Upgrade optics with crab cavities

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Content

The talk presents a consistent layout and optics solutions with:

- $\beta^* = 15\,\mathrm{cm}$ in both planes,
- two crab cravities per side per beam per IP,
- total voltage of 10MV per side per beam per IP for 10σ crossing angle $(580\,\mu\mathrm{rad})$

In detail: assumptions, layout, optics, correction of chromatic aberration and consequences, aperture margins, options and issues of crab cavity integration, final comments.

Relevant and floating quantities

For layout and collision optics the key input parameters are: β^*, emittance (ϵ), beam beam separation $d_{\mathrm{sep}}[\sigma]$) and aperture margins.

Relevant formulas (assumed hor. crossing):

$$L = \frac{N_b^2 n_b f_{\mathrm{rev}}}{4\pi\epsilon\sqrt{\beta_x^*\beta_y^*}} F_{\mathrm{geo}} F_{\mathrm{hr}},\ F_{\mathrm{geo}} = \frac{1}{\sqrt{1+\left(\frac{\sigma_z d_{\mathrm{s}}}{2\beta_x^*}\right)^2}},$$

$$\theta_{\mathrm{c}} = d_{\mathrm{s}}\sqrt{\epsilon/\beta_x^*},\ \sigma = \sqrt{\epsilon\beta}$$

Betastar

β^* determines:

- beam sizes up to Q5, quadrupole strengths, chromatic ($\propto 1/\beta^*$) and geometric aberrations constraints ,
- the required crossing angle therefore orbit corrector and crab cavity kick strengths ($\propto 1/\sqrt{\beta^*}$),
- the base line luminosity and the crab cavity enhancement and leveling range.

Values:

- $55\,\mathrm{cm}$ nominal (LHC V6.503)
- $35-40\,\mathrm{cm}$ achievable with phase I upgrade[1] with margins
- $30\,\mathrm{cm}$ achievable with phase I upgrade without margins (sLHCv2)
- $25\,\mathrm{cm}$ historical target for the upgrade [2] (without margins with Nb3Sn phase I like solution)
- $15\,\mathrm{cm}$ proposed here thanks to new concepts (sLHCv3) [3]

Increasing beta star simplifies the constraints but reduces performance. Reach the minimum possible to reach the $300\,\mathrm{fb}^{-1}$ per year target.

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[1] S.Fartoukh Chamonix 2010

[2] O. Brüning et al. LHC Project Report 626 (2002)

[3] S.Fartoukh, sLHC project report 49

Transverse emittance

Transverse emittance is used to:

- estimate aperture margins ($\propto \sqrt{\epsilon}$)
- determine the crossing angle (θ_c in rad)
- beam beam parameter ($\propto 1/\epsilon$)

Values:

- $3.75\,\mu\mathrm{m}$ nominal normalized
- $2.2 - 2.4\,\mu\mathrm{m}$ achieved in operation at $1.1 \cdot 10^{11}$ ppb with emittance growth (yet to be understood)

no way to actively control it, there are known and not yet known sources of emittance growth. Assumed $3.75\,\mu\mathrm{m}$.

beam beam separation

Beam beam separation:

- aperture requirements up Q5 ($\propto 1/\sqrt{\beta^*}$), spurious dispersion ($\propto 1/(\sqrt{\beta^*})^3$) and geometric aberrations constraints,
- determines the required crossing angle therefore orbit corrector and crab cavity kick strengths ($\propto 1/\sqrt{\beta^*}$),

Values:

- 16σ large distance (small effect),
- 12σ moderate setting (proposed for 2011 [4]),
- 9.5σ nominal (7sigma closest parasitic encounter),
- 8σ lower bound.

For the upgrade the number of parasitic interaction increases (16$\rightarrow$ 19-22). Not yet ready to decide, used 10σ.

[4] W. Herr Evian Dec. 2010

Aperture margin

The so-called (n1) method [5] has been used to find for each element a lower bound estimate of the required collimator settings (in σ) which protects the element

Margin used: 3mm closed orbit, $8.6 \cdot 10^{-4}$ energy error, 20% beta-beating (from imperfections and chromatic effects), 30% normalized spurious dispersion from the arcs, nominal tolerances for ground motion and mechanical alignments ($1\,\mathrm{mm}$ for new elements).

$n_1 > 7$ is considered safe at 7TeV provided dedicated protection (e.g. TCT), about $n_1 > 10$ recommended otherwise.

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[5] J. Jeanneret, MadX aperture module, LHC project note 111.

