Budget for HL-LHC Orbit Correctors

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Acknowledgments: S. Fartoukh, M. Giovannozzi, R. De Maria

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Outline

1. Orbit correctors in IR1/5
2. Optics parameters and standard crossing scheme
3. (Contributions to) orbit corrector budget:
   a. x-scheme and orbit offset at IP
   b. triplet misalignment and transfer function errors
   c. beam based alignment in crab cavities (if no active alignment) -> intermediate summary
   d. possible optimisations
4. Summary

1. **Orbit correctors in IR1/5**
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3. (Contributions to) orbit corrector budget:
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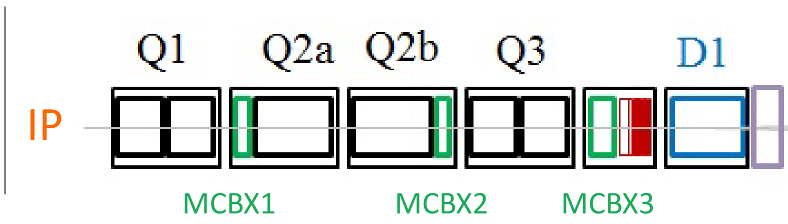
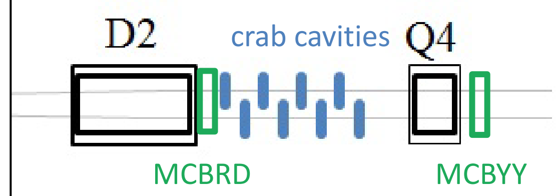
4. Summary and Conclusion

Orbit correctors in IR1/5

HLLHCV1.0: Triplet (MCBX) and D2 (MCBRD): H and V corr.

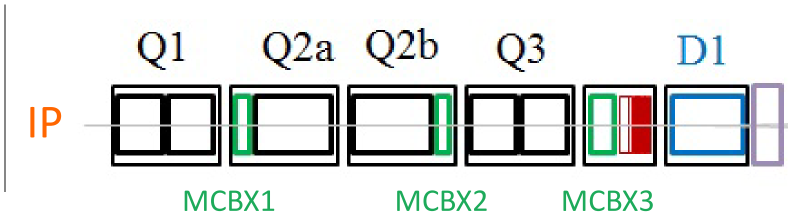


MCBX:	2.1 T
MCBRD:	3.0 T
MCBX1/2[HV]:	2.5 Tm
MCBX3[HV]:	4.5 Tm
MCBRD[HV]:	7.0 Tm

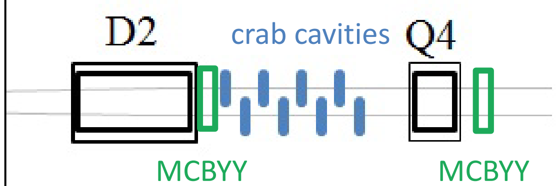


HLLHCV2.0: Triplet (MCBX) unchanged and same corrector for D2 and Q4 (MCBYY):

H and V corr.

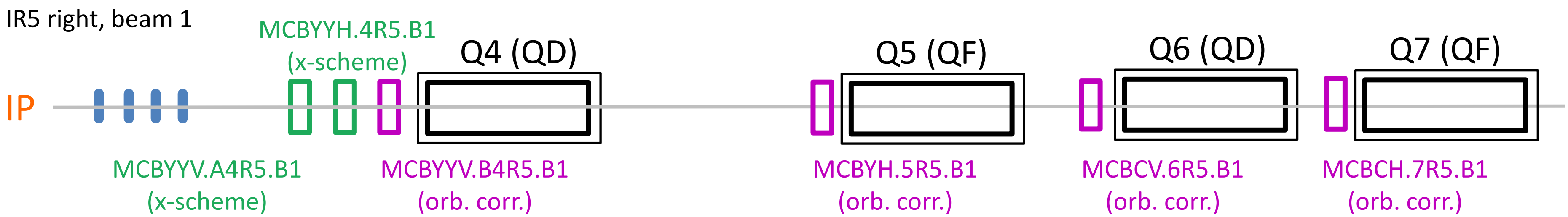


MCBX:	2.1 T
MCBYY:	3.0 T
MCBX1/2[HV]:	2.5 Tm
MCBX3[HV]:	4.5 Tm
MCBYY[HV]:	3.8 Tm



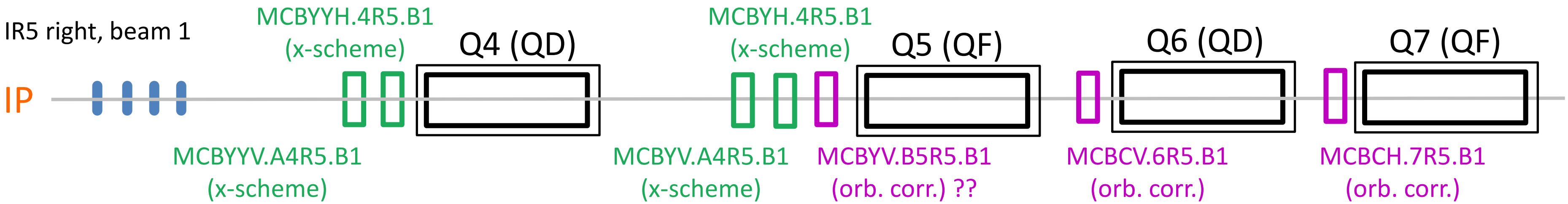
Orbit correctors in IR1/5

HLLHCV1.0: Q4 (MCBYY): H and V corr. for x-scheme, one H/V corr. for orbit corr.
Q5 (MCBY), Q6 (MCBC), Q7 (MCBC): one H/V corr. for orbit corr.



MCBYY: 2.5 T
MCBYY[HV]: 2.25 Tm

new layout HLLHCV2.0: same corr. for D2 and Q4,
reuse Q4 (MQY) of nominal LHC as Q5 of HL-LHC



MCBYY: 3.0 T
MCBYY[HV]: 3.8 Tm

MCBY: 2.5 T
MCBY[HV]: 2.25 Tm

MCBC: 2.33 T
MCBCH: 2.097 Tm (length = 0.9 m)
MCBCV: 2.106 Tm (length = 0.904 m)

1. Orbit correctors in IR1/5
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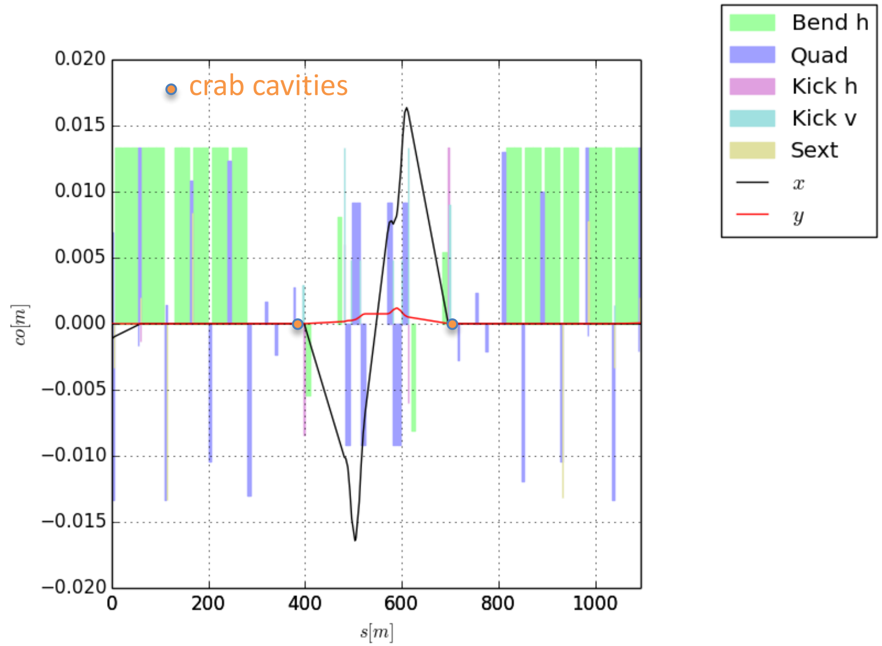
Optics parameters and standard crossing scheme

optics 7 TeV	$\beta_{x/y}$* [m]	half x-angle [µrad]	half separation [mm]	offset IP [mm]
opt round	0.15/0.15	+/-295	+/-0.75	+0.5
opt sround	0.10/0.10	+/-360		
opt injection	6.0/6.0	+/-295	+/-2.0	

Standard crossing scheme:

- IR1/5 fully symmetric except alternating crossing in IR1 and IR5
  -> IR1: hor. separation, vert. crossing
  IR5: vert. separation, hor. crossing
- MCBX[123] and MCBRD used for crossing scheme in order to close the orbit bump before crab cavities
  (in nominal LHC: no MCBRD -> crossing scheme is (mainly) matched using orbit correctors at Q4/Q5/Q6 and MCBX)



opt round: IR5 beam 1

1. Orbit correctors in IR1/5
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    a. **x-scheme and orbit offset at IP**
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X-scheme and Orbit Offset at IP

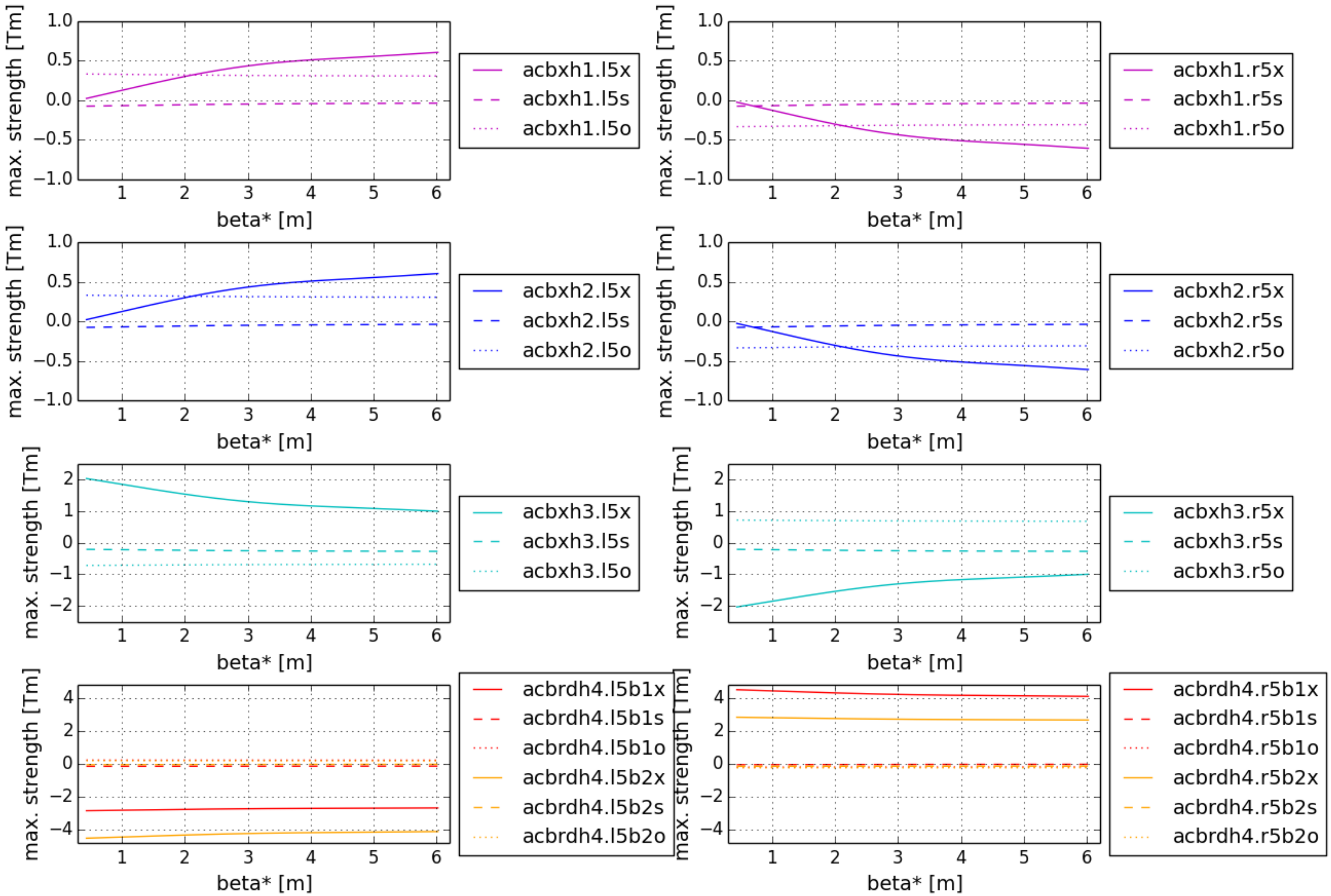
X-scheme matching and offset at IP:
use MCBX[123] and MCBRD, matching condition acbx2*:=acbx1*
note: acbx1+acbx2≈const -> total strength shared between MCBX1 and MCBX2

