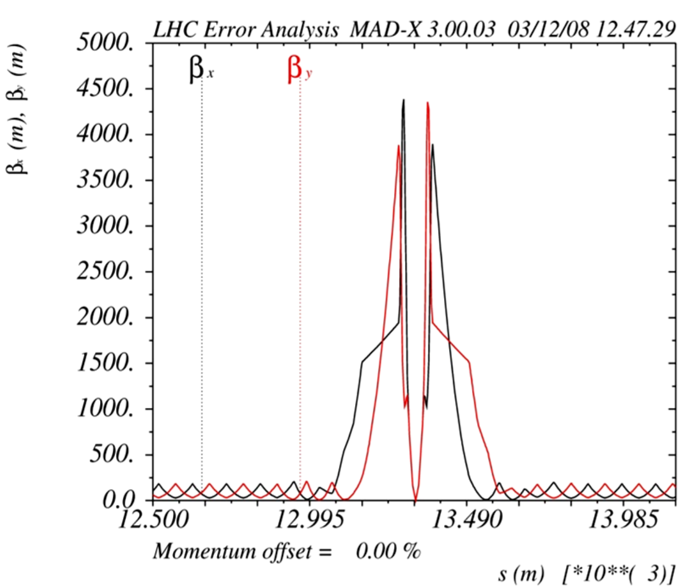
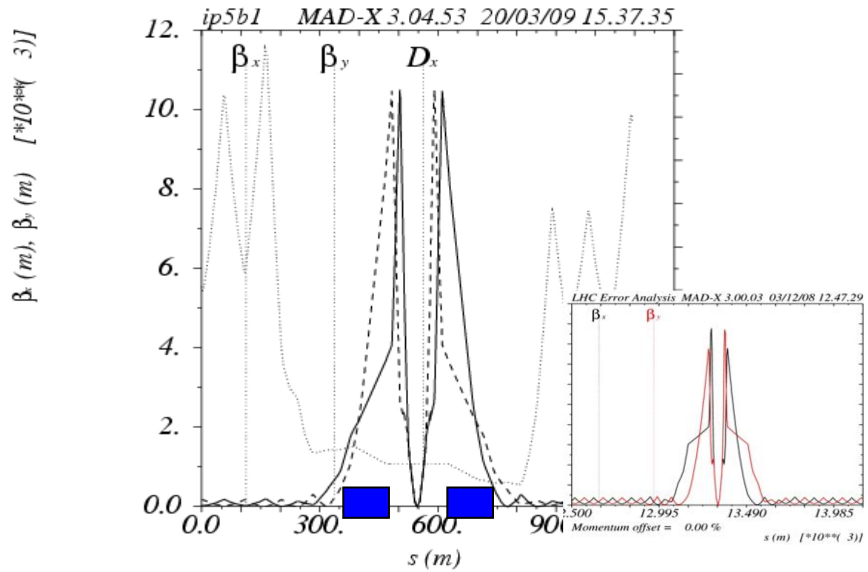
Tracking Calculations and Operational Aspects for the LHC Upgrade
- IT errors in Collision Optics -

Bernhard Holzer, CERN BE-ABP
and many colleagues !!!

LHC Standard Collision Optics ...



and the Upgrade

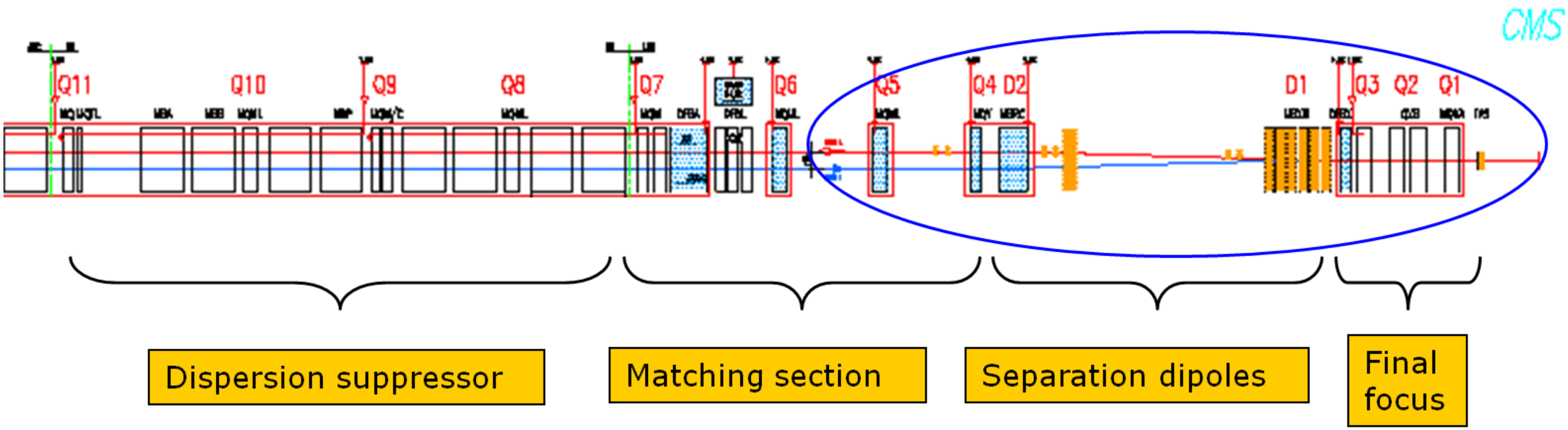


critical issues for the DA ???

error tables ... at the triplett ?
... at the new D1 ?
... at the matching section ?

and which multipoles?