Upgrade Optics

Low β^* optics are generally limited by quadrupole aperture and strength, the harder limit for the LHC is off-momentum beta beating (not observable for $\beta^* > 1\,\mathrm{m}$), long standing problem for the LHC, may broke collimator hierarchy, degrade with $1/\beta^*$: History...

- mitigation by IP1-IP5 phasing [6],
- 2006: first upgrade optics [7], beta beating studied and highlighted, not yet solution found
- 2008: phase I solution [8], two arcs per triplet, betatron phase constraints over all the machine, limits on β^*
- 2010: new ideas implemented in sLHCv3 [9], radical changes in the squeeze strategy but less constraints

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[6] A. Verdier, LHC project note 103 1997

[7] O. Brüning, R. De Maria, HHH-LUMI06

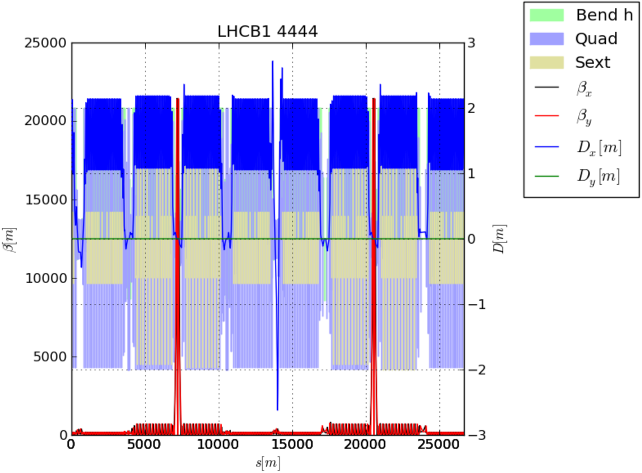
[8] S. Fartoukh, LIUWG may 2008

[9] S. Fartoukh, R. De Maria, LMC July 2010

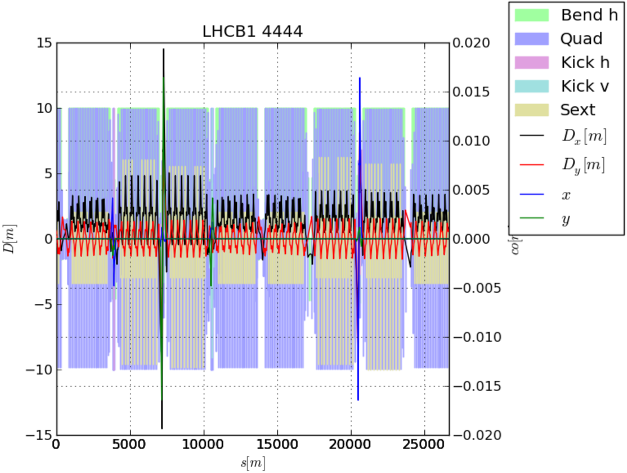
SLHCv3 ingredients

- Make a "local" achromatic line around the low beta IP till minimum possible pre-squeezed betastar using:
  - strict $\pi/2$ arc cell phase,
  - strict left right IR phase advance ($\pi/2 \mod \pi$ to MS 14, 15) (the insertion was not designed for that),
  - use only selected sextupole families to compensate the triplet chromaticity, and the remaining families for natural chromaticity and Q' trimming,
- use neighboring insertions to complete the squeeze to the target collision β^* without perturbing the line
- take advantage of the above phase conditions to compensate crossing/separation bumps induced dispersion