Corrector budget collision and injection including:
a. x-scheme + offset

	plane	MCBX[12] [Tm]			MCBX3 [Tm]			MCBRD [Tm]		
		round	sround	inj	round	sround	inj	round	sround	inj
x-scheme	x-ing	0.03	0.04	0.61	2.03	2.48	1.00	4.51	5.50	4.11
offset		0.33		0.31	0.72		0.68	0.23		0.23
x-scheme	sep.	0.08		0.10	0.21		0.72	0.14		0.35
offset		0.33		0.31	0.71		0.68	0.23		0.22
offset+x-scheme	**x-ing**	**0.36**	**0.37**	**0.92**	**2.75**	**3.20**	**1.68**	**4.74**	**5.73**	**4.29**
	sep.	**0.41**		**0.41**	**0.92**		**1.40**	**0.37**		**0.57**

X-scheme and Orbit Offset at IP

Individual orbit corrector strength during the pre-squeeze (IR5, x-plane = horizontal)
x-ing=+/-295 µrad, sep. =+/-0.75 mm, offset=+0.5 mm



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1. Orbit correctors in IR1/5
2. **(Contributions to) orbit corrector budget:**
   a. x-scheme and orbit offset at IP
   b. **triplet misalignment and transfer function errors**
   c. beam based alignment in crab cavities (if no active alignment) -> intermediate summary
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3. Summary and Conclusion

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Triplet Misalignment and Transfer function errors

Triplet alignment approx. once per year -> need for misalignment correction in between alignments

assume **uniformly** distributed **misalignment** and **transfer function** errors for all **triplet magnets:**

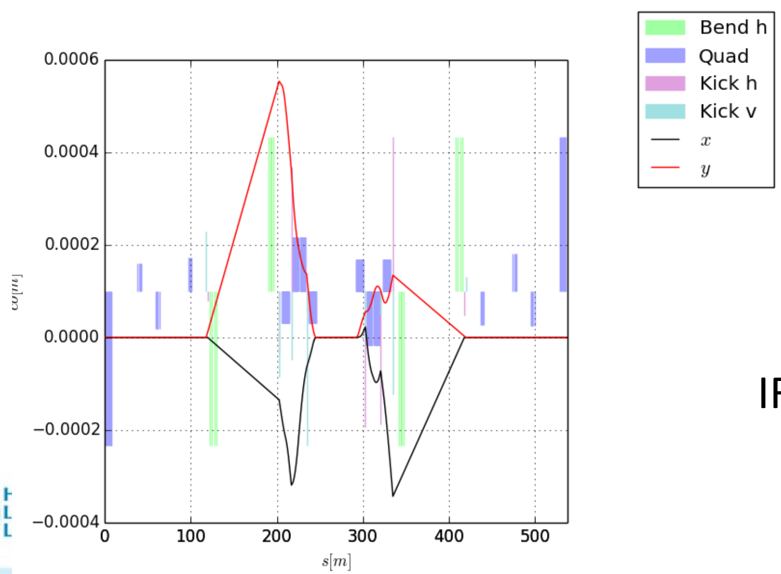
1. +/-0.5 mm transverse misalignment error (might be on the conservative side)
2. +/-10.0 mm longitudinal misalignment error
3. +/-2x10^{-3} relative quadrupole error

and simulate 10 000 seeds.

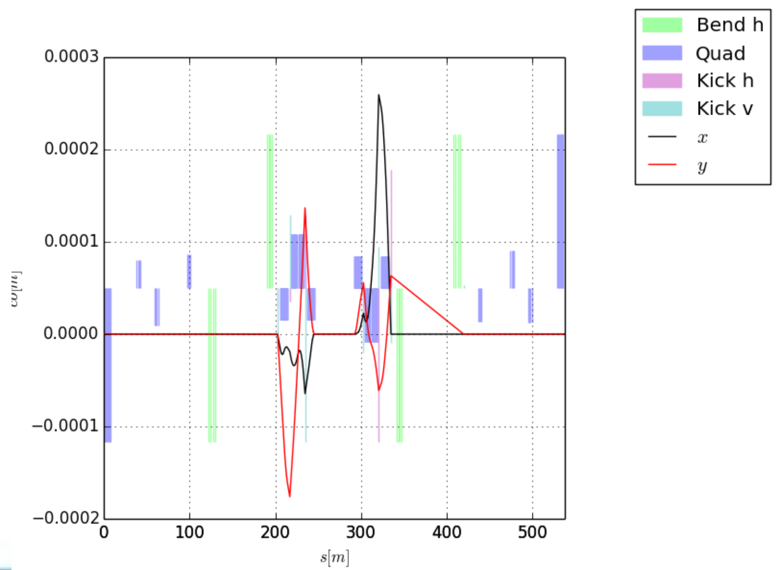
Two correction strategies:

a) limit MCBX and in particular MCBRD corrector strength -> optimization of corr. strength
b) use only 2 (out of 4) MCBRD correctors -> optimization of orbit in triplet

a)



b)



IR5, beam 1

Triplet Misalignment and Transfer function errors

Maximum and rms corrector strength including long.+transv. misalignment and transfer function errors:

optics	corr. strategy	corrector strength (max|max(rms)) [Tm]								x_{co}-x_{cross}-x_{mis} [mm]	
		MCBX1		MCBX2		MCBX3		MCBRD		max	max(rms)
opt round (thin lens)	a) corr. strength	1.0	0.3	0.8	0.3	3.1	2.1	4.9	4.5	2.2	0.35
	b) 2 MCBRDs	1.4	0.5	2.6	0.7	3.5	2.1	4.5	4.5	1.0	0.30
opt injection (+/- 2.0 mm sep.)	a) corr. strength	1.5	0.7	1.4	0.7	2.1	1.0	4.5	4.1	2.0	0.34
	b) 2 MCBRDs	1.9	0.8	3.2	0.9	2.4	1.1	4.1	4.1	1.0	0.30

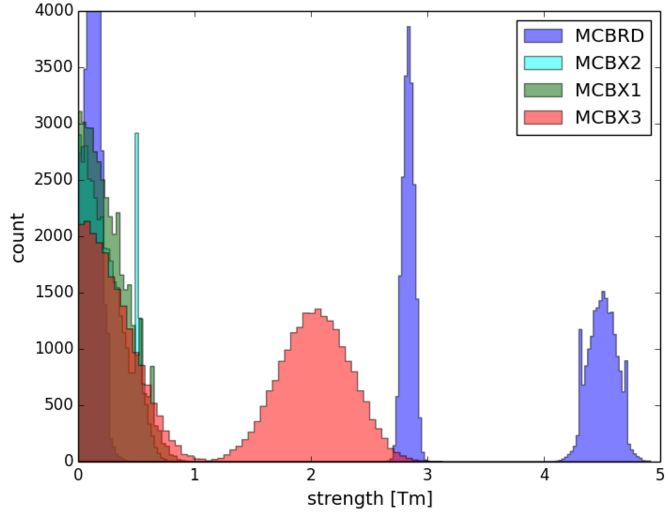
Main conclusions:

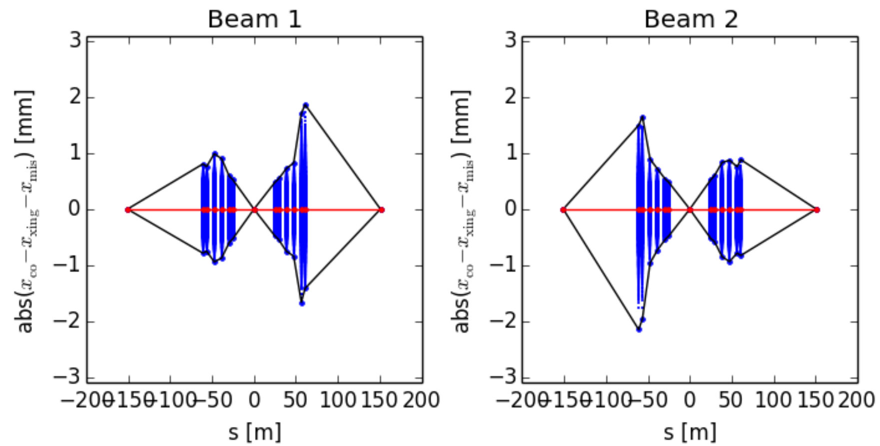
1) small effect of transfer function errors and longitudinal misalignment compared to transverse misalignment (see backup slides)
2) large MCBX2 corrector strength needed for correction scheme b) which uses only 2 MCBRDs, but distribution has long tails (<1% of cases exhibit a MCBX2 strength > 2.5 Tm)
3) reasonable corrector strength in the case of correction scheme a) which uses all 4 MCBRDs at the cost of 2.0 mm (max.) loss in aperture in the IT compared to only 1.0 mm (max.) for correction scheme b)
4) approx. linear correlation between MCBRD strength and max. orbit in triplet (see backup slides)
5) no significant improvement if position of IP is varied (x_{b1}-x_{b2}=sep., $p_{x,b1}$-$p_{x,b2}$=x-angle)

Triplet Misalignment and Transfer function errors

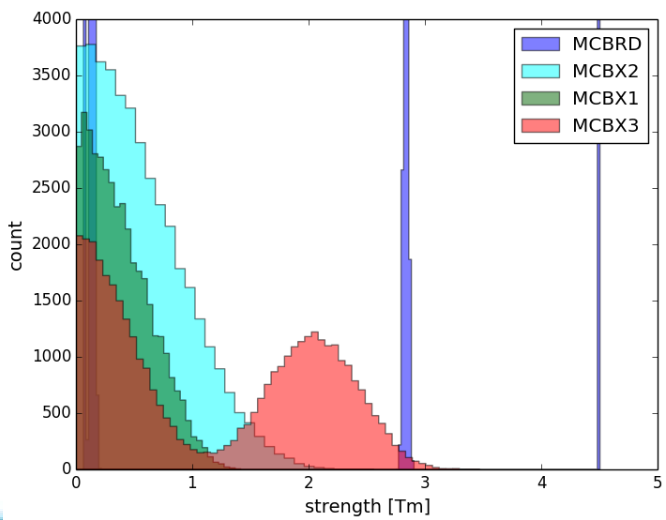
opt round (thin lens): transv.+long. misalignment and transfer function error

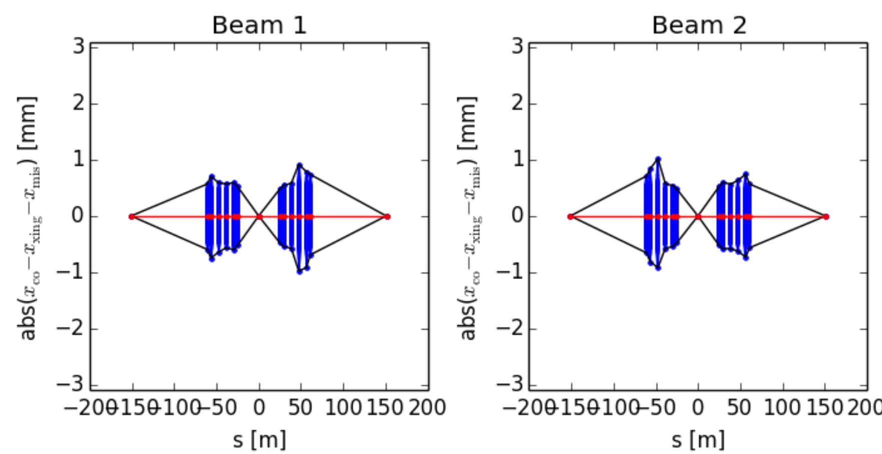
a) limit corr. strength





b) use only 2 (out of 4) MCBRD





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Triplet Misalignment and Transfer function errors

Corrector budget collision and injection including:

a. x-scheme + offset
b. transv.+long. misalignment and transfer function errors using correction scheme a) (optimize corr. strength)

	plane	MCBX1 [Tm]		MCBX2 [Tm]		MCBX3 [Tm]		MCBRD [Tm]	
		round	inj	round	inj	round	inj	round	inj
x-scheme*	x-ing	0.03	0.61	0.03	0.61	2.03	1.00	4.51	4.11
offset		0.33	0.31	0.33	0.31	0.72	0.68	0.23	0.23
x-scheme+errors**		0.96	1.52	0.82	1.41	3.13	2.05	4.92	4.51
x-scheme	sep.	0.08	0.10	0.08	0.10	0.21	0.72	0.14	0.35
offset		0.33	0.31	0.33	0.31	0.71	0.68	0.23	0.22
x-scheme+errors**		0.98	0.92	0.75	0.84	1.19	1.66	0.45	0.49
offset+x-scheme+errors	**x-ing**	**1.29**	**1.83**	**1.15**	**1.72**	**3.85**	**2.73**	**5.15**	**4.74**
	sep.	**1.31**	**1.23**	**1.08**	**1.15**	**1.9**	**2.34**	**0.68**	**0.71**

* for opt sround one has to mainly add additional 0.4 Tm for MCBX3 and 1.0 Tm for MCBRD in the x-ing plane
** maximum corrector strength over 10 000 – note: up to 2.0 mm orbit in triplet in respect to the center of the aperture for opt round