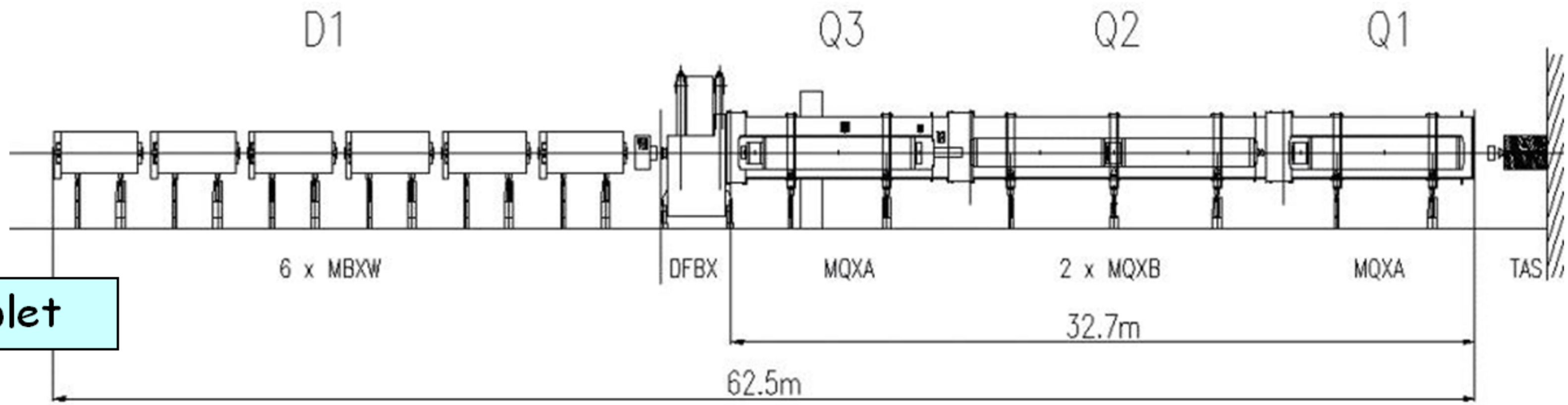
The ATLAS and CMS interaction regions



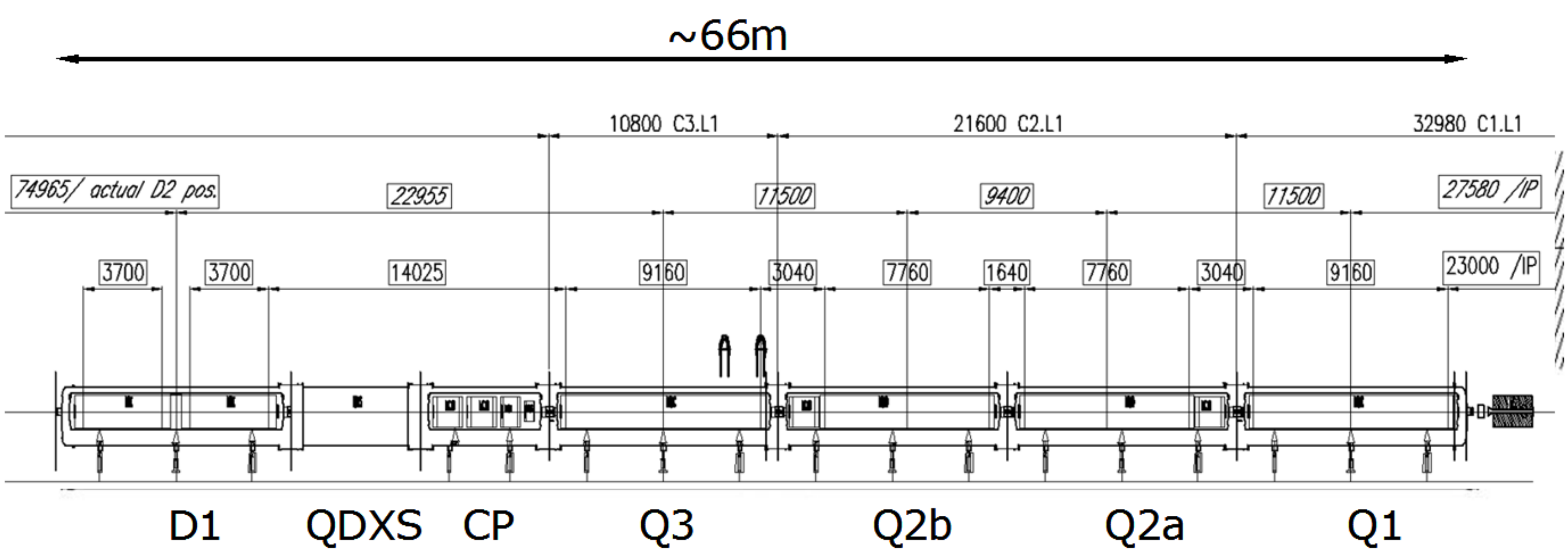
LHC low-β triplet	
• Position	L* = 23 m
• Quad gradient	205 T/m
• Coil aperture	70 mm
• β*, ℒ	55 cm, $10^{34} cm^{-2}s^{-1}$
• Dissipated power	180 W @ 1.9 K

Nominal Luminosity $1 \cdot 10^{34}$ $cm^{-2}s^{-1}$

Interaction Region Layout: Triplet Focusing, D1 Separation Dipole Matching Quadrupoles & Dispersion Suppressor



LHC triplet

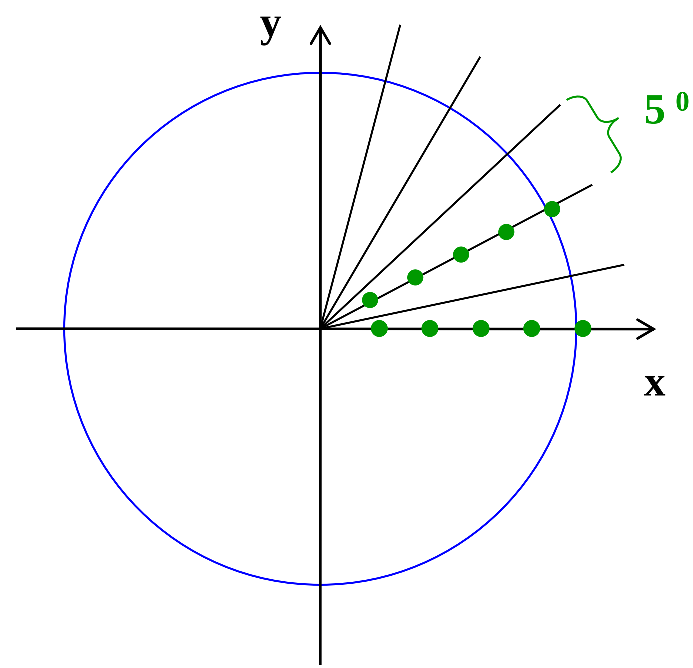


Phase-1 triplet

SIXTRACK

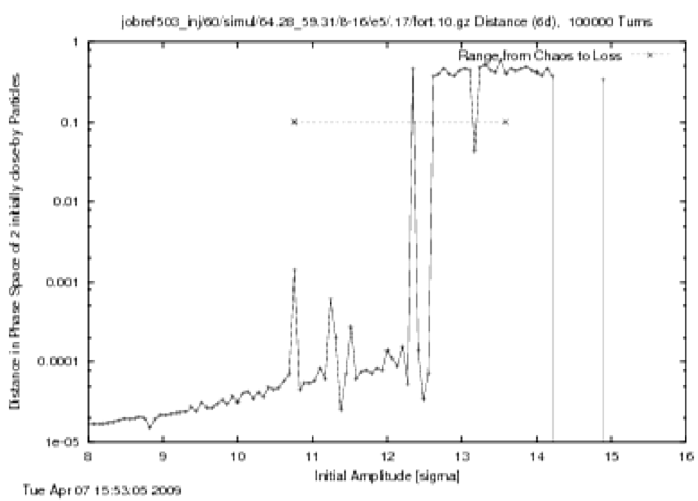
Tracking Parameters:

10^5 turns
30 particle pairs per aperture step
amplitude values 6 ... 22 sigma of the beam size
17 angles -> 5^0 per step
60 seeds of the error distribution
momentum error $\Delta p/p = 2*10^{-3}$

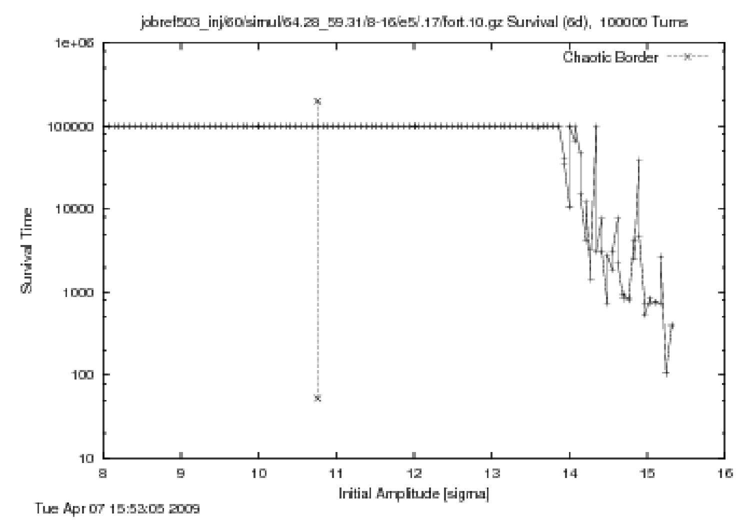


Criteria:

particle survival time, onset of chaotic behavior



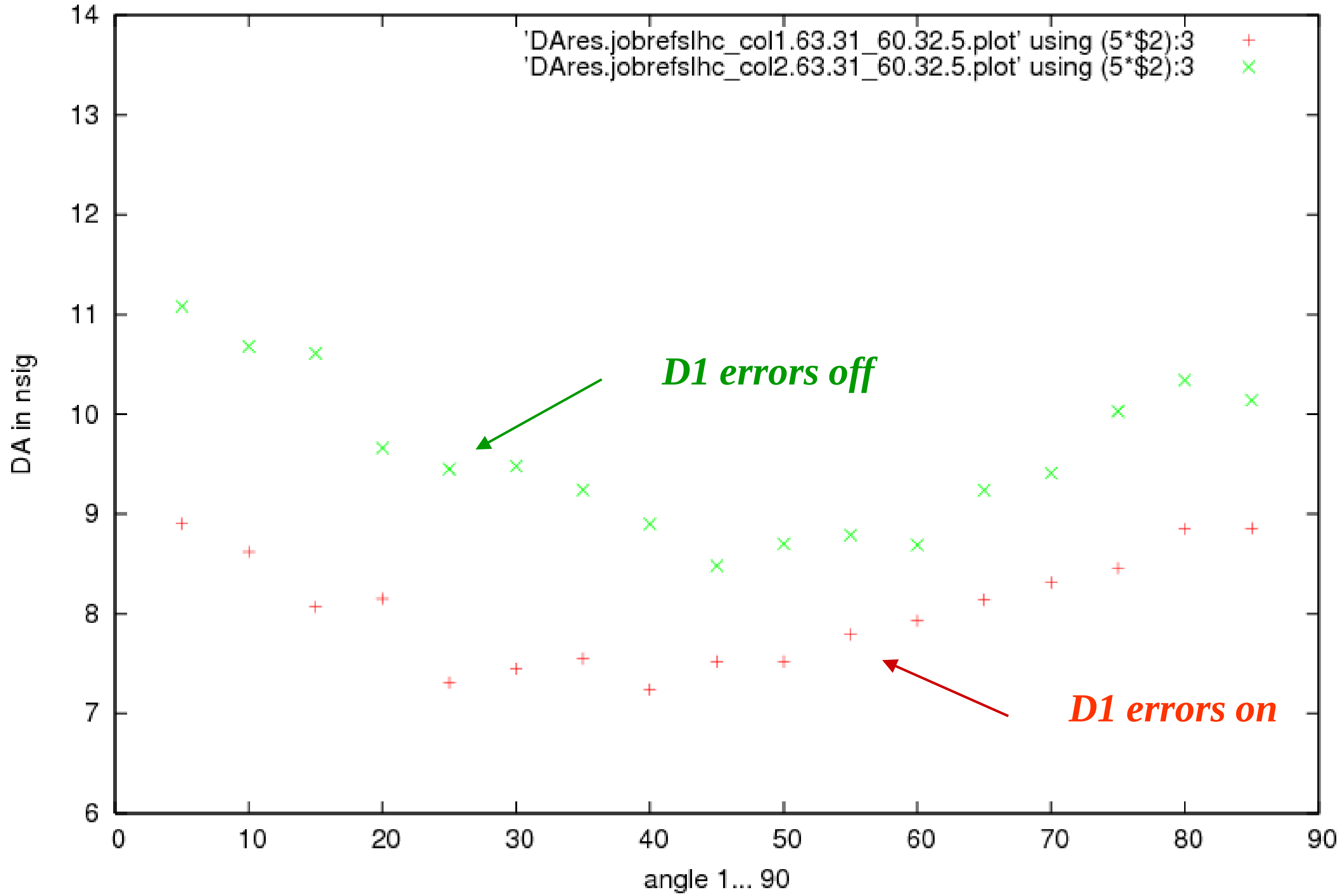
distance of particle pair in phase space



survival time

Reminder: The D1 Magnet "a problem of its own ..."

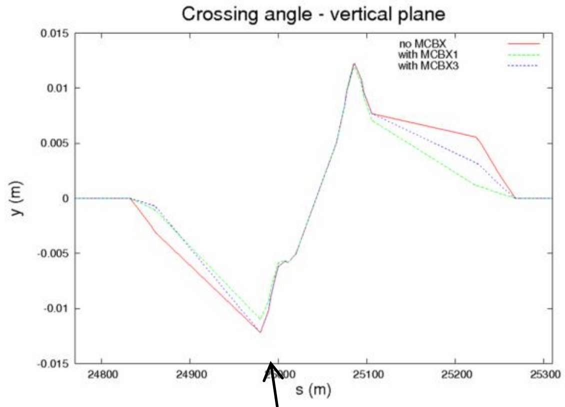
in addition to the effect of the IT we get a strong effect on the Dynamic Aperture
in case of ... D1 errors on
D1 errors off



... the D1 errors needed special investigation

Operational Aspects of the low order D1 multipole errors

to make it even more interesting
large beam offset due to crossing angle
$\Phi/2 = 205\ \mu rad$



tune shift
beta beat — *direct via b2* / *feed down via b3, a3*

coupling — *direct via a2* / *feed down via b3, a3*

$$\Delta Q = \frac{1}{4\pi}\int \beta \Delta k ds$$

$$\frac{\Delta\beta}{\beta} = \frac{1}{2\sin(2\pi Q)}\oint \beta(\tilde{s})(\Delta k(\tilde{s})\cos(2|\phi(\tilde{s})-\phi(s)|-2\pi Q)d\tilde{s}$$

$$c_{-} = \frac{1}{2\pi}\sqrt{\beta_x\beta_y}k_s l_q$$

we assume ...