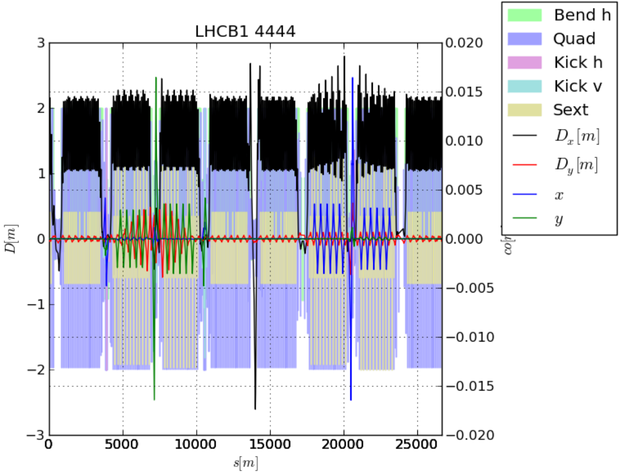
SLHCv3 outcome



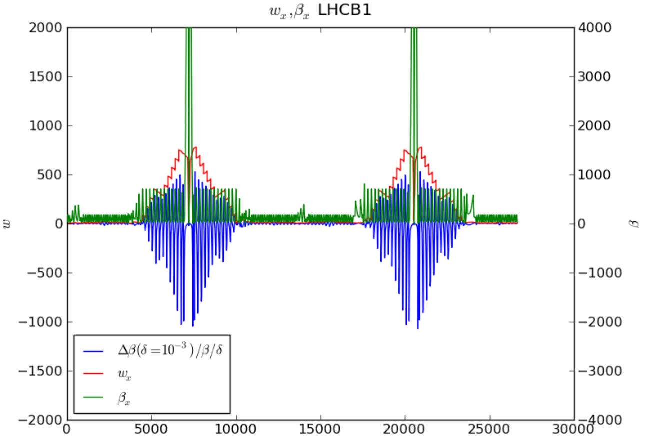
SLHCv3 outcome



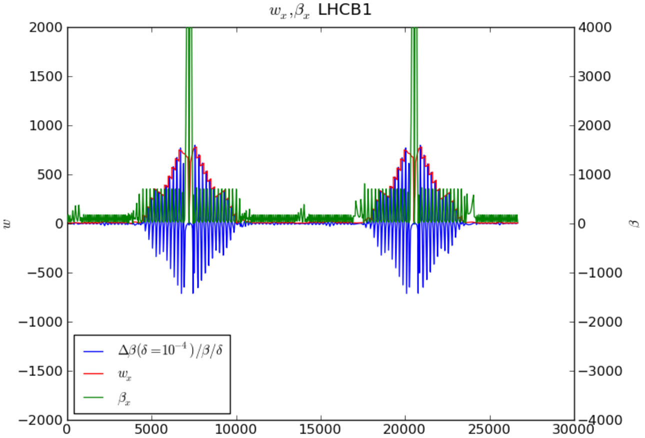
SLHCv3 outcome



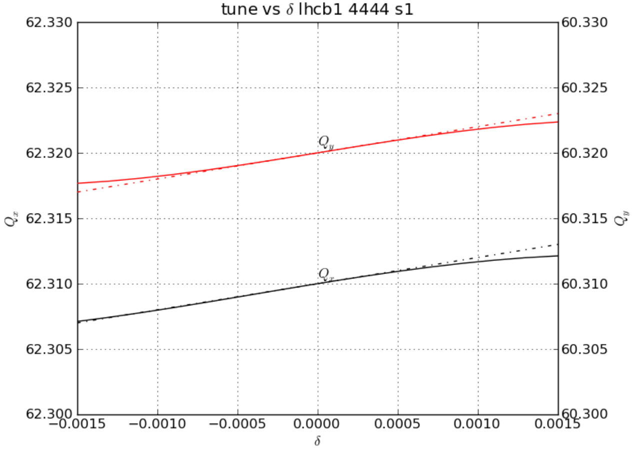
SLHCv3 outcome



SLHCv3 outcome



SLHCv3 outcome



SLHCv3 outcome

The main result is large momentum window:

- very limited chromatic beating in most of the machine in particular in the collimation insertions and the triplets
- very linear tune vs δp
- flexibility in IP phasing (not available in Phase I solution)
- IR1-5 optics flexibility (to be used with care)
- very low β^* finally achievable with arbitrary aspect ratio

at the cost of:

- increase beta in the arcs 81,12,45,56 (e.g. reduced aperture margin in the arcs at 7TeV, additional non linear pertubations induced by the MS and MB, MQ imperfections, maybe impedance effects)
- squeeze involving IR4 and IR6 as well

SLHCv3 requirements

SLHCv3 requires:

- new elements in IR1/5 for aperture: Q1-Q3 and corrector (nested MCBX), D1 close to Q3, TAN, D2, Q4, Q5,
- new orbit corrector MCBY (40% increase neede due to > 0.5 mrad crossing angle)
- 25% longer MQY(Q5) in IR6 for optics matching
- test the concept in operation
- possibly new dedicated collimators (TCT like)

For additional confidence in keeping $\beta^* = 15\,\mathrm{cm}$:

- solve the "spare sextupole" issue:
  - new phase advance selection (attemped, but success only at 5.5TeV due to strength limit in Q8)
  - additional sextupole at Q10 in IR1 and IR5
  - disabling one sextupole in 4 arcs (reducing performance by 20%)
- push the pre-squeezed optics if more sextupole strength is available to reduce the beta in the arcs