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1. Orbit correctors in IR1/5
2. **(Contributions to) orbit corrector budget:**
    a. x-scheme and orbit offset at IP
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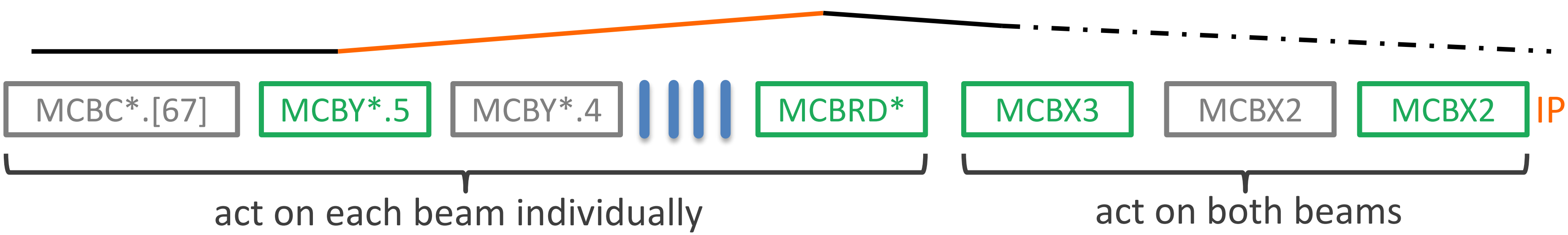
Beam Based Alignment in Crab Cavities

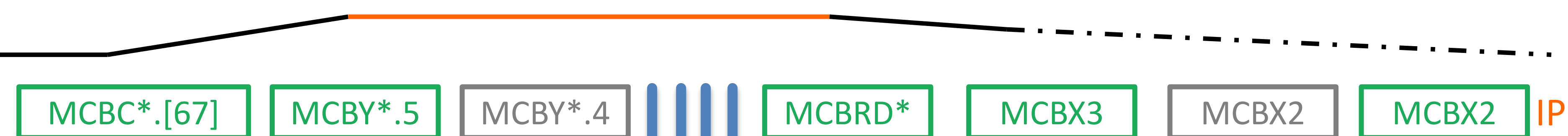
create knob for orbit (reference value = 1.0 mm) in crab cavities:

1) x_{b1}(crab)= x_{b2}(crab)
2) x_{b1}(crab)=-x_{b2}(crab)

Option 1: use only orb. corr. at Q5 + MCBRD + different combinations of 2 MCBX (see backup slide) -> larger corr. strength (see backup slides) and $p_{x/y} \neq 0$ in crab cavities



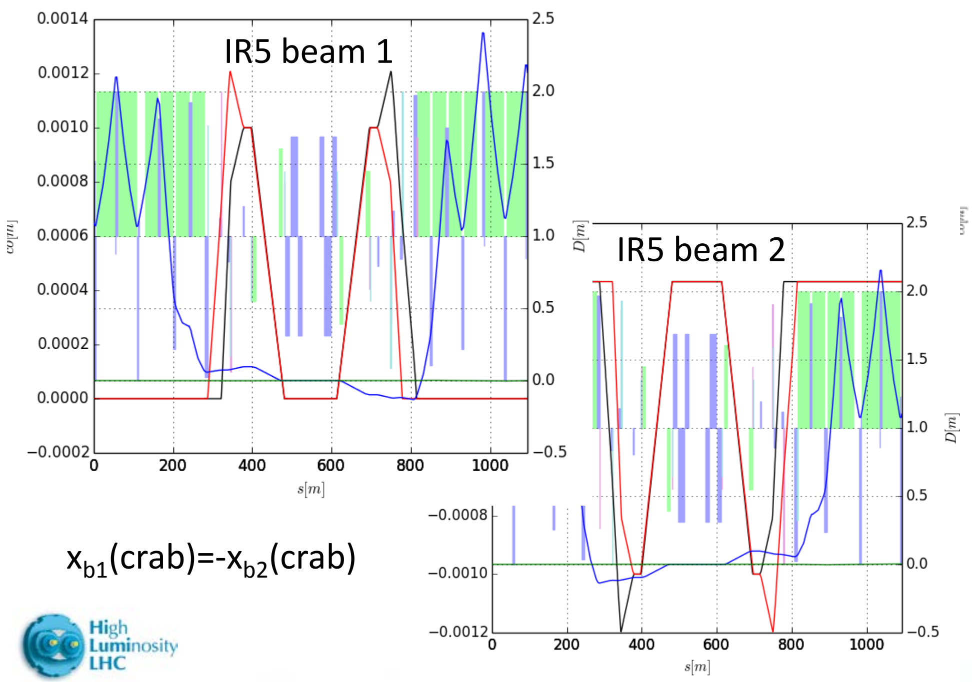
Option 2: use Q7/Q6 and Q4/Q5 orb. corr. + MCBRD + different combinations of 2 MCBX (see backup slide) -> preferred option as smaller corr. strength, $p_{x/y}=0$ in crab cavities and slope could be controlled by using in addition orb. corr. at Q4 (here orb. corr. at Q5 are used instead of Q4 as Q4 orb. corr. could be beneficial to reduce strength of MCBRD corr.)



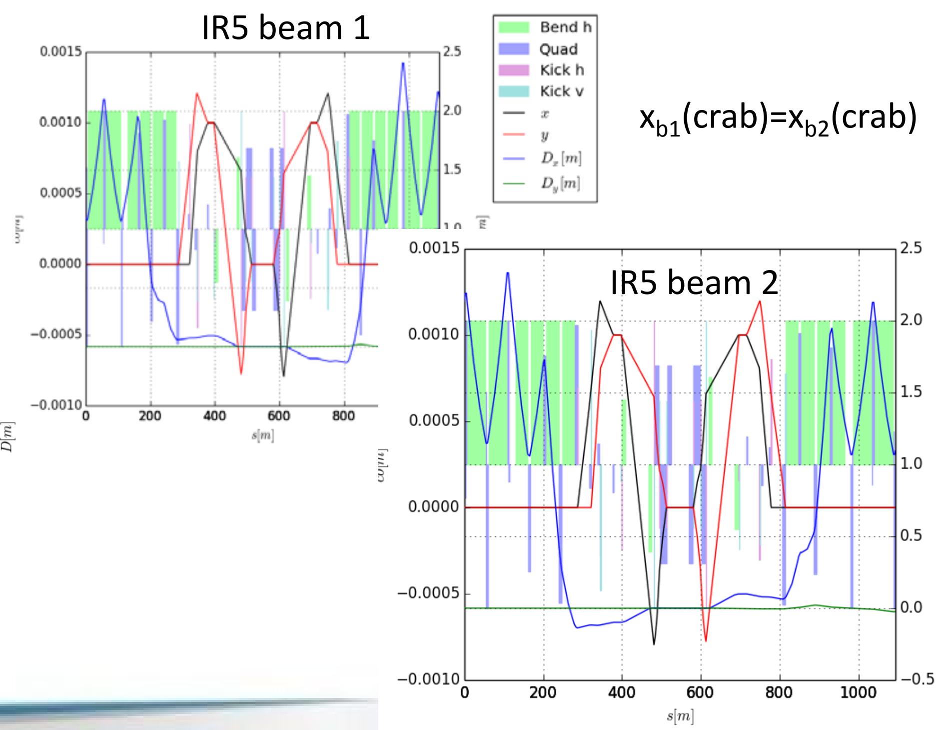
Beam Based Alignment in Crab Cavities

Option 2: use Q7/Q6 and Q5 orb. corr. + MCBRD + MCBX[123] with MCBX1=MCBX2

knob	plane	corrector strength [Tm]							
		MCBX1	MCBX2	MCBX3	MCBRD	MCBY4	MCBY5	MCBC6	MCBC7
x(b1)=x(b2) =1.0 mm	x-ing	0.38	0.38	0.85	0.51	0.00	0.72	0.76	0.52
	sep.	0.37	0.37	0.83	0.49			0.78	
x(b1)=-x(b2) =1.0 mm	x-ing	0.00	0.00	0.28	0.28	0.00	0.72	0.76	0.52
	sep.	0.00	0.00	0.28	0.28			0.78	



$x_{b1}(crab)=-x_{b2}(crab)$



$x_{b1}(crab)=x_{b2}(crab)$

Intermediate Summary

Corrector budget collision and injection including:

a. x-scheme + offset
b. transv.+long. misalignment and transfer function errors using correction scheme b) (optimize corr. strength)
c. beam based alignment in crab cavities

	plane	MCBX1 [Tm]		MCBX2 [Tm]		MCBX3 [Tm]		MCBRD [Tm]	
		round	inj	round	inj	round	inj	round	inj
x-scheme*	x-ing	0.03	0.61	0.03	0.61	2.03	1.00	4.51	4.11
offset		0.33	0.31	0.33	0.31	0.72	0.68	0.23	0.23
x-scheme+errors**		0.96	1.52	0.82	1.41	3.13	2.05	4.92	4.51
bb align. crab***		0.38	-	0.38	-	0.85	-	0.51	-
x-scheme	sep.	0.08	0.10	0.08	0.10	0.21	0.72	0.14	0.35
offset		0.33	0.31	0.33	0.31	0.71	0.68	0.23	0.22
x-scheme+errors**		0.98	0.92	0.75	0.84	1.19	1.66	0.45	0.49
bb align. crab		0.37	-	0.37	-	0.83	-	0.49	-
offset+x-scheme+errors+bb-align crab	**x-ing**	**1.67**	**1.83**	**1.53**	**1.72**	**4.70**	**2.73**	**5.66**	**4.74**
	sep.	**1.68**	**1.23**	**1.45**	**1.15**	**2.73**	**2.34**	**1.17**	**0.71**

* for opt sround one has to add additional 0.4 Tm for MCBX3 and 1.0 Tm for MCBRD in the x-ing plane

** maximum corrector strength over 10 000 and 2.0 mm separation for opt inj – note: up to 2.0 mm orbit in triplet in respect to the center of the aperture for opt round

*** max. corr. strength for option 2 using MCBX[123] and MCBX1=MCBX2

1. Orbit correctors in IR1/5
2. (Contributions to) orbit corrector budget:
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   b. triplet misalignment and transfer function errors
   c. beam based alignment in crab cavities (if no active alignment) -> intermediate summary
   d. **possible optimisations**
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Possible optimisations

1) **IP offset knob:** useful for MCBX optimisation
   -> Reduction of MCBX1/2 at the cost of an increase of the MCBX3 strength and vice versa
   -> sum(MCBX1 + MCBX2) is (approx.) independent of the matching strategy
   (no mcbx1, no mcbx2, mcbx2*=mcbx1*)

   Questions:

   - Does an optimisation of the orb. corr. strength also optimize the aperture in the IT?

2) **Orbit in crab cavities:** useful for MCBRD optimisation
   -> strength can be shared between orb. corr. at Q4 and MCBRD

   Questions:

   - Tolerable orbit in the crab cavities? (at the moment: max. 0.5 mm)
   - Aperture loss in D2? (still to be checked)

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Possible optimizations

1) IP offset knob – MCBX optimisation:

at injection: optimise MCBX1/2 strength -> assume -0.5 mm offset

at collision: optimise MCBX3 strength -> assume +0.5 mm offset

	plane	MCBX1 [Tm]			MCBX2 [Tm]			MCBX3 [Tm]		
		round	sround	inj	round	sround	inj	round	sround	inj
offset	x-ing	+0.33		-0.31	+0.33		-0.31	-0.72		+0.68
x-scheme+errors*		0.96	0.97	1.52	0.82	0.83	1.41	3.13	3.58	2.05
bb align. crab		0.38		-	0.38		-	0.85		-
offset	sep.	+0.33		-0.31	+0.33		-0.31	-0.71		+0.68
x-scheme+errors		0.98		0.92	0.75		0.84	1.19		1.66
bb align. crab		0.37		-	0.37		-	0.83		-
offset+x-scheme+ errors+bb-align crab	**x-ing**	**1.67**	**1.68**	**1.21**	**1.53**	**1.54**	**1.10**	**3.26**	**3.71**	**2.73**
	sep.	**1.68**		**0.61**	**1.45**		**0.53**	**1.31**		**2.34**

*corr. strength(sround)=corr. strength(round) + additional corr. strength for x-angle of +/-360 µrad