$$\Delta x_{\max} = 15mm$$

$$\beta = 4km \quad \ldots \quad 10km$$

$$\int Bdl = 30Tm$$

$$B\rho = 23000Tm$$

1.) direct effect from b2

$$\Delta k = \frac{\partial B}{\partial r}\frac{1}{B\rho} = B_0 b_2 \frac{1}{r_0}\frac{1}{B\rho} = \frac{4T * 2.3*10^{-4}}{2.3*10^{4}Tm * 40*10^{-3}m} = 1*10^{-6}\frac{1}{m^2}$$

will cause an optics distortion of

$$\Delta Q \approx \frac{1}{4\pi}\beta \Delta k\, l = \frac{1*10^{-6}/m^2 * 7.4m * 10000m}{4\pi} = 5.8*10^{-3}$$

$$\frac{\Delta\beta}{\beta} \approx \frac{1*10^{-6}/m^2 * 7.4m * 10000\, m}{2*\sin(2\pi Q)} = 4\ \%$$

2.) in-direct effect via feed down from b3

$$k_2 = \frac{\partial^2 B}{\partial r^2}\frac{1}{B\rho} = 2B_0 b_3 \frac{1}{r_0^2}\frac{1}{B\rho}$$

quadrupole error due to feed down:

$$k_1 L = \frac{2B_0 b_3 \Delta x L}{r_0^2}\frac{1}{B\rho} = \frac{2*30Tm*15mm*3*10^{-4}}{(40mm)^2}\frac{1}{2.3*10^{4}Tm}$$

and as effect on the optics we get

$$\Delta Q \approx 5.9*10^{-3} \qquad \frac{\Delta\beta}{\beta} \approx 3.9\ \%$$

per D1 magnet !!!

for Stephane

Remember: phase advance over a mini beta section ≈ π
-> the effects left & right of the IP add up

D1 field specifications

	~V2 values D1	target_10 values D1 tracking	target values D1 operation
reference radius	40 mm	40 mm	40 mm
b 2	0.5+3*0.6 = 2.3	0.5+3*0.6 = 2.3	1.2
a 2	3.0+3*3.5 = 13.5	1.5+3*1.7 = 6.6	2.5
b 3	3.0+3*1.1 = 6.3	1.5+3*0.5 = 3.0	1.2
a 3	2.0+3* 0.3 = 2.9	1.0+3*0.3 = 1.9	1.2

$\Delta\beta/\beta \leq 1\%$
$\Delta Q \leq 0.001$

c_- for the coupling we assume the contribution should not exceed the tolerance for the roll angle error in one triplet quadrupole , ... $\Delta\varphi = 0.1$ mrad

Strategy for Improving the Field Quality of APUL D1 Dipoles
Ramesh Gupta and Peter Wanderer
March 10, 2010

Summary.

Recent accelerator physics studies by Holzer and Fartoukh [1] have established multipole specifications for the D1 dipoles (each consisting of two LDX cold masses [4]) based on dynamic aperture studies and on the effect of low-order terms on the operation of the LHC (tune shift, coupling, beta beat). The specifications were developed for 7 TeV. The specifications based on the dynamic aperture studies are stated as limits on the uncertainty in the mean and on the rms variation. The studies based on operational parameters result in tolerances (hard limits) on the maximum absolute values of the quadrupole and sextupole terms.

These specifications (including the Tolerances in Table 3 of [1]) can be met by adopting the following strategies:

- Reshim collared coils to obtain multipoles within the tolerances for each LDX.
- Before assembly of the four D1 combined cold masses:
  - Cold test all eight individual cold masses
  - Sort and rotate individual cold masses to minimize D1 multipoles
  - Test prototype D1 magnet at CERN
  - Insert iron rods into axial holes in yoke to adjust multipoles at 7 TeV.

The expected values for the low-order D1 multipoles are given at 40 mm reference radius in Table 1, and scaled to 60 mm in Table 2. For all D1s, the quadrupole and sextupole harmonics will fall within the tolerances with 100% confidence level. For these terms,

The Topic of the Day: MQXC Quadrupole

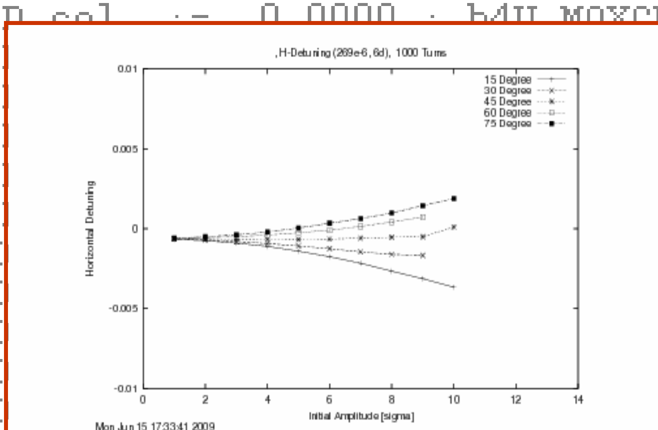
Large Aperture Mini Beta Quad MQXC

- *analyse the multipole errors*
- *determine the dynamic aperture*
- *determine the most harmful harmonics*
- *and establish tolerance limits*

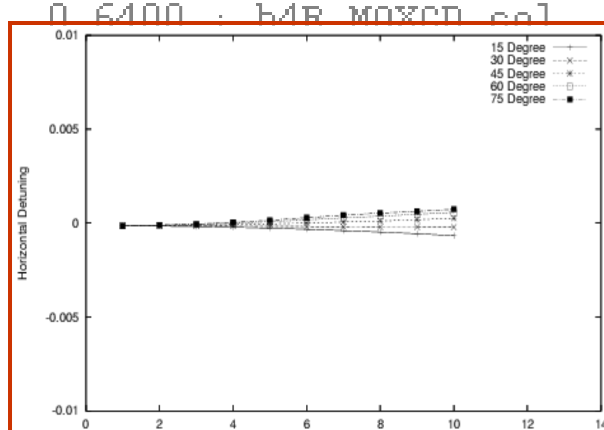
$$B_y + i B_x = B_{ref} * \sum_{n=1}^{\infty} \left(b_n + i a_n\right) \left(\frac{x + i y}{r_0}\right)^{n-1}$$

