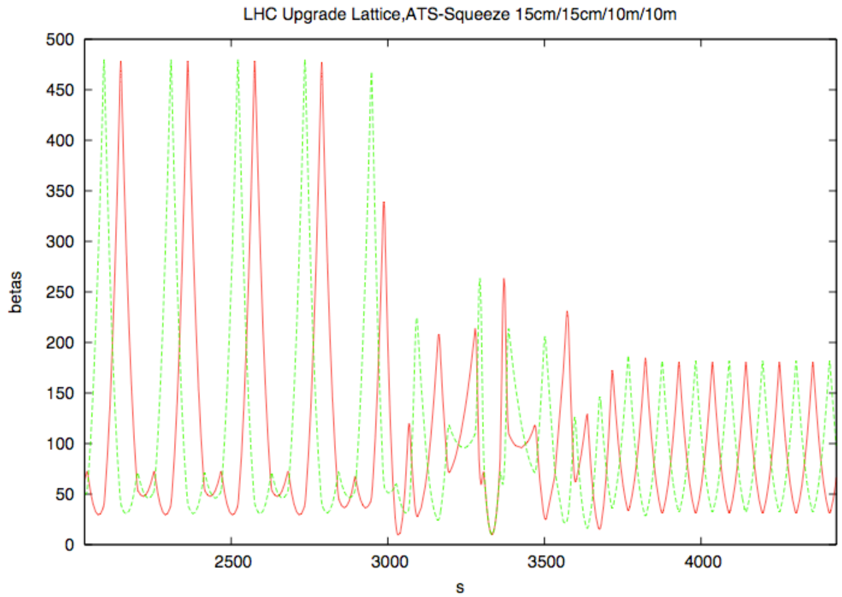
LHC Standard Lattice

HL-LHC Lattice V1.0

longer triplet quadrupoles
Q1 and Q3 split in two magnets
D1 shifted away from IP
D1 sc and only 1 magnet
D2 shifted towards IP for crab cavities Δs = -15m

Q5 shifted away from IP
Δs = +11m

HL-LHC Optics in IR2 / IR8



the "ATS Squeece Optics (15cm/15cm/10m/10m)

court. A. Bogomyagkov

IP1, ATS Optics ⟵ IP2 ⟶ IP3, Standard FoDo Optics

Serious Optics changes in the matching section ...
But no Lattice Changes foreseen so far.
Ceterum Censeo: β-leveling will be difficult

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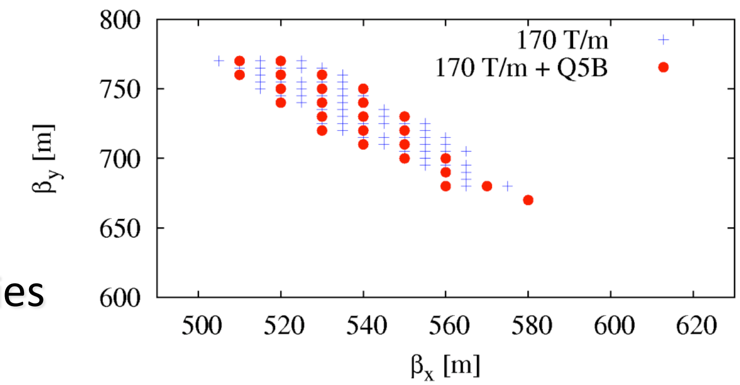
Lattice Optimisation for Crab Cavities

court. B. Dalena

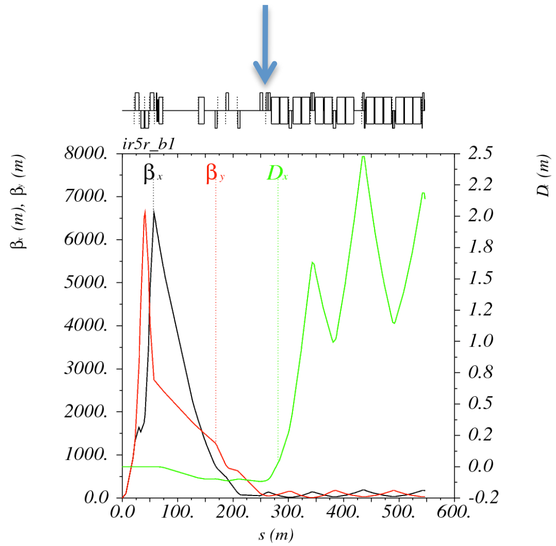
Study of additional quadrupoles at Q5 / Q6 / Q7 ...