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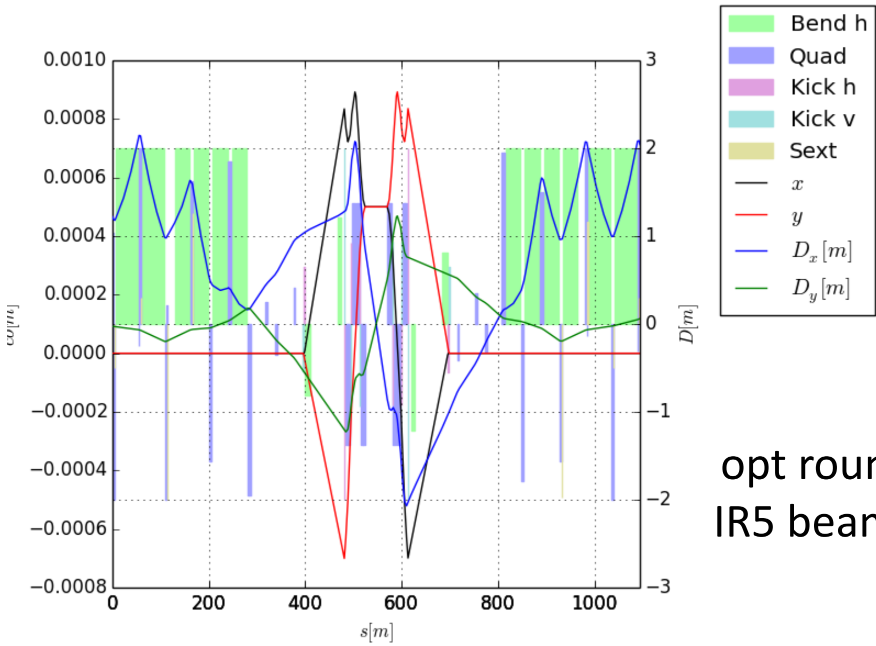
Possible optimizations

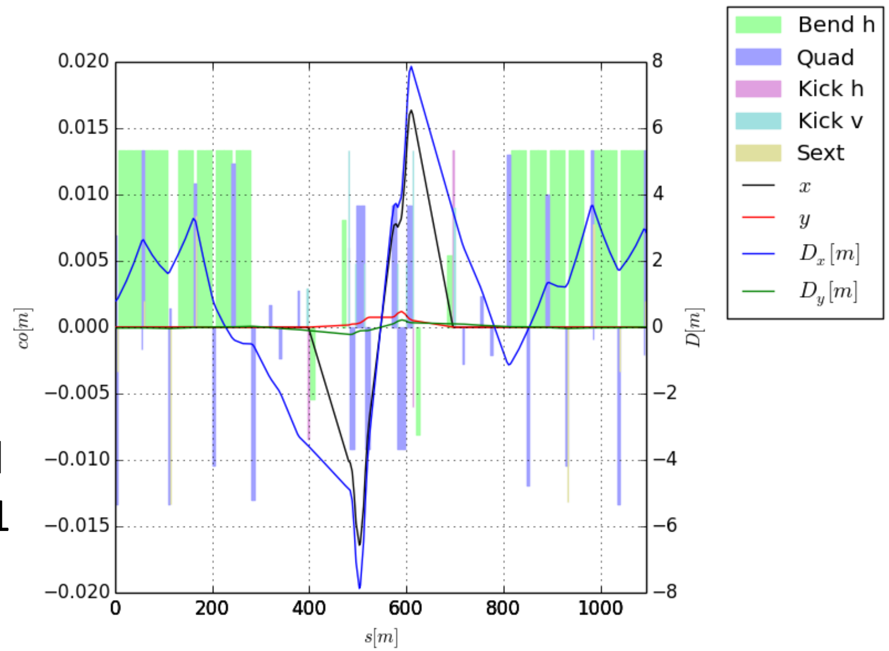
1) IP offset knob - Aperture optimization:

-> + offset of the IP reduces orbit in the IT in the x-plane

-> no beneficial effect for the separation plane



opt round
IR5 beam1



➡ at collision: + offset reduces MCBX3 strength (as wanted) and optimises the aperture in the x-plane (orbit reduction by 0.5-0.8 mm for +0.5 mm offset)

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Possible optimisations

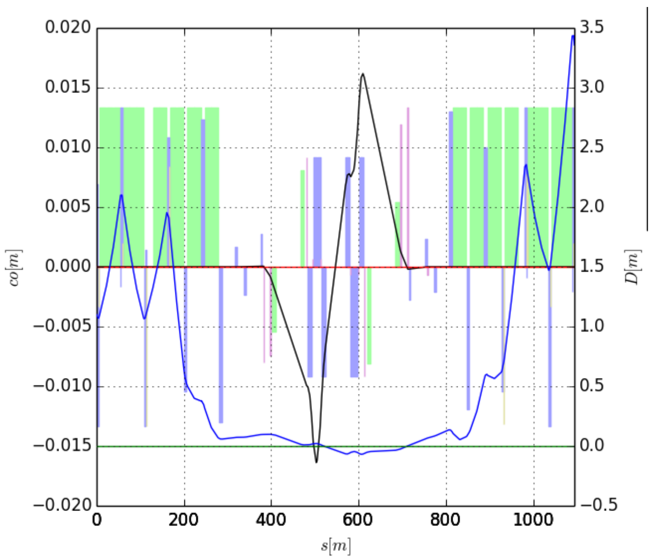
2) Orbit in crab cavities – reduction of MCBRD strength:

Idea: share strength between orb. corr. at Q4 and MCBRD

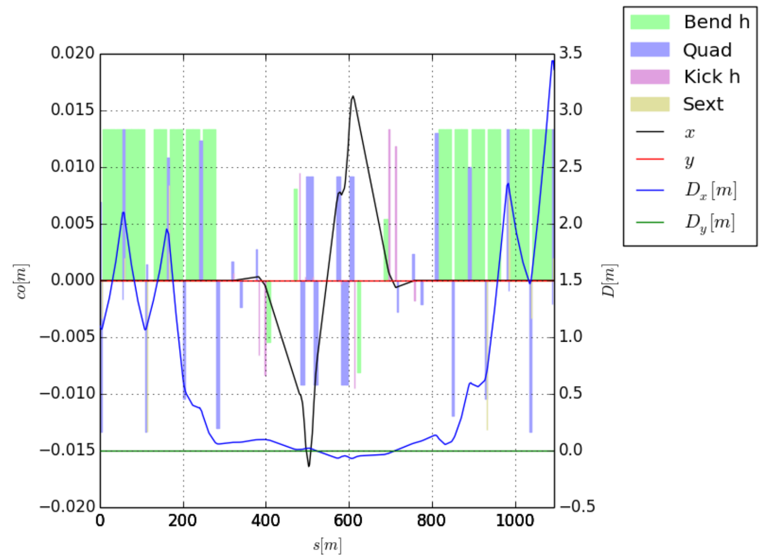
-> Two limitations:

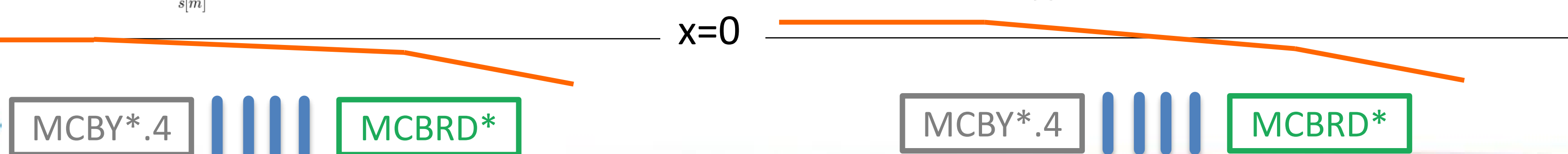
1. orbit in crab cavities (reference <0.5 mm)
2. max. strength of orbit corrector in Q4

x(Q4)=0 optimizes **corr. strength** in Q4



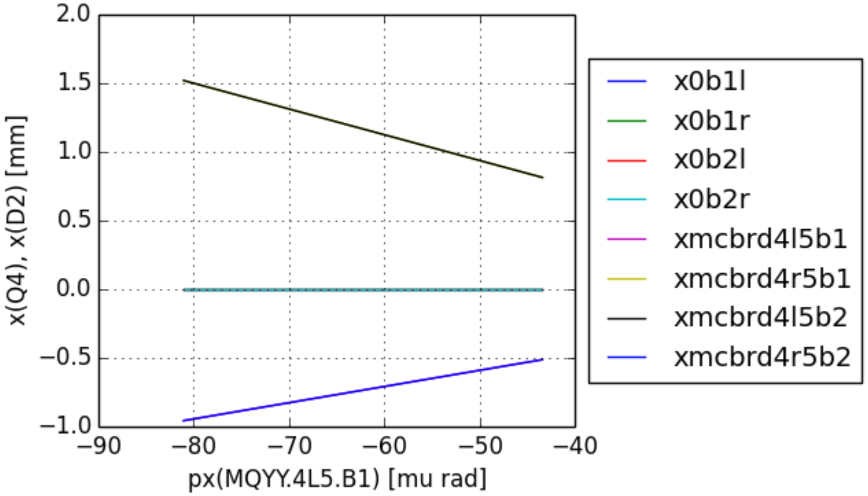
x(Q4)=-x(D2) optimizes **orbit in crab cavities**





X-Scheme Optimisation

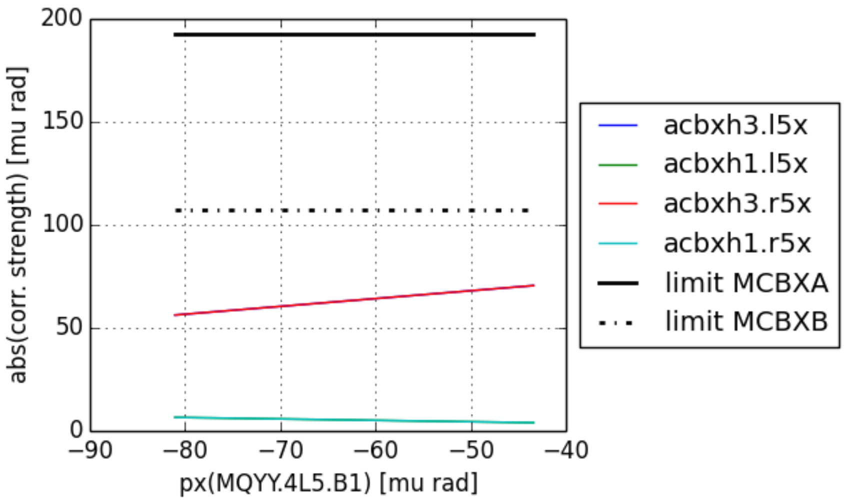
2) Orbit in crab cavities – matching strategy x(Q4)=0:

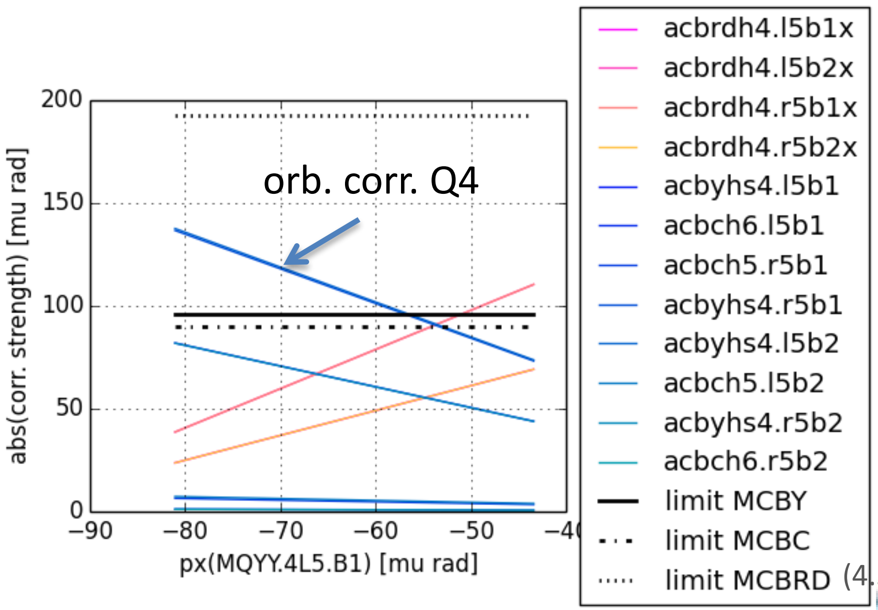


- optics: opt round
- use same matching strategy as for standard x-scheme (acbx1:=acbx2)
- match x/p_x at Q4L (initial conditions) and Q4R (matching constraint) with:

  $x(Q4)=0$ and $p_x(Q4)=n_{scale} * p_{x0}$

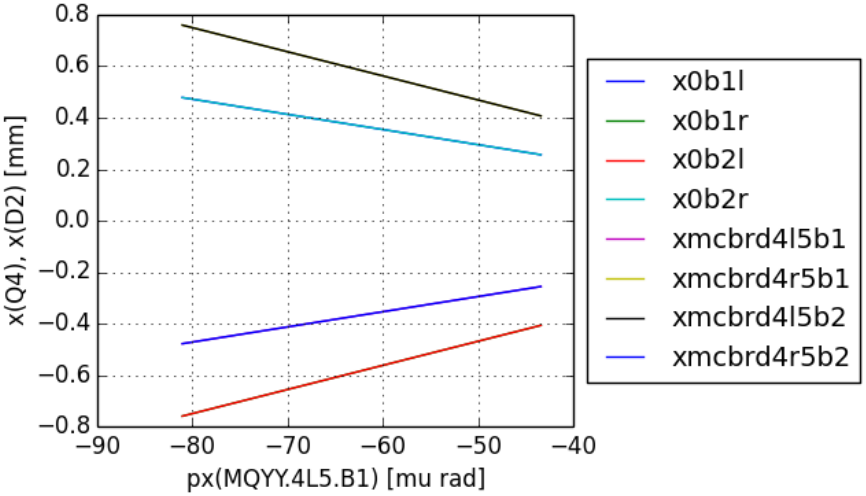
  with $p_{x0} = p_x(D2)$ for standard x-schemes