Qualitative Analysis: Detuning with Amplitude

for the originally given multipole errors

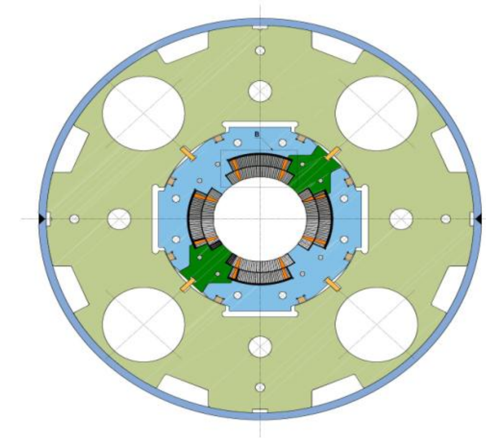


for the optimised field quality



MQXC Quadrupole

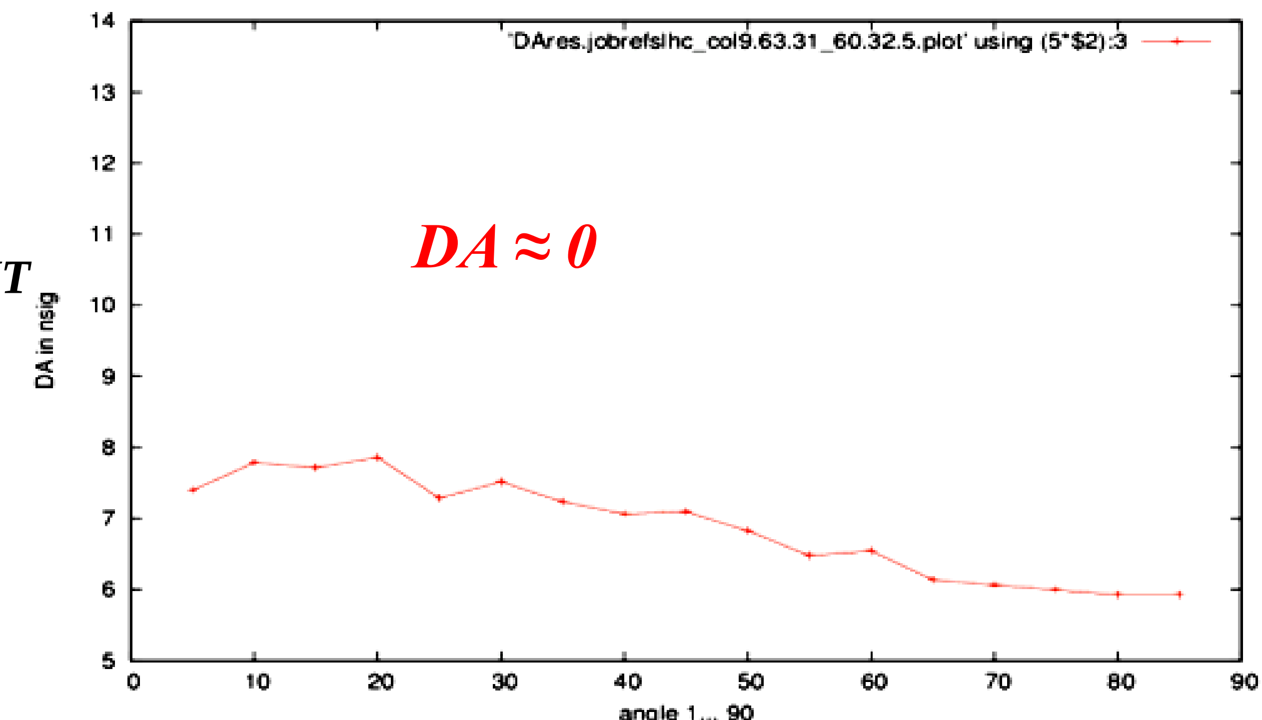
	MQXC	MQXA/B
Coil aperture	*120 mm*	*70 mm*
Gradient	*123 T/m*	*205 T/m*
Operating temperature	*1.9 K*	*1.9 K*
Nominal current	*13.8 kA*	*7 / 12 kA*



large aperture mini beta quadrupole "MQXC"

The Starting Point:

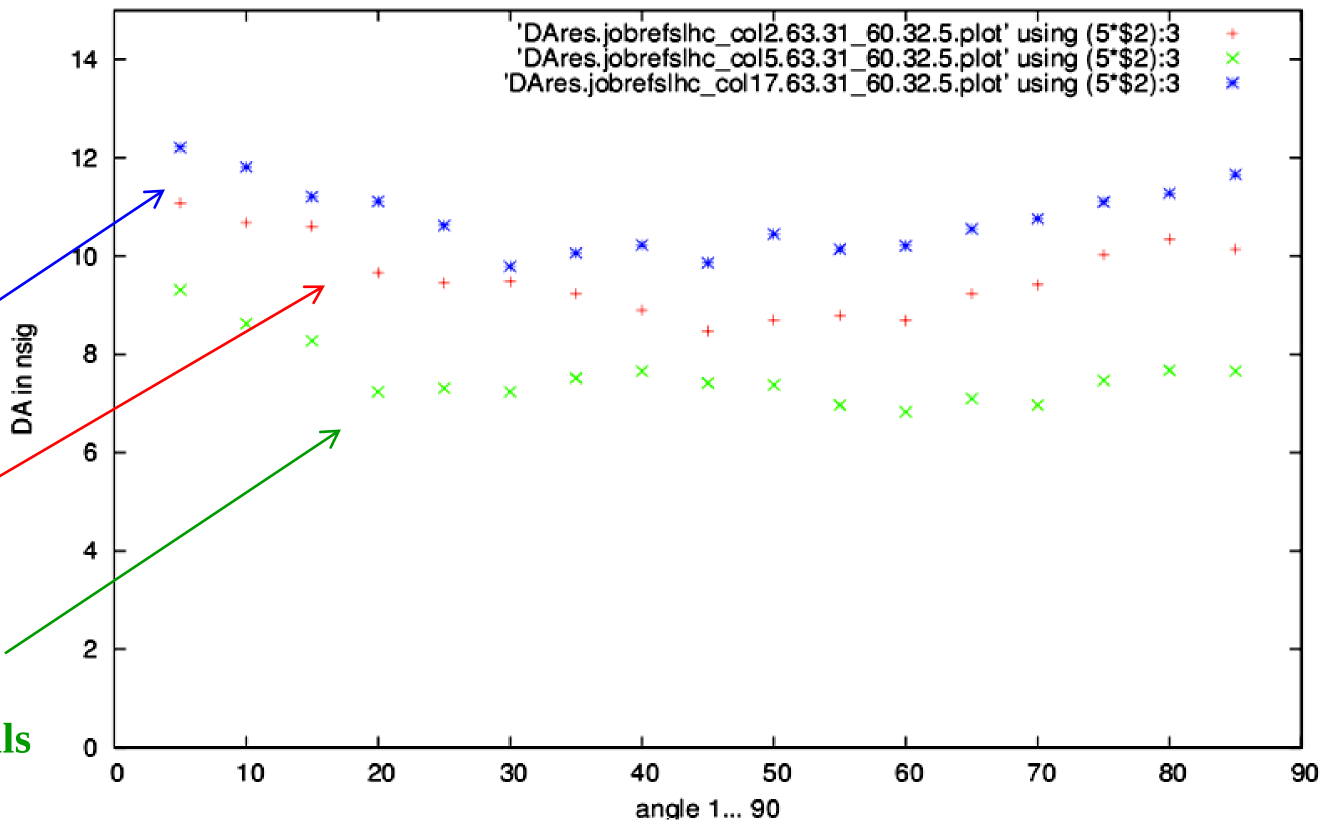
error table ~v2
field harmonics for D1 & IT



MQXC Quadrupole Errors:

Re-Introducing the Multipole Compensation Coils

... to save time, money & space multipole correctors were originally not foreseen (! ?)



a3, b3, a4, b4, b6

b3, b6

no multipole coils

Where does the problem come from ?