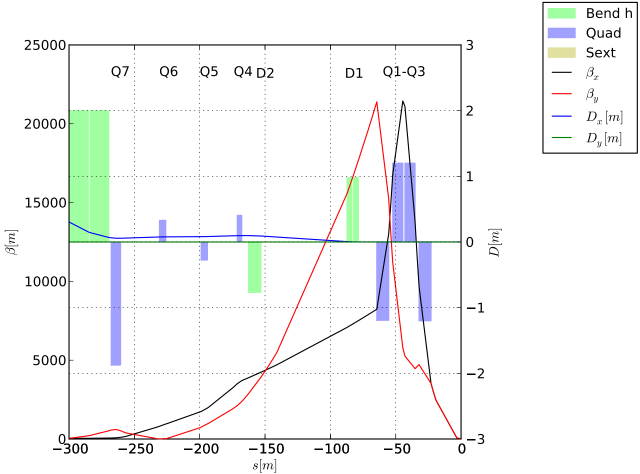
SLHCv3: results for $\beta^* = 15\,\mathrm{cm}$

Conclusion for SLHCv3 solution for $\beta^* = 15\,\mathrm{cm}$

- magnet strengths ok, power supply ok
- aperture just ok (n1=7.1 Triplets, n1=7 TAN)
- dynamic aperture without beam beam and new magnets (15σ [10]) acceptable only if we have exceptional field quality in the new elements
- dynamic aperture might reduce margin for the beam beam perturbations
- optics flexibility available for further improvements

[10] compared to 40σ under the same conditions for the nominal LHC

Crab cavities integration



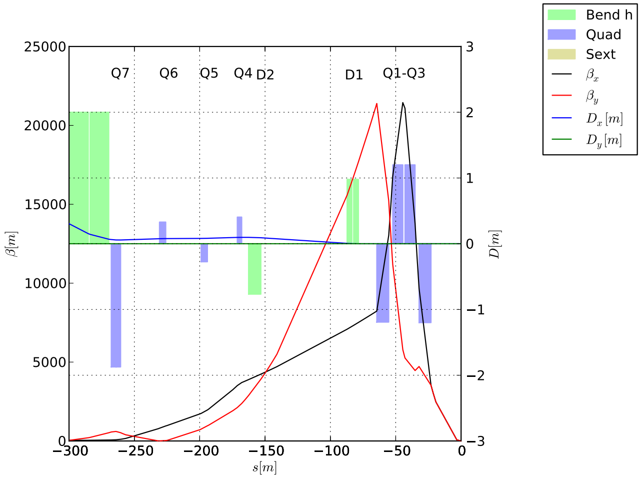
Crab cavity integration

We need to install crab cavities where: high beta functions, close to the IP, nominal beam separation (compact cavities), longitudinal space for 4 modules per side.
Possibilities:

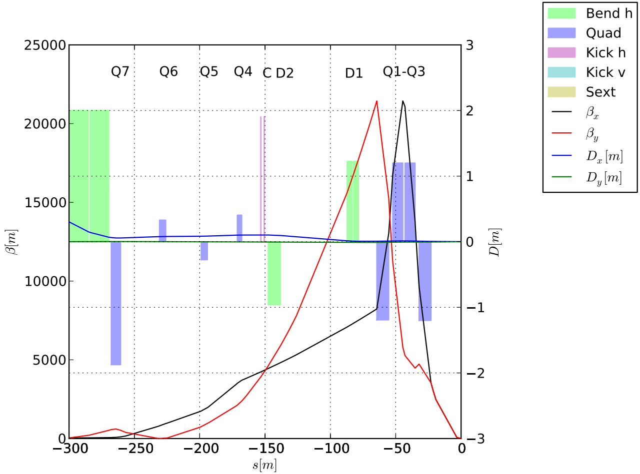
- after Q5 → low beta
- before D2 → small separation
- dogleg (with or without including Q4 [11]) → more complicated but necessary for standard cavity
- move Q4 toward the arcs → good for optics, low beta
- move D2 toward the IP → beta compatible with 10MV (74mm aperture), D2 aperture still acceptable [12]
- further increase beta in D2 → not possible for D2 aperture and antithetic for chromatic correction phase constraints.

[11] R. Tomas LHC-CC 09
[12] E. Todesco, private comm.