Possible optimisations

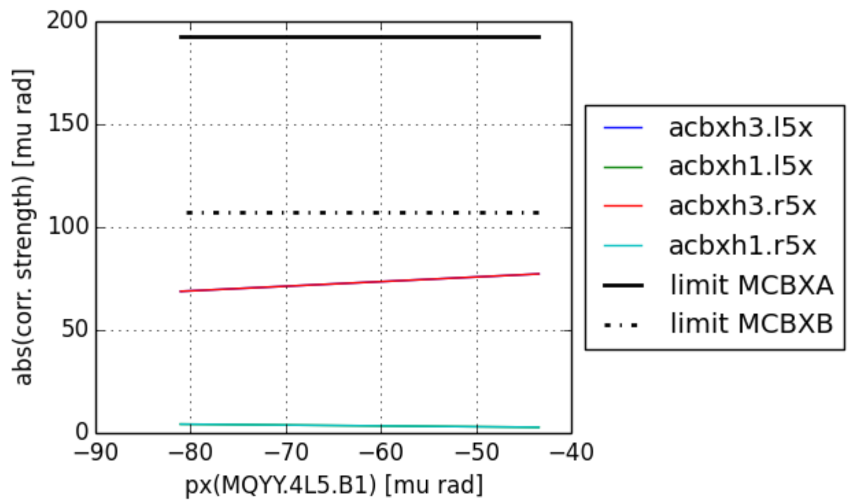
2) Orbit in crab cavities – matching strategy x(Q4)=-x(D2):

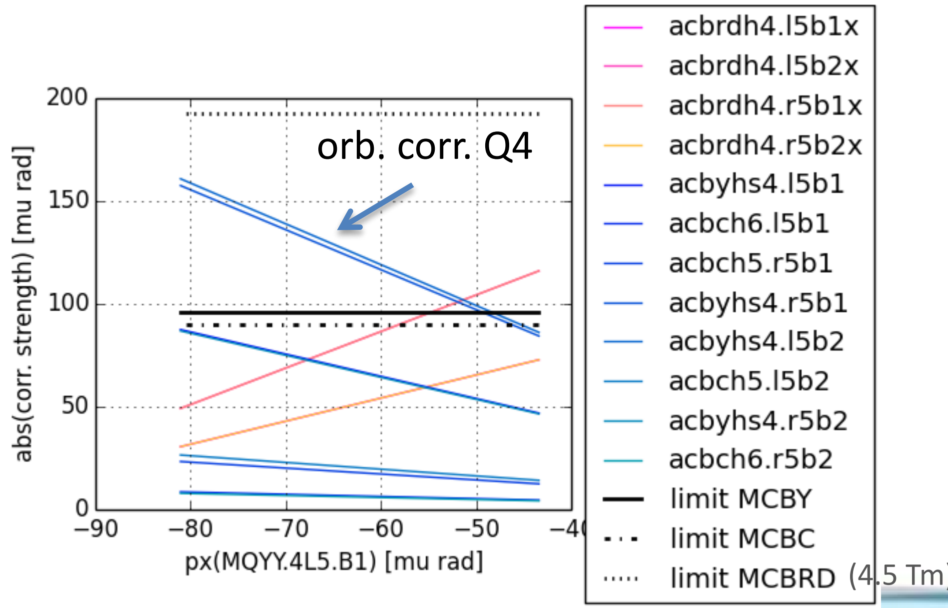


- optics: opt round
- use same matching strategy as for standard x-scheme (acbx1:=acbx2)
- match x/p_x at Q4L (initial conditions) and Q4R (matching constraint) with:

$$\mathbf{x(Q4)=-2*p_{x0}*d(Q4,D2)/2;\ p_x(Q4)=n_{scale*}p_{x0}}$$

with $p_{x0} = p_x(D2)$ for standard x-schemes
and d(Q4,D2) = distance between D2 and Q4





Possible optimizations

2) Orbit in crab cavities – reduction of MCBRD strength:
assume a maximum orbit of +/-0.5 mm in crab cavities

	plane	MCBYH.4* [Tm]	MCBRD [Tm]	max. orb. crab cavities [mm]
x-scheme*	x-ing	0.00	4.51	0.00
x(Q4=0)		1.06	3.32	0.50
x(Q4)=-x(D2) (HLLHCV1.0)		2.25	2.50	0.46
x(Q4)=-x(D2) (HLLHCV2.0)		2.47	2.30	0.50

Main conclusions:

1) x(Q4) limited by max. orbit in crab cavities and
2) x(Q4)=-x(D2) limited by corr. strength of orb. corr. at Q4 for HLLHCV1.0, but limited by max. orb. in crab cavities for HLLHCV2.0

-> reduction of MCBRD strength by max. 2.2 Tm is possible (for HLLHCV2.0) using corr. scheme x(Q4)=-x(D2) and limiting the orbit in the crab cavities to < +/-0.5 mm

Still to be checked: Aperture loss in D2

Summary

1) Orbit corrector budget has to account for x-scheme and offset at IP, misalignment and transfer function errors and beam based alignment of crab cavities
2) Taking all contributions into account and using the misalignment correction scheme which optimizes the corrector strength, the budget for the MCBX1/2 correctors is within limits whereas the MCBX3 with 4.7 Tm exceeds the current limit of 4.5 Tm (for opt sround (4.7+0.4) Tm = 5.1 Tm). For round optics a MCBRD strength of 5.7 Tm would be needed (for opt sround (5.7+1.0) Tm = 6.7 Tm).
1) By introducing an offset of the IP of +0.5 mm the MCBX3 strength (in the x-plane) could be reduced to 3.3 Tm (at the cost of increasing the MCBX1/2 strength) while at the same time reducing the orbit in the IT and thus optimising the aperture
2) By allowing for a +/-0.5 mm orbit in the crab cavities the MCBRD strength can be reduced by 2.2 Tm (loss in D2 aperture still to be checked!)

Proposal for corrector accounting for an offset at the IP and x-scheme, misalignment and transfer function errors and beam based alignment of the crab cavities

optics	corrector strength [Tm]			
	MCBX1	MCBX2	MCBX3	MCBRD/MCBYY
no orb. in crab cavities	2.5		**5.0**	**6.0**
orb. in crab cavities				**3.8**

High
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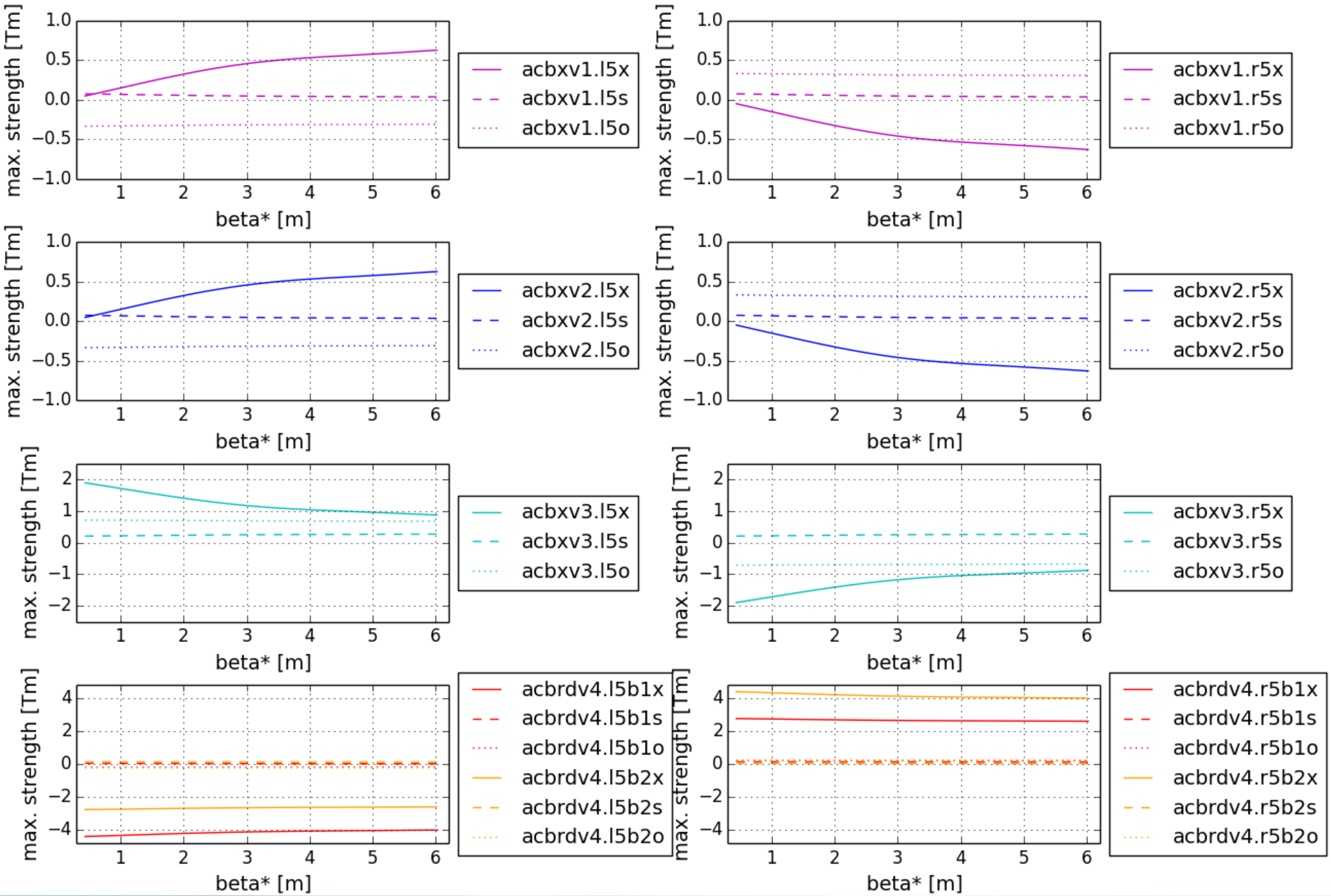
LHC

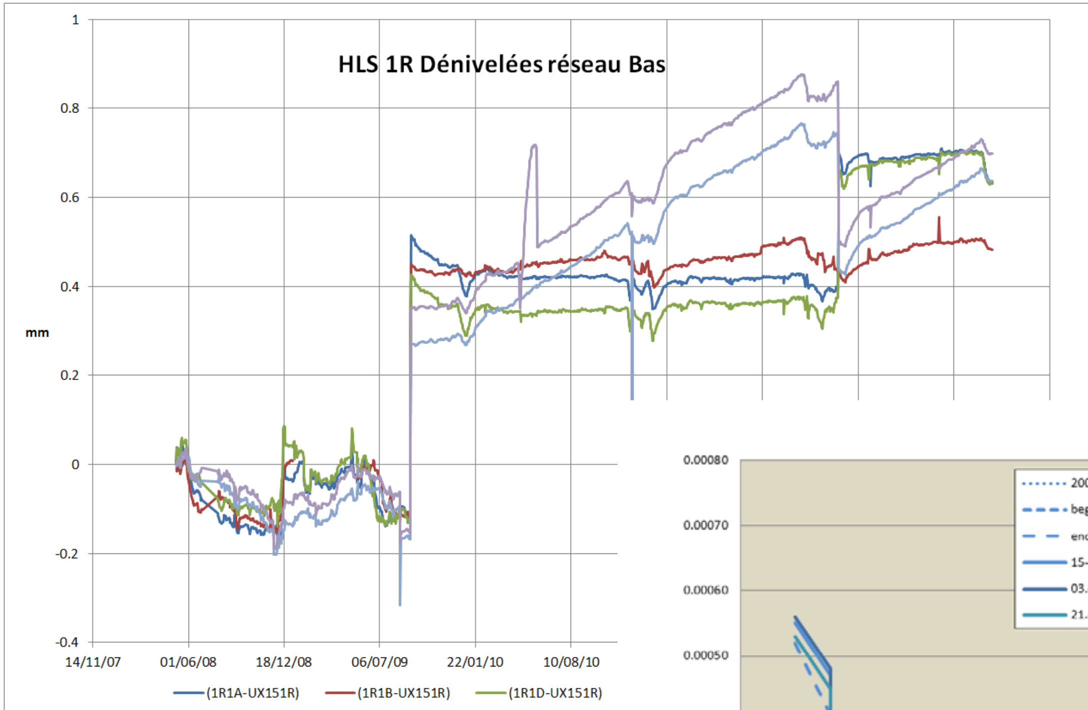
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