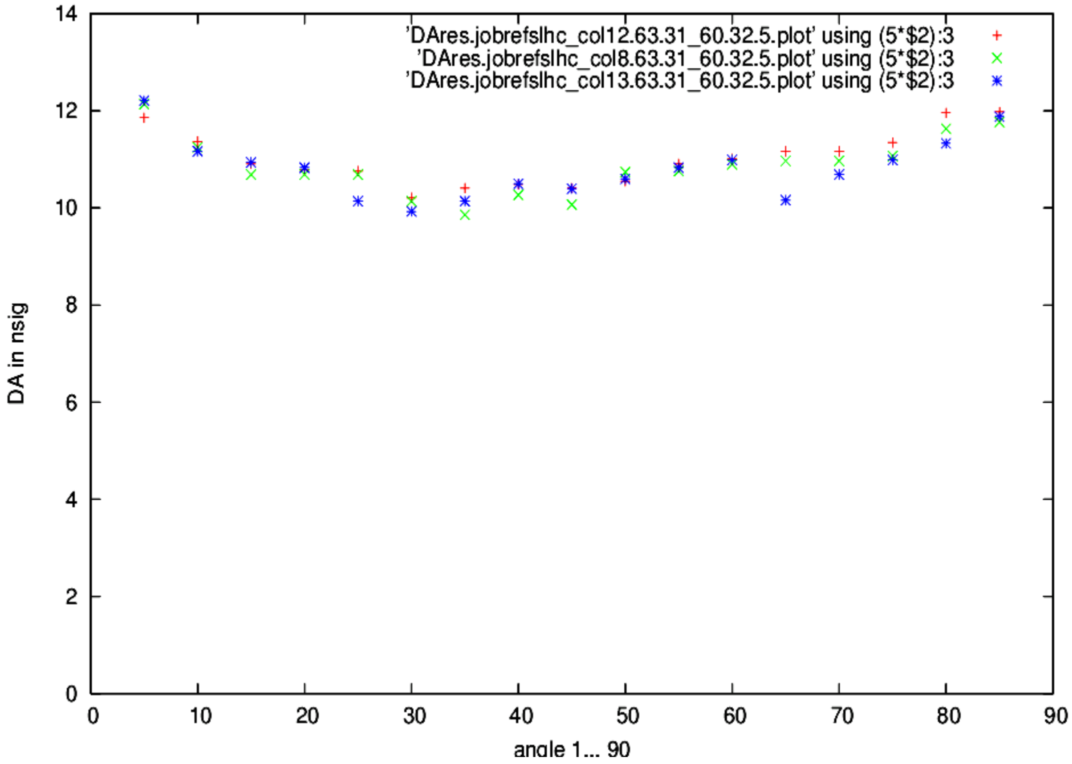
MQXC, matching quadrupoles, dispersion suppressor, D2 ?

errors of the ...

matching quadrupoles switched off

D2 errors switched off

n = 12 ... 15 switched off



The DA is limited by a combination of "low order" field harmonics in the IT quadrupoles (... ignoring the D1 !)

Scaling Multipole Coefficients

simple question: “ ... how to proceed with 36 field harmonics ? ”

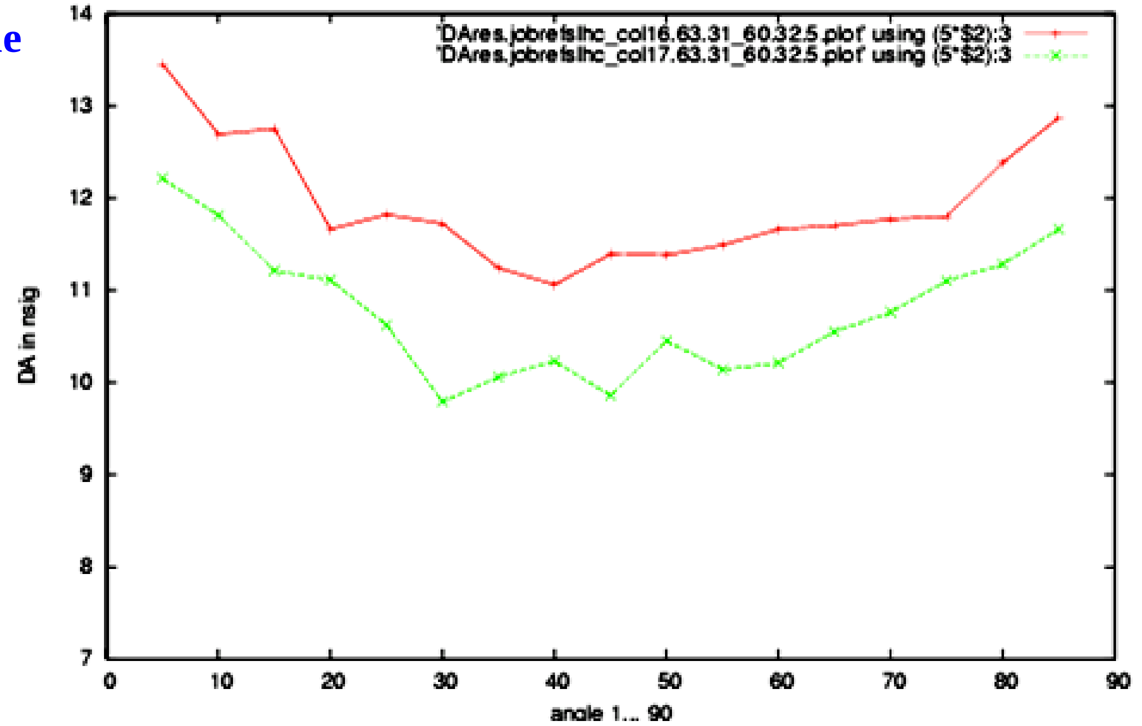
simple answer: take a good quadrupole, scale with respect to reference radius
beta function -> beam sensitivity

choose good (not excellent) quadrupole
MQXB = “Q2”