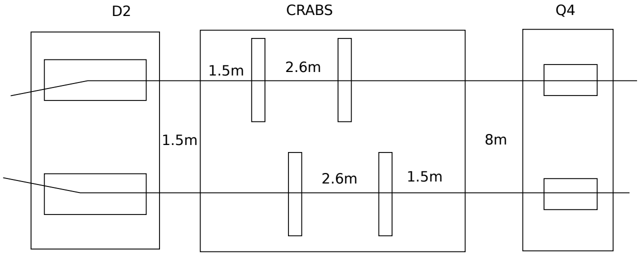
Crab cavities integration



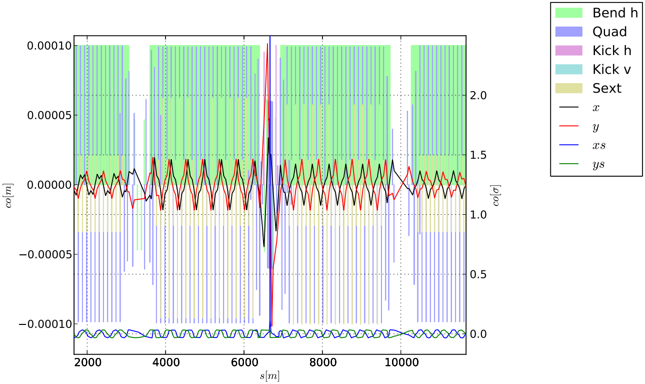
Crab cavities integration



Tentative layout for cryostats

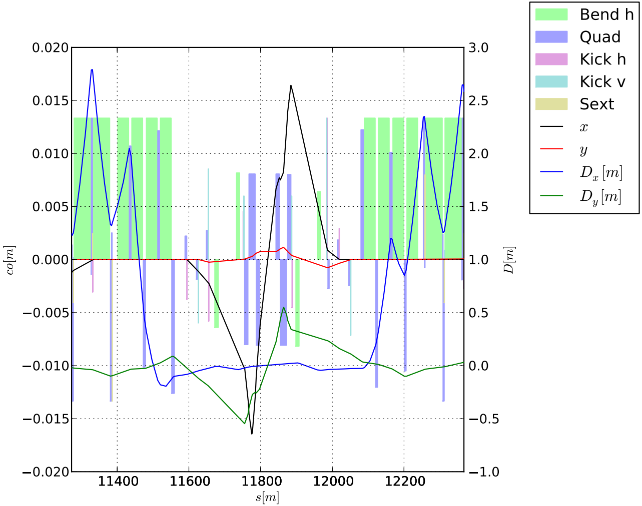


crab cavity orbit leakage



σ_s orbit, 2% leakage due to not exact π-bump

crossing scheme



crab cavity and crossing scheme

The crab cavities are installed in the region of the crossing/separation close orbit bumps resulting in a closed orbit excursions.
In fact the LHC :

- remove the parallel separation before collision
- may need adjust d_{sep} in the $8 - 14\sigma$ range in operation
- inversion of sign vertical crossing angle
- may need to change of H,V crossing scheme orientation

The max close orbit excursion at the cavity is:

- $3.354\,\mathrm{mm}$ for 10σ crossing angle
- $0.67\,\mathrm{mm}$ for $1.5\,\mathrm{mm}$ separation

Do we need to realign the cavities each time the crossing angle is adjusted?

possible issues to be studied

- non linear ac fields:

a cavity kick has a transverse dependence $\Delta p_t(x, y)$,
since $\nabla \times \Delta p_t = 0$, $\nabla \cdot \Delta p_t = 0$ [13]
it is harmonic and can be expressed by a potential [14]
described by multipole components.

  - How big are these components for the crab cavities?

- synchro-betatron resonance due to the crossing angle:

The ratio $\frac{\theta_c \sigma_s}{2\sigma^*} = \frac{d_{\text{sep}} \sigma_s}{2\beta^*}$ should be smaller that 1 [15].
We have 0.7 for nominal LHC, 2.5 for $\beta^* = 15\,\text{cm}$,

- How do the crab cavities mitigate the effect?
- Can we still make leveling?

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[13] P-W theorem and corollary, Ng., Physics of intensity dependent beam instabilities.

[14] $H = -Re[\sin(wt + \phi) \sum_{n=1}^{\infty} (b_n + i a_n)^n \frac{(x+iy)^n}{n r_o^{n-1}}]$ as implemented in PTC, E. Forest, private comm.

[15] W. Herr EPAC 1990

Conclusion

- tentative optics solution for $\beta^* = 15\,\mathrm{cm}$ ready
  - for realistic one we need new magnet designs, iterations with hardware responsible and additional optics optimization and beam dynamics studies
- 2 cavities are need for a total of 10MV per side, per beam, per IP
  - room for 3 cavities available in principle...
- issues to be investigated: crossing scheme flexibility, synchro-betatron resonances, crab cavity field quality.