add. Quad at Q5: no big change



Q4 / Q5 / Q6 in triplet configuration & add. Q7

... allows for much larger βs at the Crab Cavities

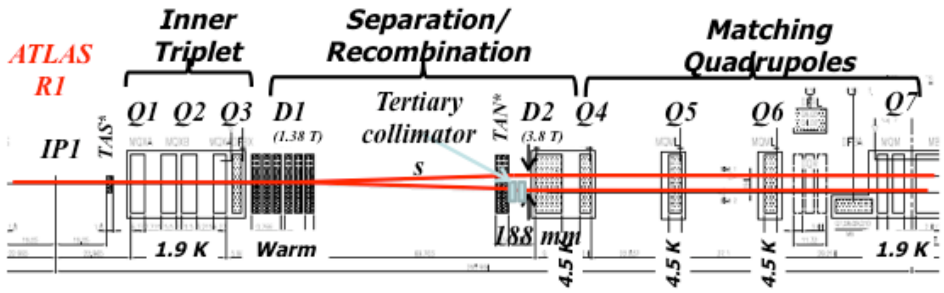


CRAB side and beam	HL-LHC baseline [MV]	Best optimization [MV]
Horizontal L5 Beam 1	11.8	8.0
Horizontal R5 Beam 1	13.4	8.2
Horizontal L5 Beam 2	13.4	8.2
Horizontal R5 Beam 2	11.8	8.0

HL-LHC Lattice, Loss Factor & Crab Cavities

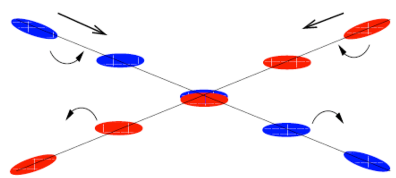
$$\mathcal{L} = \frac{N_1 N_2 f n_b}{2\pi\sqrt{\sigma_{1x}^2+\sigma_{2x}^2}\sqrt{\sigma_{1y}^2+\sigma_{2y}^2}} * F$$

$$F = \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\tan\frac{\phi}{2})^2}} \approx \frac{1}{\sqrt{1+(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2})^2}}$$



LHC Standard Lattice

"crab" crossing scheme



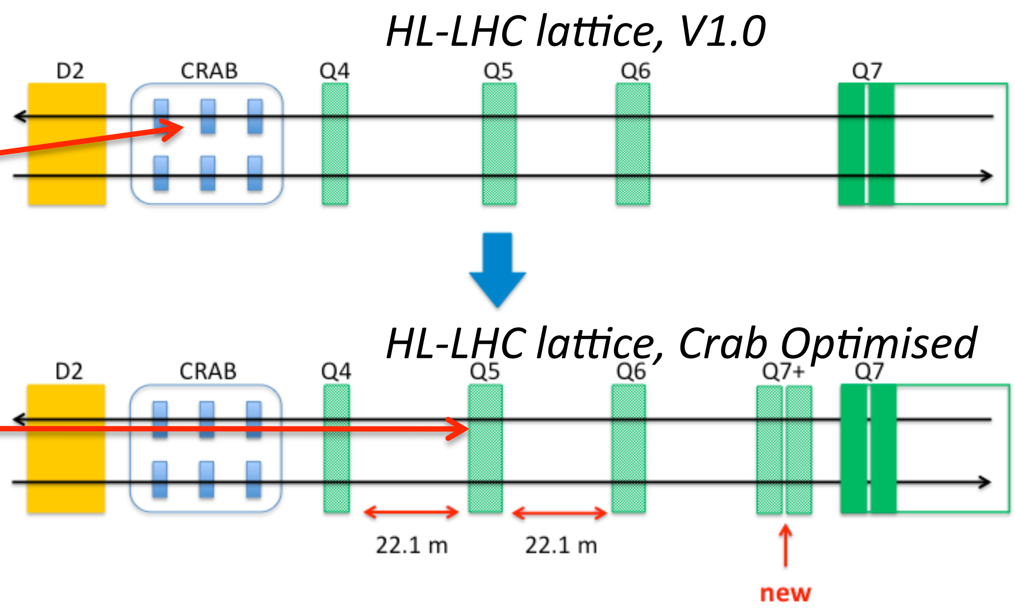
Provide Space for Crab Installation

-> *D2 shift*

-> *optimise lattice*

Q4,5,6 in "triplet configuration"