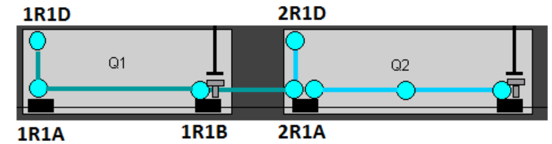
X-scheme and Orbit Offset at IP

Individual orbit corrector strength during the pre-squeeze (IR5, sep-plane = vertical)
x-angle=+/-295 µrad, sep.=+/-0.75 mm, offset=+0.5 mm



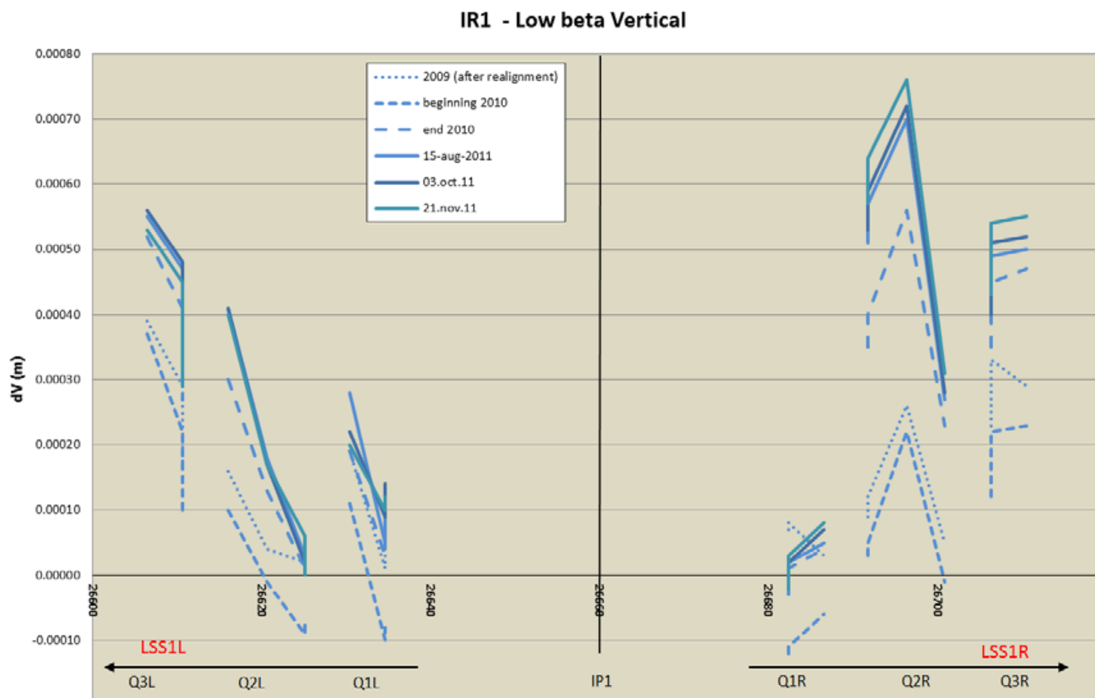
Ground motion measurements LHC IT





H. Mainaud Durand

4th HL-LHC PLC meeting



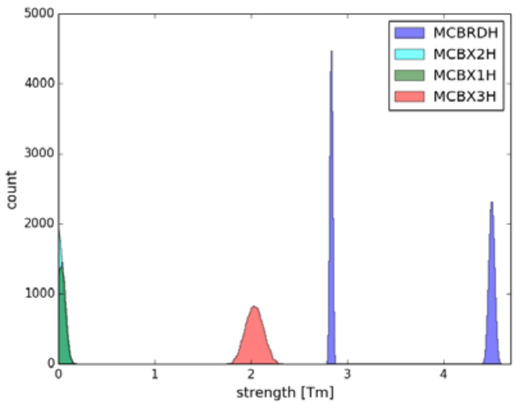
- Leveling measurements once per year during the winter shutdown
- > 0.3 mm shift in position of Q2R in 2010

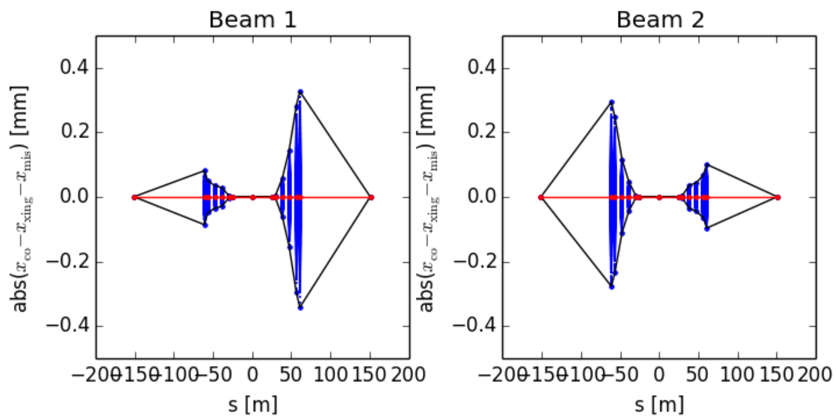
High Luminosity LHC

Triplet Misalignment and Transfer function errors

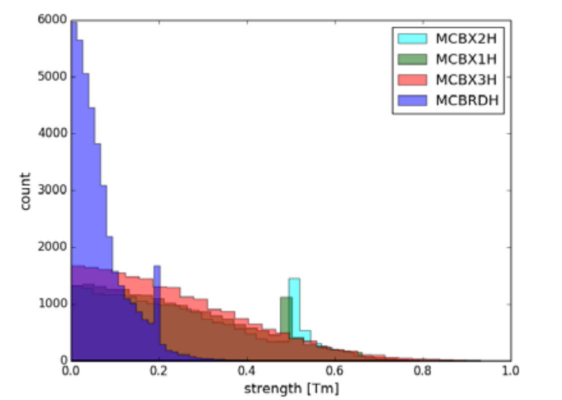
Influence of transv. misalignment and transfer function error (exemplary for strategy a) and opt round)

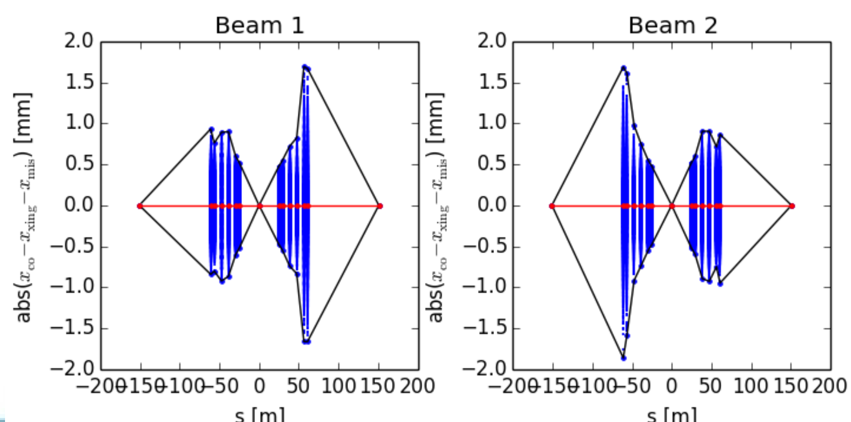
-> small effect of transfer function error compared to effect of transverse misalignment





transfer function (with x-scheme matching)



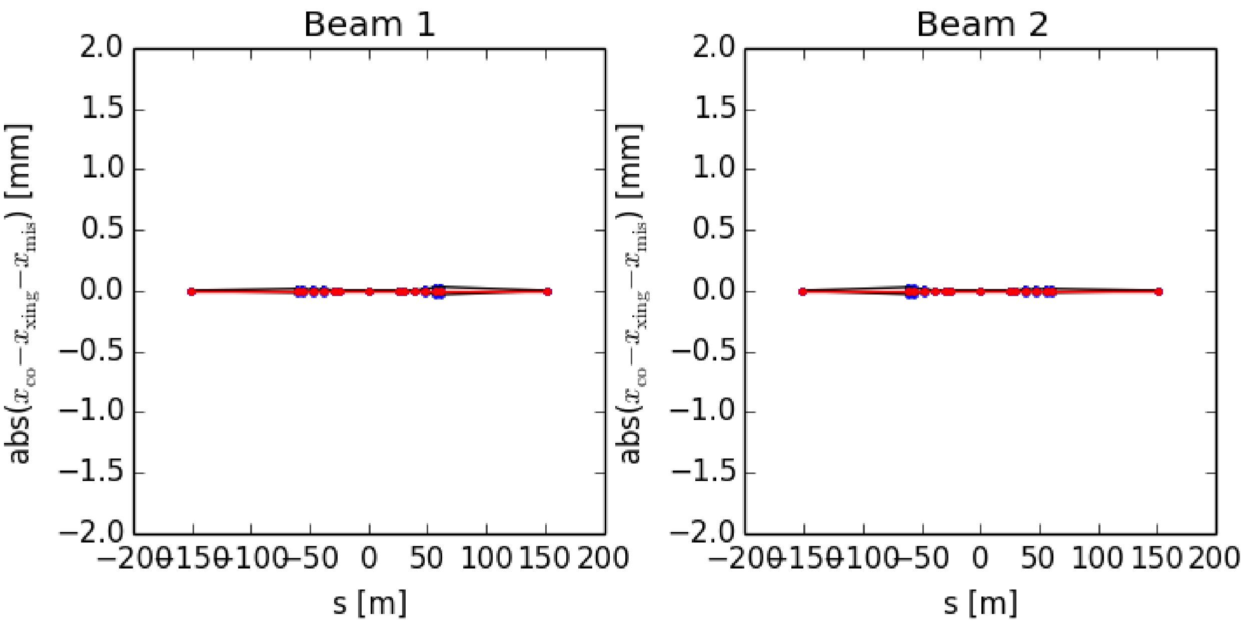


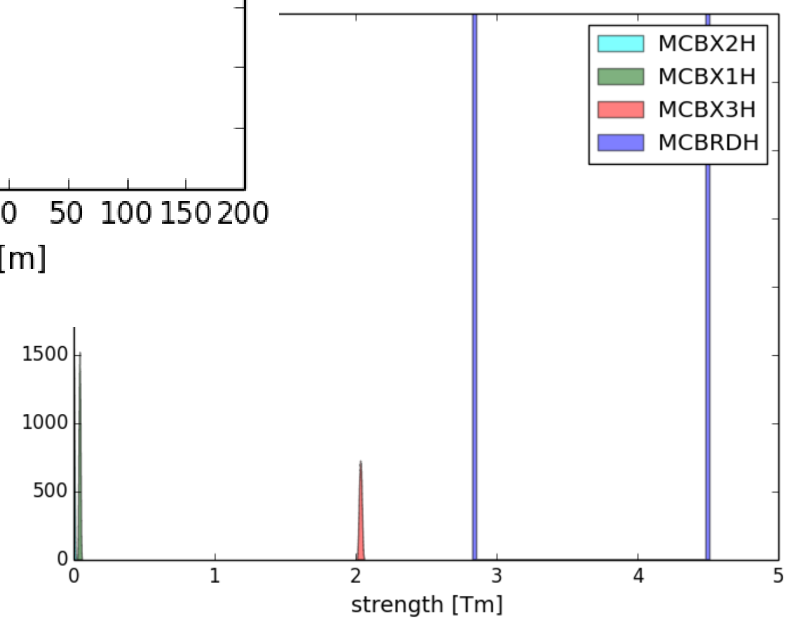
transv. misalignment (without x-scheme matching)

Triplet Misalignment and Transfer function errors

Influence long. misalignment (exemplary for strategy a) and opt round)

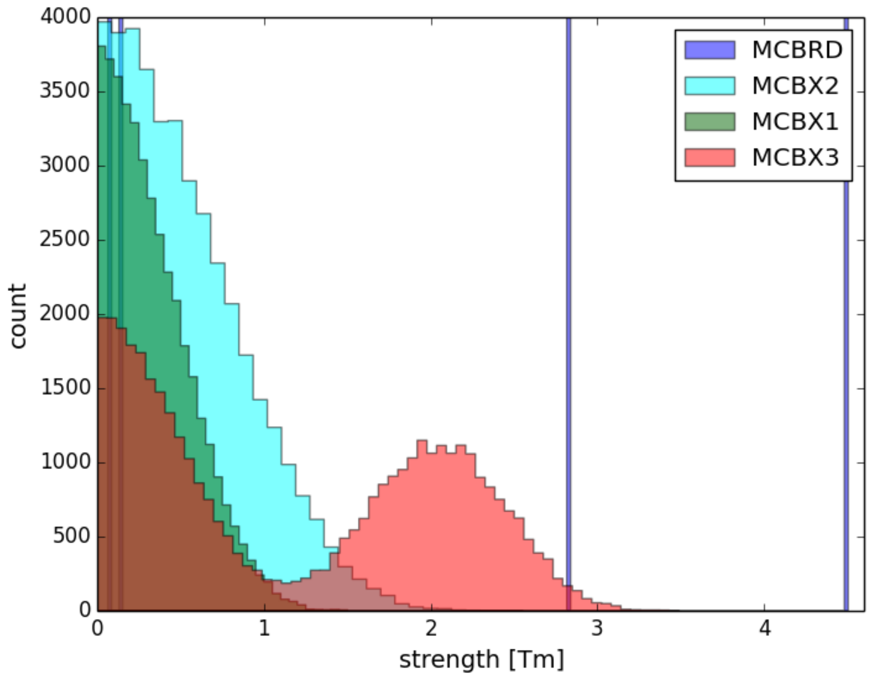
-> negligible effect of transfer function error compared to effect of transv. misalignment