Acknowledgements

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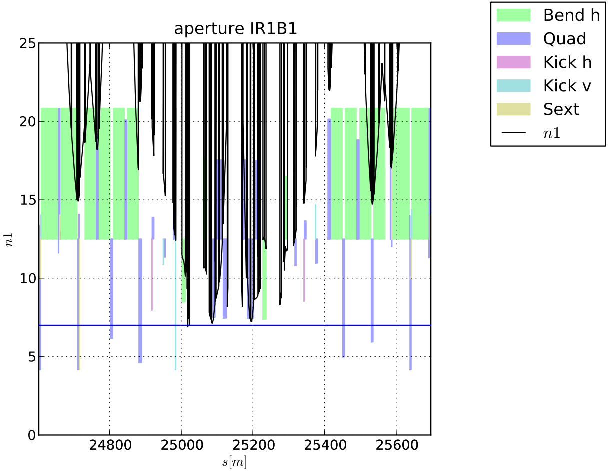
Backup

New IR1,5 elements specifications

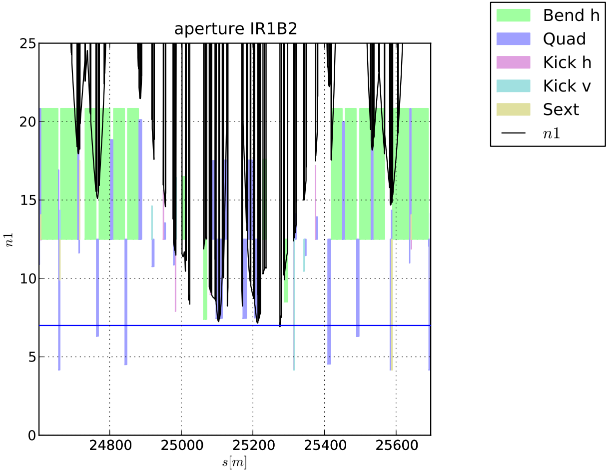
Element	length [m]	field	c.b. ap	b.s ap.	sep.
Q1,Q3	9.145	123 T/m	150	49.5,30.7	n/a
Q2a,Q2b	7.735	123 T/m	150	62.0,57	n/a
MCBX	1.05	1.1 T	150		
D1	7.735	5.1T			n/a
TAN	3.7	n/a		41,37	0.145
D2	7.735	4.0T	105	37,42	0.186
Q4	3.4	160T/m	85	30,35	0.194
Q5	3.4	160T/m	70	24,28.9	0.194

Aperture



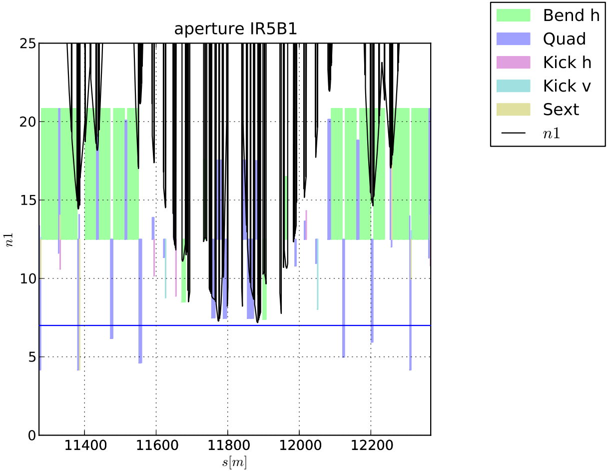
aperture IR1B1
25
20
15
10
5
0
24800
25000
25200
25400
25600
$s[m]$
$n1$
Bend h
Quad
Kick h
Kick v
Sext
$n1$

Aperture



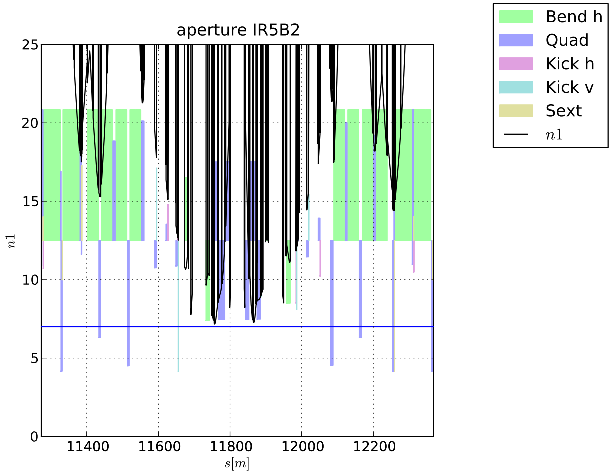
aperture IR1B2
25
20
15
10
5
0
24800
25000
25200
25400
25600
$n1$
$s[m]$
Bend h
Quad
Kick h
Kick v
Sext
$n1$