-> *optimise optics*



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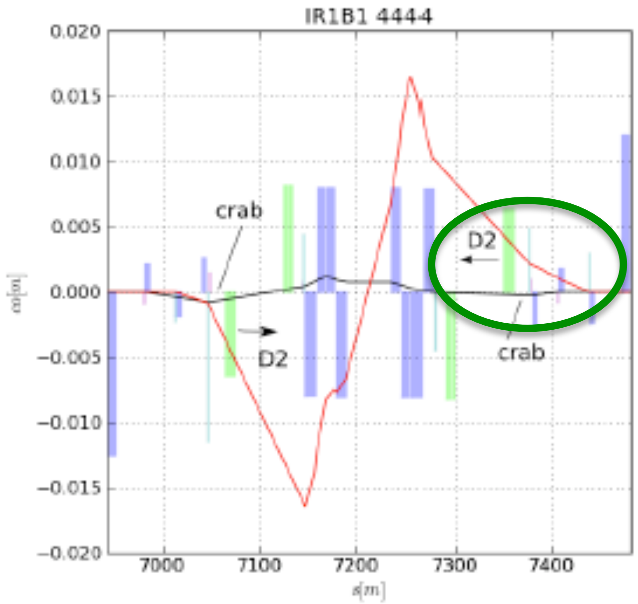
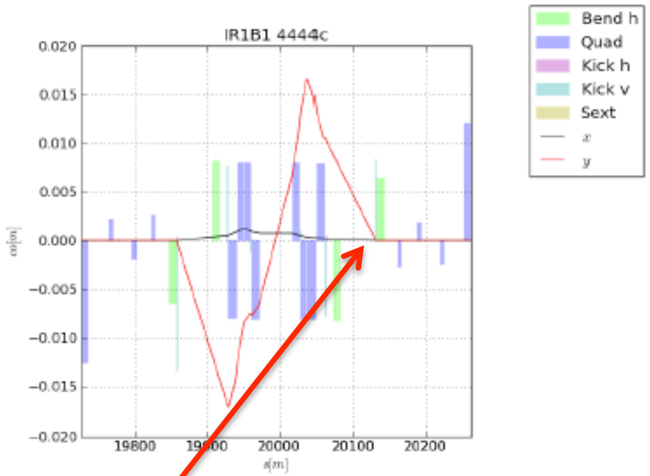
Lattice & Crab Cavities: Beam Orbit

court. R. DeMaria



Implication for layout

The best compromise between large beta function and beam separation is between D2 and Q4:



with new crossing scheme to avoid orbit excursions

Standard Bump for Crossing angle & beam separation closes at Q5 ... and leads to (varying) orbit offsets at the crab cavity location.

-> bump closure by strong dipole magnet at D2.

-> Alternative: transverse cavity positioning feedback following the beam orbits

Lattice & Crab Cavities: Beam Orbit

- ULANC developed time-domain model so study LLRF behaviour including noise propagation
- Power requirement/position alignment:

  Assuming $\Delta y = 0.2\ \sigma_y$ results in 250 µm. RF power to compensate for this: 16 kW.
- Simulation result: assuming instantaneo… amplitude reduces to small le… …phase change significant.