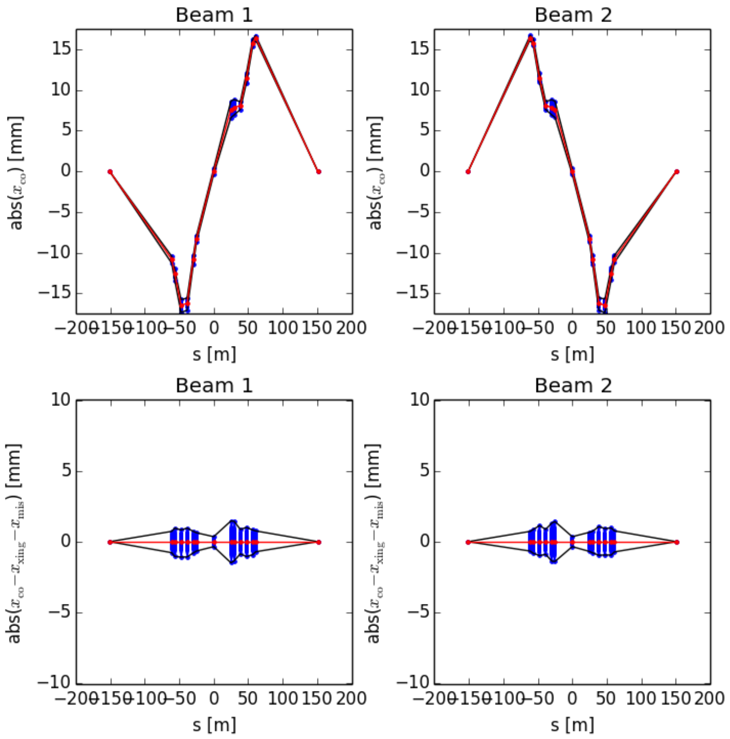




Triplet Misalignment and Transfer function errors

opt round (thin lens): transv.+long. misalignment and transfer function error
correct errors using only the MCBX and x_{b1}-x_{b2}=sep., $p_{x,b1}$-$p_{x,b2}$=x-angle

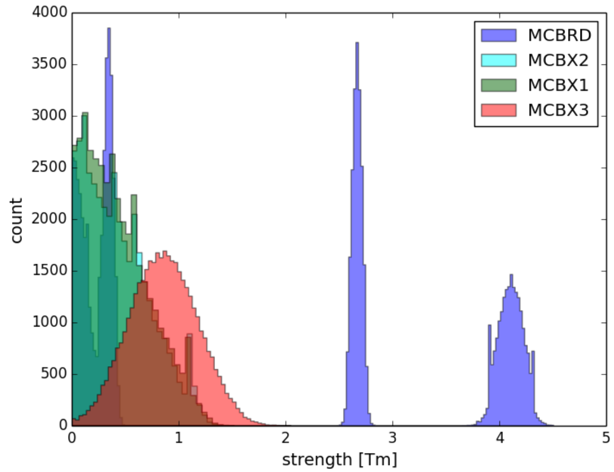


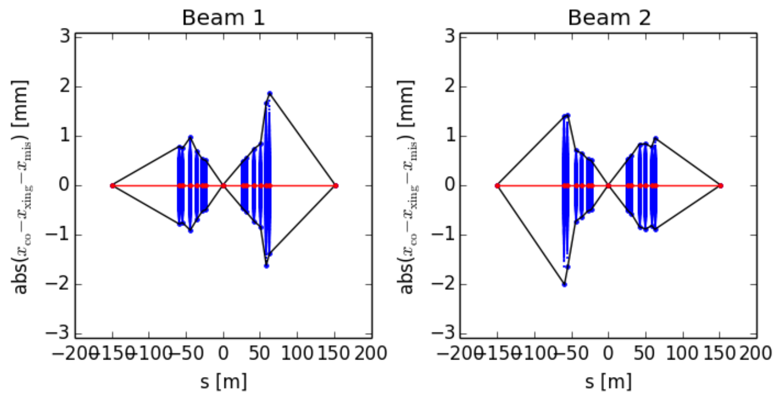


optics	corrector strength (max|max(rms)) [Tm]								x_{co}-x_{cross}-x_{mis} [mm]	
	MCBX1		MCBX2		MCBX3		MCBRD		max	max(rms)
opt round (thin lens)	1.5	0.4	2.6	0.7	3.5	2.1	4.5	4.5	1.5	0.35

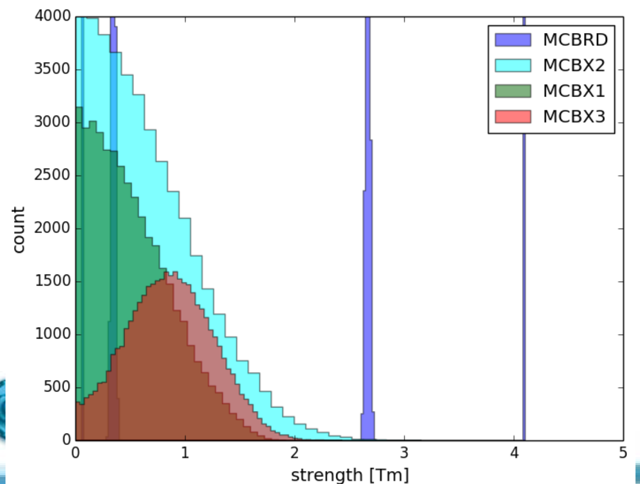
Triplet Misalignment and Transfer function errors

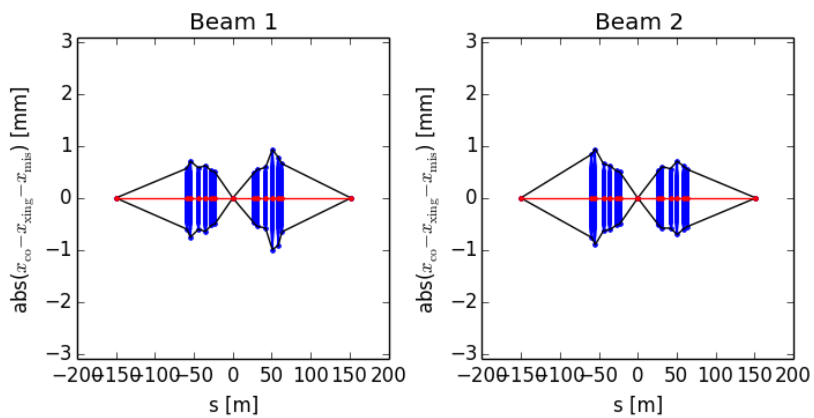
opt injection (thick lens): transv.+long. misalignment and transfer function error





a) limit corr. strength





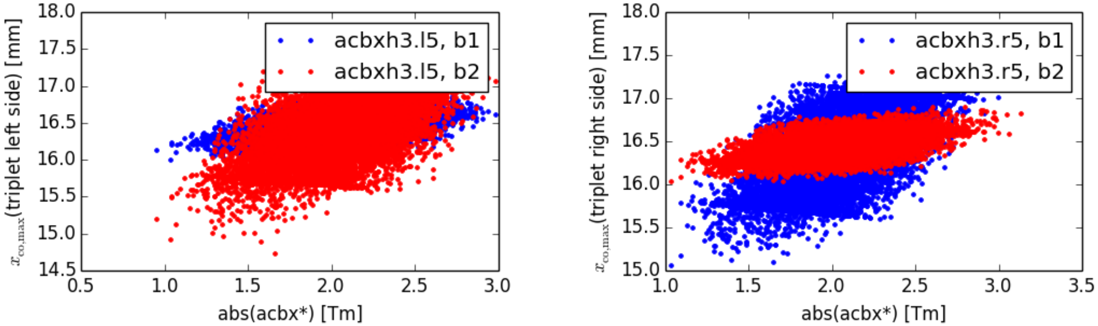
b) use only 2 (out of 4) MCBRD

Triplet Misalignment and Transfer function errors

Correlation corrector strength and orbit in triplet (opt_inj, +/- 295 µrad x-ing, +/- 2.0 mm separation)

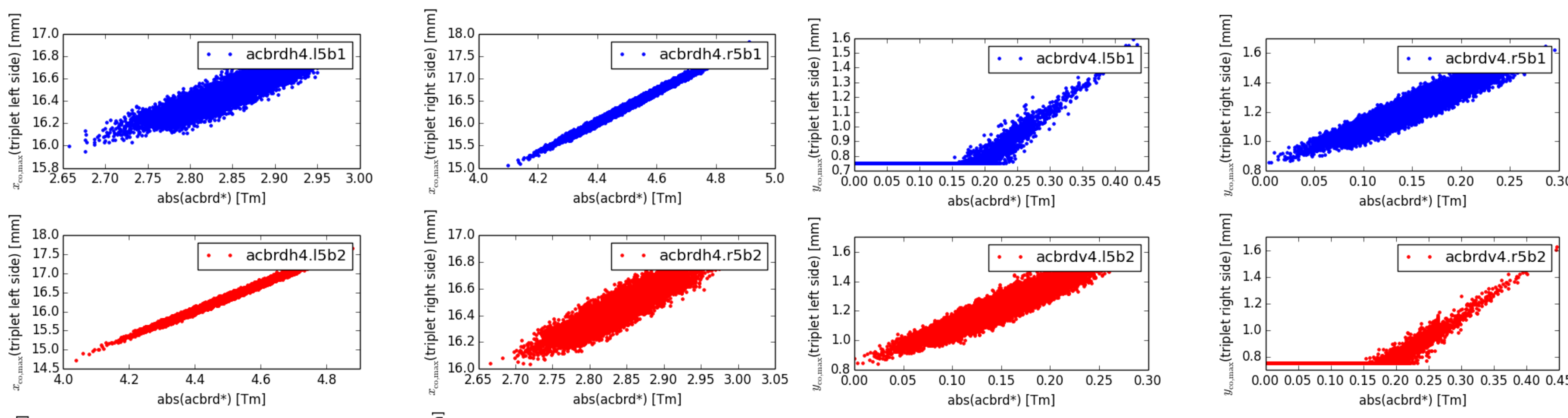
a) limit corr. strength

MCBXH3



(weak) correlation between MCBXH3 and (strong) correlation between MCBRD and maximum orbit in triplet

MCBRD

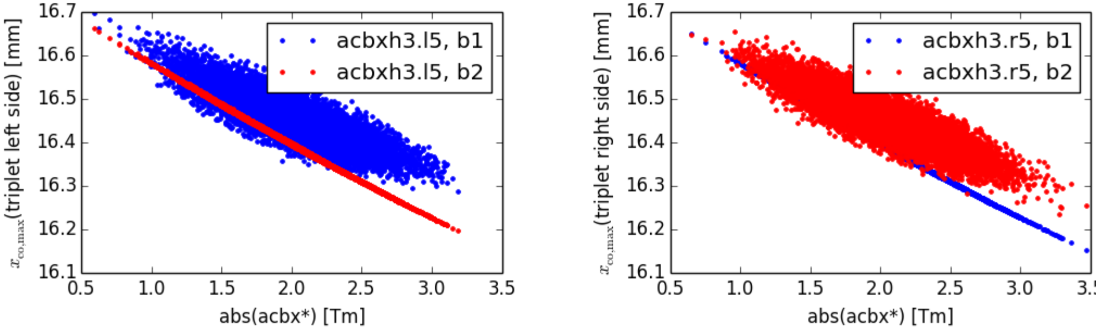


Triplet Misalignment and Transfer function errors

Correlation corrector strength and orbit in triplet (opt_inj, +/- 295 µrad x-ing, +/- 2.0 mm separation)