$$b_{n\,new} = b_{n\,old} * \left(\frac{\hat{\beta}_{old}}{\hat{\beta}_{new}}\right)^{n/2} * \left(\frac{r_{new}}{r_{old}}\right)^{n-2}$$

$$r_{old} = 17\,mm, \quad r_{new} = 40\,mm$$

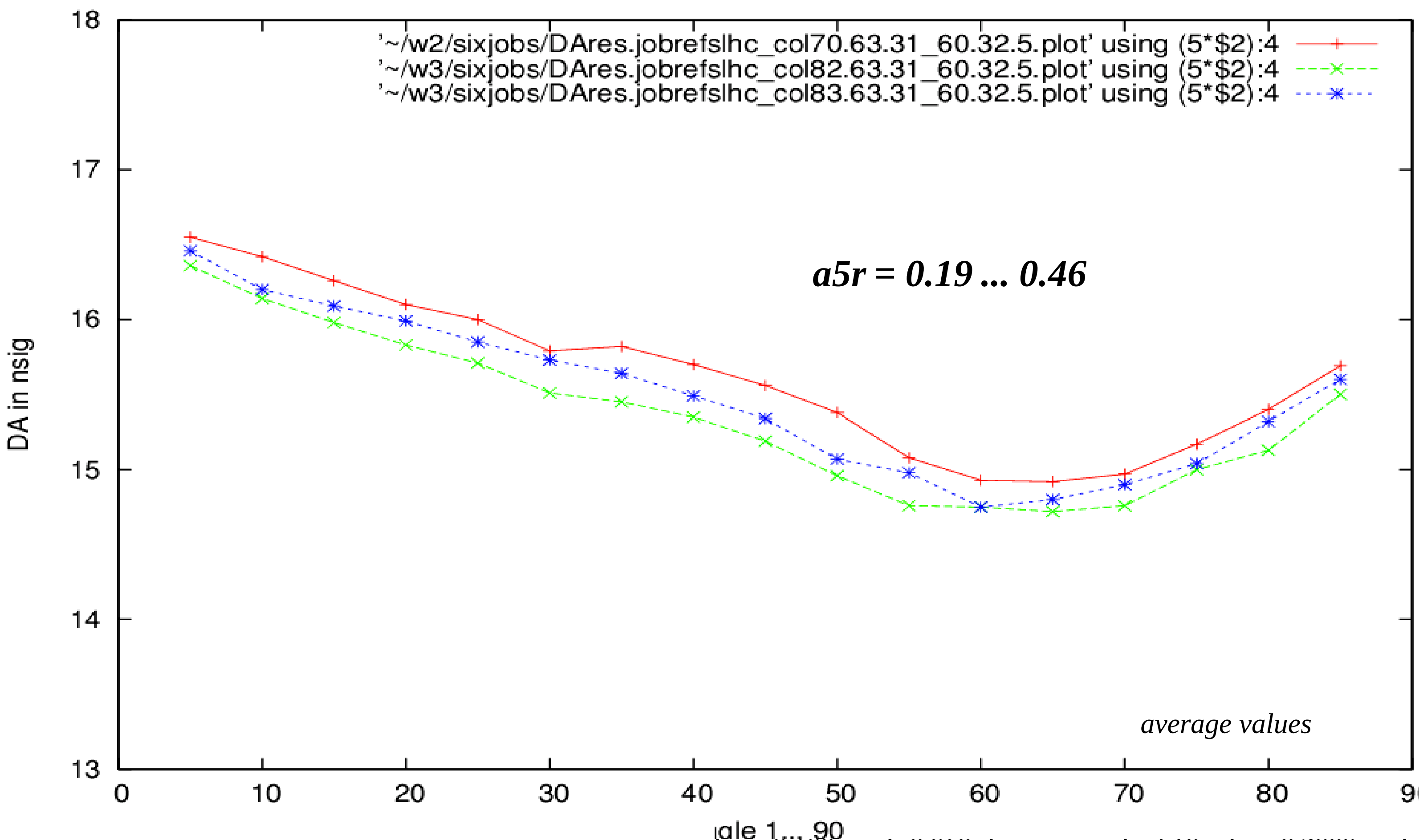
$$\hat{\beta}_{old} = 4.5\,km, \quad \hat{\beta}_{new} = 11\,km$$



Probing Single Multipole Coefficients

error table ~ v2

skew	uncertainty	rms		normal	uncertainty	rms
a1						
a2						
a3						
a4						
a5						
a6						
a7						
a8						
a9						
a10						
a11						
a12						
a13						
a14						
a15						



...et 0

...ns
...000
...000
...485
...144
...303
...648
...118
...455
...08

	0.100	0.060	b10	0.2000	0.060
	0.030	0.030	b11	0.0300	0.030
	0.020	0.020	b12	0.0200	0.020
	0.010	0.010	b13	0.0200	0.010
a14	0.030	0.010	b14	0.0400	0.010
a15	0.000	0.000	b15	0.0000	0.000