Aperture



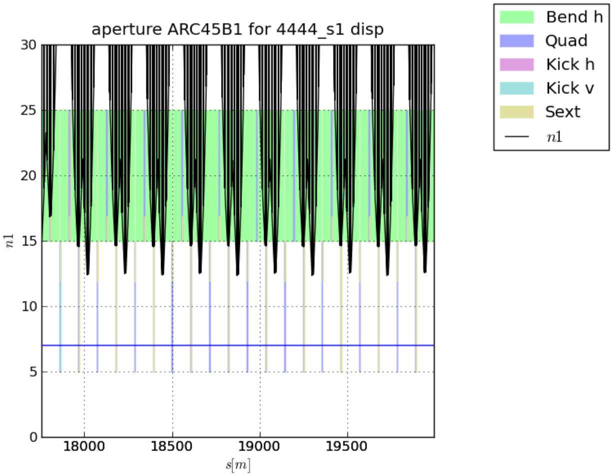
aperture IR5B1
25
20
15
10
5
0
11400
11600
11800
12000
12200
$s[m]$
$n1$
Bend h
Quad
Kick h
Kick v
Sext
$n1$

Aperture



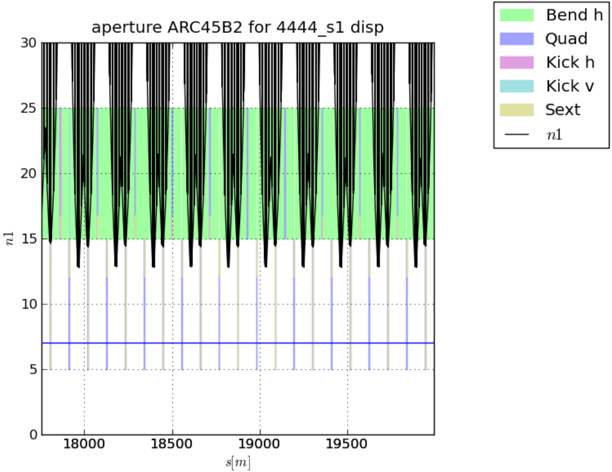
aperture IR5B2
25
20
15
10
5
0
11400
11600
11800
12000
12200
$s[m]$
$n1$
Bend h
Quad
Kick h
Kick v
Sext
$n1$

Aperture



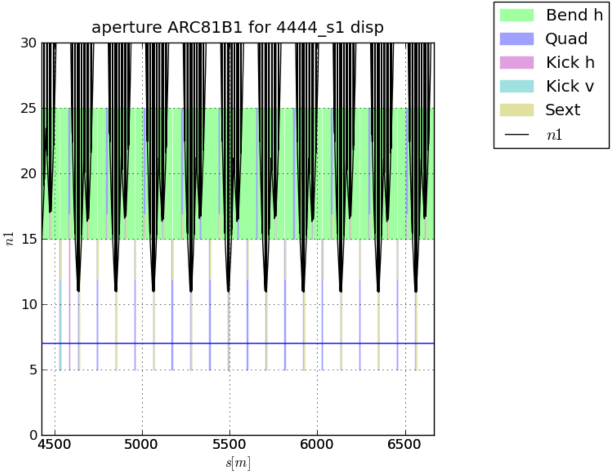
aperture ARC45B1 for 4444_s1 disp
30
25
20
15
10
5
0
$n1$
18000
18500
19000
19500
$s[m]$
Bend h
Quad
Kick h
Kick v
Sext
$n1$

Aperture



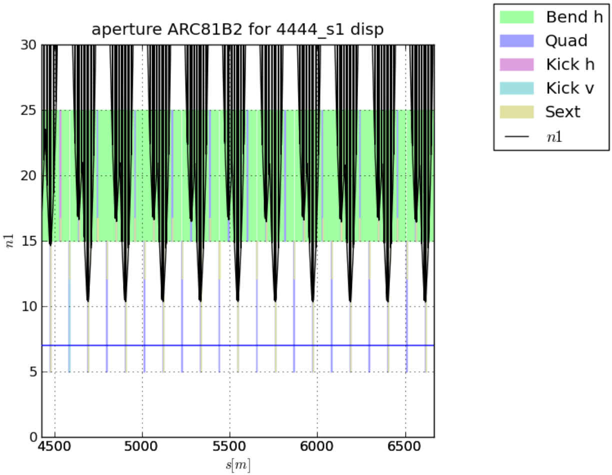
aperture ARC45B2 for 4444_s1 disp
30
25
20
15
10
5
0
n1
18000
18500
19000
19500
s[m]
Bend h
Quad
Kick h
Kick v
Sext
n1

Aperture



aperture ARC81B1 for 4444_s1 disp
30
25
20
15
10
5
0
4500
5000
5500
6000
6500
$n1$
$s[m]$
Bend h
Quad
Kick h
Kick v
Sext
$n1$