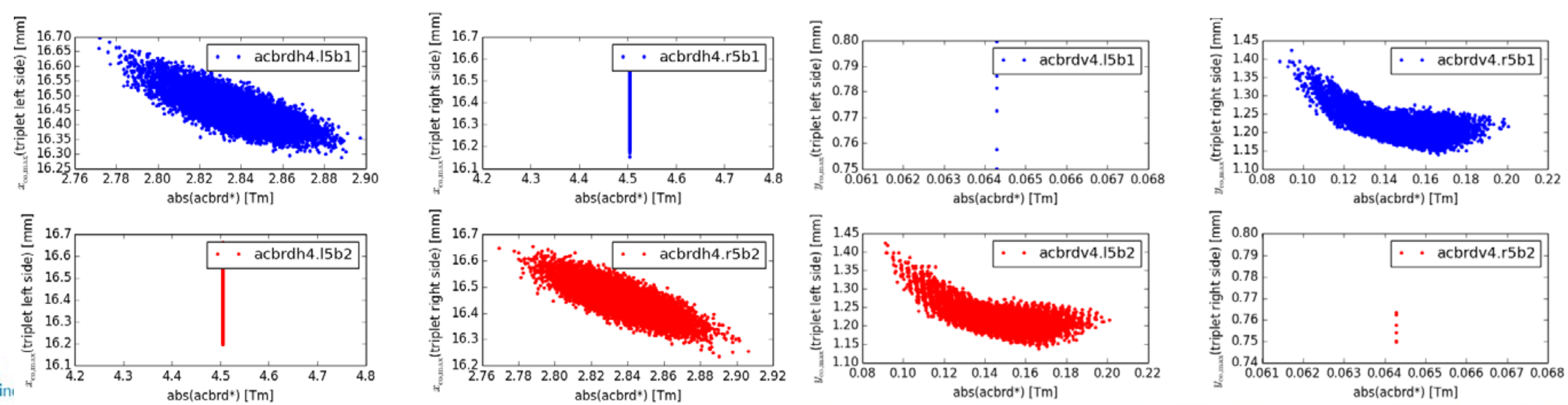
b) use only 2 (out of 4) MCBRD

MCBXH3



correlation between MCBXH3/MCBRD and maximum orbit in triplet

MCBRD



High Lumino LHC

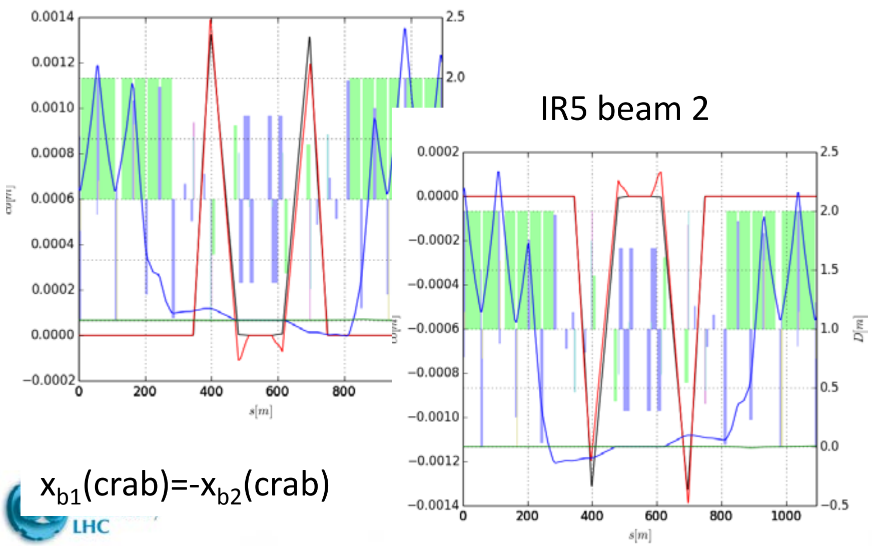
Beam Based Alignment in Crab Cavities

create orbit bump only with Q5 and MCBRD+MCBX orbit correctors
-> larger corr. strength and $p_{x/y} \neq 0$ in crab cavities

corrector scheme	plane	corrector strength ($x_{b1}=x_{b2}$ | $x_{b1}=-x_{b2}$) [Tm]									
		MCBX1		MCBX2		MCBX3		MCBRD		MCBY.5	
MCBX1+MCBX3	x-ing	0.95	0.00	0.00	0.00	1.02	0.37	1.44	1.01	0.64	0.64
MCBX2+MCBX3		0.00	0.00	1.06	0.01	1.26	0.37	1.17	1.01	0.64	0.64
MCBX1+MCBX3	sep.	0.90	0.07	0.00	0.00	1.00	0.43	1.49	1.12	0.59	0.59
MCBX2+MCBX3		0.00	0.00	1.02	0.08	1.24	0.45	1.24	1.10	0.59	0.59

IR5 beam 1

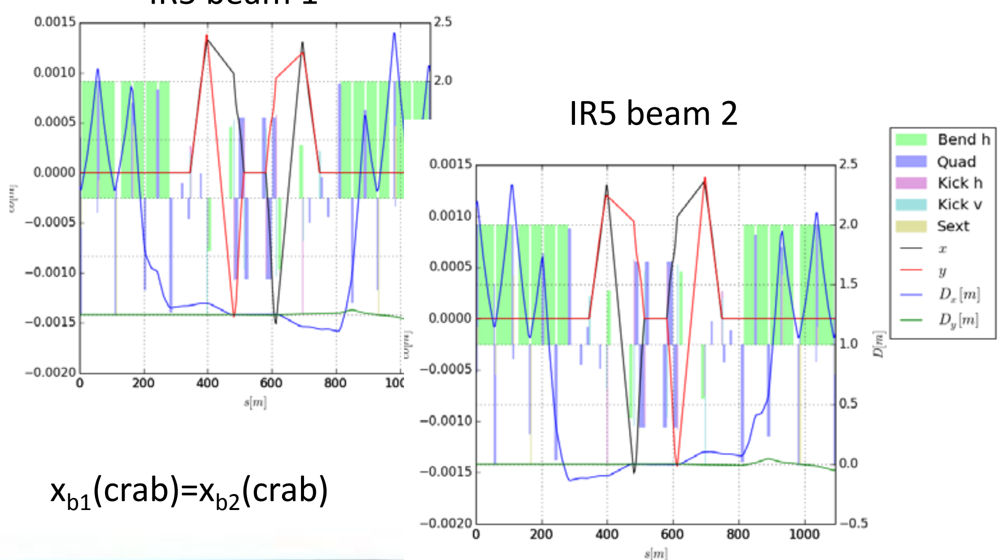
IR5 beam 2



$x_{b1}(crab)=-x_{b2}(crab)$

IR5 beam 1

IR5 beam 2



$x_{b1}(crab)=x_{b2}(crab)$

Beam Based Alignment in Crab Cavities

create orbit bump with Q5/Q6/Q7 and MCBRD+MCBX orbit correctors
-> smaller corr. strength and $p_{x/y}$=0 in crab cavities

<table>
<tr><th rowspan="2">corr. scheme</th><th rowspan="2">knob</th><th rowspan="2">plane</th><th colspan="8">corrector strength [Tm]</th></tr>
<tr><th>MCBX1</th><th>MCBX2</th><th>MCBX3</th><th>MCBRD</th><th>MCBY4</th><th>MCBY5</th><th>MCBC6</th><th>MCBC7</th></tr>
<tr><td>MCBX2+MCBX3</td><td rowspan="12">x(b1)=x(b2) =1.0 mm</td><td rowspan="6">x-ing</td><td>0.00</td><td>0.8</td><td>0.95</td><td>0.4</td><td rowspan="12">0.00</td><td rowspan="12">0.72</td><td rowspan="6">0.76</td><td rowspan="12">0.52</td></tr>
<tr><td>MCBX1+MCBX2</td><td>3.75</td><td>3.4</td><td>0.00</td><td>1.47</td></tr>
<tr><td>MCBX1+MCBX3</td><td>0.71</td><td>0.00</td><td>0.77</td><td>0.60</td></tr>
<tr><td>MCBX1=MCBX2</td><td>0.38</td><td>0.38</td><td>0.85</td><td>0.51</td></tr>
<tr><td>MCBX1=MCBX3</td><td>1.27</td><td>2.22</td><td>1.27</td><td>0.22</td></tr>
<tr><td>MCBX3=MCBX2</td><td>1.27</td><td>0.63</td><td>0.63</td><td>0.76</td></tr>
<tr><td>MCBX2+MCBX3</td><td rowspan="6">sep.</td><td>0.00</td><td>0.78</td><td>0.93</td><td>0.39</td><td rowspan="6">0.78</td></tr>
<tr><td>MCBX1+MCBX2</td><td>3.49</td><td>3.15</td><td>0.00</td><td>1.36</td></tr>
<tr><td>MCBX1+MCBX3</td><td>0.69</td><td>0.00</td><td>0.74</td><td>0.58</td></tr>
<tr><td>MCBX1=MCBX2</td><td>0.37</td><td>0.37</td><td>0.83</td><td>0.49</td></tr>
<tr><td>MCBX1=MCBX3</td><td>1.26</td><td>2.2</td><td>1.26</td><td>0.21</td></tr>
<tr><td>MCBX3=MCBX2</td><td>1.23</td><td>0.6</td><td>0.6</td><td>0.73</td></tr>
<tr><td>MCBX2+MCBX3</td><td rowspan="12">x(b1)=-x(b2) =1.0 mm</td><td rowspan="6">x-ing</td><td>0.00</td><td>0.00</td><td>0.28</td><td>0.28</td><td rowspan="12">0.00</td><td rowspan="12">0.72</td><td rowspan="6">0.76</td><td rowspan="12">0.52</td></tr>
<tr><td>MCBX1+MCBX2</td><td>1.12</td><td>1.25</td><td>0.00</td><td>0.6</td></tr>
<tr><td>MCBX1+MCBX3</td><td>0.00</td><td>0.00</td><td>0.28</td><td>0.28</td></tr>
<tr><td>MCBX1=MCBX2</td><td>0.00</td><td>0.00</td><td>0.28</td><td>0.28</td></tr>
<tr><td>MCBX1=MCBX3</td><td>0.38</td><td>0.42</td><td>0.38</td><td>0.26</td></tr>
<tr><td>MCBX3=MCBX2</td><td>0.21</td><td>0.23</td><td>0.23</td><td>0.34</td></tr>
<tr><td>MCBX2+MCBX3</td><td rowspan="6">sep.</td><td>0.00</td><td>0.00</td><td>0.28</td><td>0.28</td><td rowspan="6">0.78</td></tr>
<tr><td>MCBX1+MCBX2</td><td>1.04</td><td>1.18</td><td>0.00</td><td>0.57</td></tr>
<tr><td>MCBX1+MCBX3</td><td>0.00</td><td>0.00</td><td>0.28</td><td>0.28</td></tr>
<tr><td>MCBX1=MCBX2</td><td>0.00</td><td>0.00</td><td>0.28</td><td>0.28</td></tr>
<tr><td>MCBX1=MCBX3</td><td>0.38</td><td>0.42</td><td>0.38</td><td>0.25</td></tr>
<tr><td>MCBX3=MCBX2</td><td>0.2</td><td>0.22</td><td>0.22</td><td>0.33</td></tr>
</table>

Possible optimisations

1) IP offset knob collision:

strength + aperture optimisation (opt_round: xing=+/-295 μrad)

IR5		offset (**+0.5 mm**)	crossing+separation	crossing+separation+offset
no MCBX1				
max. orbit triplet [mm]	Beam 1	**0.59842**	16.35577	16.08505
	Beam 2	**0.66918**	15.9948	15.85512
max. corr. strength x-plane (h) [Tm]	MCBXH3	0.80274	2.03192	**1.22917**
	MCBXH2	0.70706	0.02387	**0.73093**
	MCBXH1	0	0.02387	**0.02387**
no MCBX2				
max. orbit triplet [mm]	Beam 1	**0.95007**	16.35577	15.40566
	Beam 2	**0.8607**	15.9948	15.15073
max. corr. strength x-plane (h) [Tm]	MCBXH3	0.64119	2.03192	**1.39072**
	MCBXH2	0	0.02387	**0.02387**
	MCBXH1	0.62999	0.02387	**0.65386**
MCBX1*=MCBX2*				
max. orbit triplet [mm]	Beam 1	**0.74555**	16.35577	15.72578
	Beam 2	**0.77046**	15.9948	15.48262
max. corr. strength x-plane (h) [Tm]	MCBXH3	0.71731	2.03192	**1.3146**
	MCBXH2	0.33315	0.02387	**0.35702**
	MCBXH1	0.33315	0.02387	**0.35702**

High Luminosity LHC

Possible optimisations

1) IP offset knob injection:

strength optimisation (xing=+/-295 µrad) at the cost of IT aperture

IR5		offset (**-0.5 mm**)	crossing+separation	crossing+separation+offset
no MCBX1				
max. orbit triplet [mm]	Beam 1	0.59669	15.00314	15.26026
	Beam 2	0.66256	14.81291	14.94437
max. corr. strength x-plane (h) [Tm]	MCBXH3	0.76988	0.9974	**1.76728**
	MCBXH2	0.66339	0.60709	**0.0563**
	MCBXH1	0	0.60709	**0.60709**
no MCBX2				
max. orbit triplet [mm]	Beam 1	0.86833	15.00314	15.8662
	Beam 2	0.83092	14.81291	15.57646
max. corr. strength x-plane (h) [Tm]	MCBXH3	0.6021	0.9974	**1.5995**
	MCBXH2	0	0.60709	**0.60709**
	MCBXH1	0.57388	0.60709	**0.03321**
MCBX1*=MCBX2*				
max. orbit triplet [mm]	Beam 1	0.73636	15.00314	15.58515
	Beam 2	0.75283	14.81291	15.28328
max. corr. strength x-plane (h) [Tm]	MCBXH3	0.67992	0.9974	**1.67732**
	MCBXH2	0.3077	0.60709	**0.29939**
	MCBXH1	0.3077	0.60709	**0.29939**

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