A. Dexter/ E. Jensen Frascati Workshop 2012

strong orbit corrector needed in front of D2

for crossing angle bump & separation bump

first estimates: $\int B dl = 6 Tm \quad / \quad 1 Tm$

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Lattice Modifications: Summary

Magnet	LHC	SLHC V3.1b	HL-LHC V1.0
triplet layout	standard machine	150T/m, 140mm	140T/m, 150mm
MQXA	22.2...26.2m		
MQXB	31.8...34.8m		
MQXB	38.3...41.3m		
MQXA	46.8...50.2m		
MBXW D1	59...83m, 6 magnets		
MBRC D2	152.1...157.9m		
MQY Q4	167.7...169.6m		
MQML Q5	194.0...196.5m		
MQML Q6	225.9...228.4m		
MQM Q7A	259.6...261.7		
MQM Q7B	263.6...265.5		

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Lattice Modifications: Summary

Magnet	*LHC*	*SLHC V3.1b*	*HL-LHC V1.0*
triplet layout	*standard machine*	*150T/m, 140mm*	*140T/m, 150mm*
MQXA	*22.2...26.2m*	*MQXC 22.2...26.8m*	
MQXB	*31.8...34.8m*	*MQXD 33.6...37.5m*	
MQXB	*38.3...41.3m*	*MQXD 42.2...46.0m*	
MQXA	*46.8...50.2m*	*MQXC 52.5...56.7m*	
MBXW D1	*59...83m, 6 magnets*	*MBXA 68.6...72.8m, 1 magnet*	
MBRC D2	*152.1...157.9m*	*MBRD 137.1...142.9m*	
MQY Q4	*167.7...169.6m*	*MQYY 167.7...169.6m*	
MQML Q5	*194.0...196.5m*	*MQYL 205.0...207.5m*	
MQML Q6	*225.9...228.4m*	*MQML 225.9...228.4m*	
MQM Q7A	*259.6...261.7*	*MQM 259.6...261.7*	
MQM Q7B	*263.6...265.5*	*MQM 263.6...265.5*	

Lattice Modifications: Summary

Magnet	*LHC*	*SLHC V3.1b*	*HL-LHC V1.0*
triplet layout	*standard machine*	*150T/m, 140mm*	*140T/m, 150mm*
MQXA	*22.2...26.2m*	*MQXC 22.2...26.8m*	*MQXC 1 22.2...25m* *MQXC 2 27.2...29.5m*
MQXB	*31.8...34.8m*	*MQXD 33.6...37.5m*	*MQXD 34.7...38.7m*
MQXB	*38.3...41.3m*	*MQXD 42.2...46.0m*	*MQXD 43.5...47.5m*
MQXA	*46.8...50.2m*	*MQXC 52.5...56.7m*	*MQXC 1 54.1...56.7m* *MQXC 2 58.9...61.2m*
MBXW D1	*59...83m, 6 magnets*	*MBXA 68.6...72.8m, 1 magnet*	*MBXA 71.2...76.0m, 1 magnet*
MBRC D2	*152.1...157.9m*	*MBRD 137.5...142.9m*	*MBRD 137.5...142.9m*
MQY Q4	*167.7...169.6m*	*MQYY 167.7...169.6m*	*MQYY 167.7...169.6m*
MQML Q5	*194.0...196.5m*	*MQYL 205.0...207.5m*	*MQYL 205.0...207.5m*
MQML Q6	*225.9...228.4m*	*MQML 225.9...228.4m*	*MQML 225.9...228.4m*
MQM Q7A	*259.6...261.7*	*MQM 259.6...261.7*	*MQM 259.6...261.7*
MQM Q7B	*263.6...265.5*	*MQM 263.6...265.5*	*MQM 263.6...265.5*

Lattice Modifications: Summary

And finally B. Dalena et al:
additional Quadrupole to support Q7

... crab cavitiy conditions

Magnet	*LHC*	*Crab Cavity Story*
triplet layout	*standard machine*	*170T/m, 120mm*
MQXA	*22.2...26.2m*	
MQXB	*31.8...34.8m*	
MQXB	*38.3...41.3m*	
MQXA	*46.8...50.2m*	
MBXW D1	*59...83m, 6 magnets*	
MBRC D2	*152.1...157.9m*	
MQY Q4	*167.7...169.6m*	*MQYY ≈ 167.9*
MQML Q5	*194.0...196.5m*	*MQYL ≈ 193.4m*
MQML Q6	*225.9...228.4m*	*MQML ≈ 220.3m*
		MQML7 ≈ 248.9...253.7m
MQM Q7A	*259.6...261.7*	*MQM ≈ 260*
MQM Q7B	*263.6...265.5*	*MQM ≈ 263.7*

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Reminder:

... all this is WORK IN PROGRESS

depending on the hardware available we will have to decide for one version and do the fine tuning / hardware follow up