Aperture


aperture ARC81B2 for 4444_s1 disp
n1
s[m]
0
5
10
15
20
25
30
4500
5000
5500
6000
6500
Bend h
Quad
Kick h
Kick v
Sext
n1

Tracking studies

- tune (62.28,60.31), (62.31,60.32)
- using $\delta = 0.00027 = (2.5\sigma_\delta)$
- include multipole error a,b from 2 to 15 order for: MB, MBRB, MBRS, MBX, MBW, MBXW
- include multipole error a,b from 3 to 15 order for: MQW, MQTL, MQMC, MQX, MQM, MQML, MQ
- exclude: MQY, new MQX, new D1/D2
- correct triplet error:
  - A2(1,-1), A3(2,1)(1,2) partial with MQSX
  - A3(0,3)(3,0), with MCSSX
  - A4(1,3), A4(3,1), with MCOSX
  - B4(4,0), B4(0,4), B4(2,2) partial with MCOX
  - B3(3,0)(0,3) partial,B3(1,2)(2,1) with MCSX
  - B6(6,0), B6(0,6), B6(4,2) partial, B6(2,4) partial, with MCTX
- correct arcs errors:
  - beta beating and tune with MQT weak sector
  - correct coupling with MQS
  - chromaticity with MS weak sector
  - chromatic coupling with MSS
  - b3 dipoles with MCS
  - b4 dipoles with MCO full strength
  - b5 dipoles with MCD

DA

ms (no imperfection), mb (imperfection excluding new elements), mbdc (with dispersion correction)

		15	30	45	60	75
jobslhc3_1_4444_ms_v1	min	[27.42	25.68	24.58	17.99	22.56]
jobslhc3_1_4444_mbdc_v1	min	[16.85	17.17	16.32	13.42	14.19]
jobslhc3_1_4444_mb_v5	min	[15.72	16.41	15.86	13.25	14.48]
jobslhc3_1_4444_mbdc_v1	avg	[17.46	17.9	17.11	14.31	14.64]
jobslhc3_1_4444_mb_v5	avg	[16.75	18.38	17.14	14.25	15.28]
jobslhc3_1_4444_mbdc_v1	max	[18.21	18.87	18.08	14.97	15.21]
jobslhc3_1_4444_mb_v5	max	[17.79	22.15	18.2	14.96	16.05]
jobslhc3_2_4444_ms_v1	min	[25.65	-28.	26.12	-28.	-28.]
jobslhc3_2_4444_mb_v5	min	[16.9	17.79	17.93	17.24	16.11]
jobslhc3_2_4444_mbdc_v1	min	[17.07	16.55	16.41	16.28	14.97]
jobslhc3_2_4444_mb_v5	avg	[18.34	20.35	19.38	18.38	16.74]
jobslhc3_2_4444_mbdc_v1	avg	[17.72	17.95	17.55	16.97	15.64]
jobslhc3_2_4444_mb_v5	max	[19.56	22.52	21.97	19.91	17.68]
jobslhc3_2_4444_mbdc_v1	max	[18.68	20.75	18.69	17.72	16.14]

crab beta

names	betx	bety	x	y
CRABA.L5B1	4.259e+03	3.928e+03	-3.142e-03	-220.842e-06
CRABB.L5B1	4.358e+03	4.243e+03	-3.354e-03	-213.780e-06
CRABB.R5B1	4.093e+03	4.298e+03	3.062e-03	-632.817e-06
CRABA.R5B1	3.784e+03	4.200e+03	2.659e-03	-663.815e-06
CRABA.L1B1	4.158e+03	3.773e+03	-672.423e-06	-2.571e-03
CRABB.L1B1	4.255e+03	4.081e+03	-641.331e-06	-2.974e-03
CRABB.R1B1	4.199e+03	4.346e+03	-239.681e-06	3.266e-03
CRABA.R1B1	3.888e+03	4.247e+03	-246.414e-06	3.054e-03
CRABA.L5B2	3.788e+03	4.192e+03	2.659e-03	646.680e-06
CRABB.L5B2	4.097e+03	4.290e+03	3.062e-03	615.482e-06
CRABB.R5B2	4.363e+03	4.232e+03	-3.354e-03	231.000e-06
CRABA.R5B2	4.264e+03	3.919e+03	-3.142e-03	237.412e-06
CRABA.L1B2	3.885e+03	4.239e+03	246.435e-06	3.054e-03
CRABB.L1B2	4.196e+03	4.338e+03	239.704e-06	3.266e-03
CRABB.R1B2	4.252e+03	4.073e+03	641.310e-06	-2.974e-03
CRABA.R1B2	4.155e+03	3.766e+03	672.402e-06	-2.572e-03