In the end and after all: massive tracking studies

≈ 95 studies

≈ 61 error tables

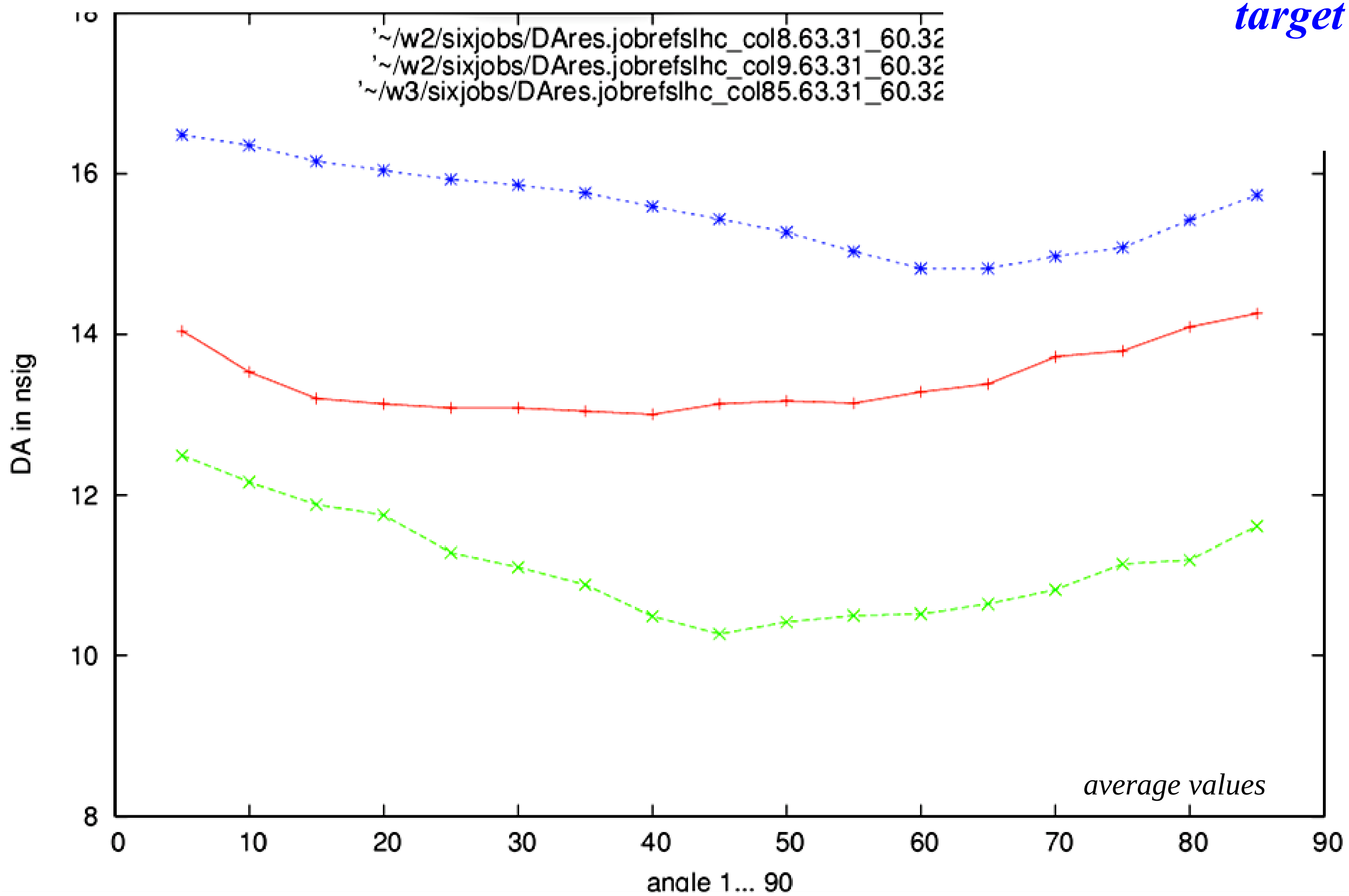
... in the end and after all:

DA resume: (average values)

original errors no correction

~ a3,b3,a4,b4,b6

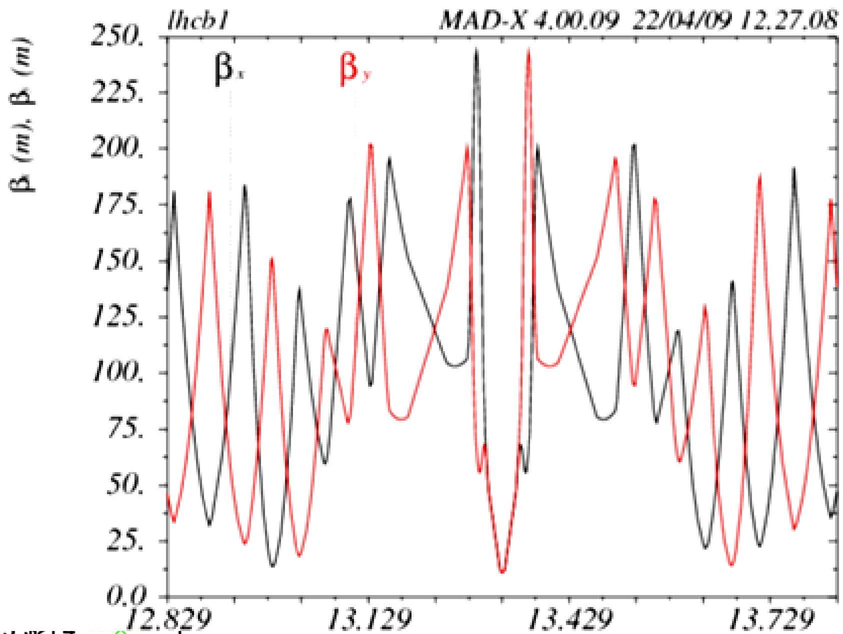
target table "61" & ~

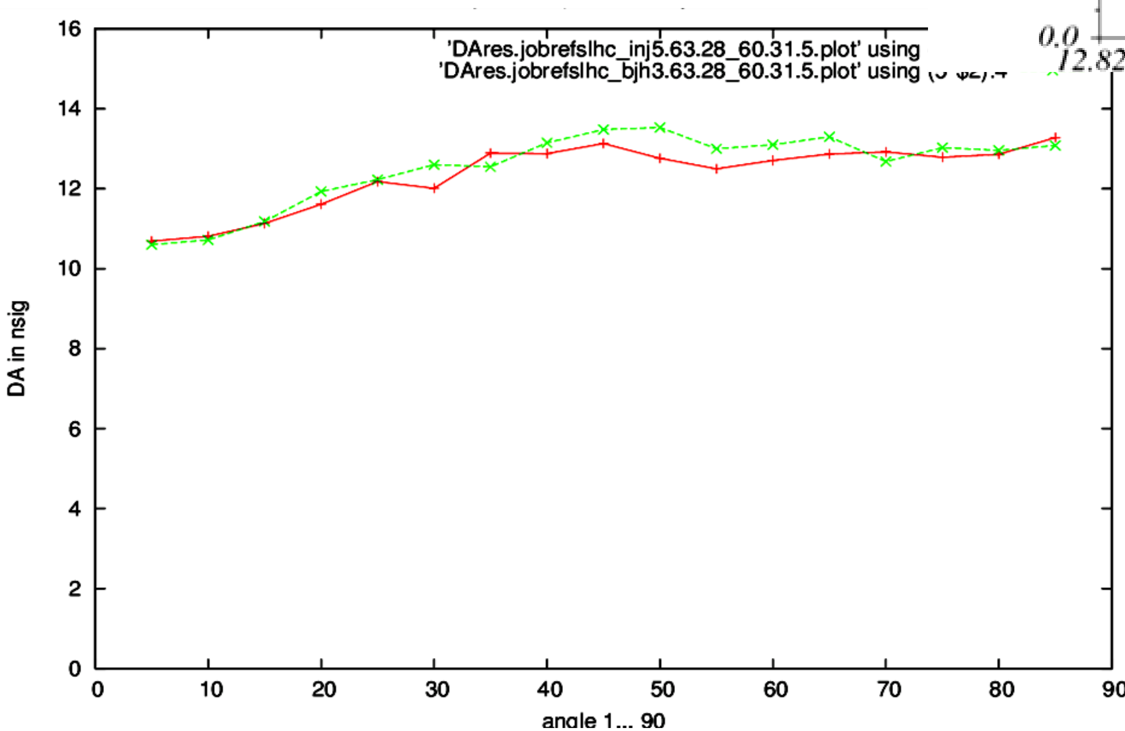


... and a clear field specification for the IT quadrupoles !!!

Injection Optics:

moderate beta values





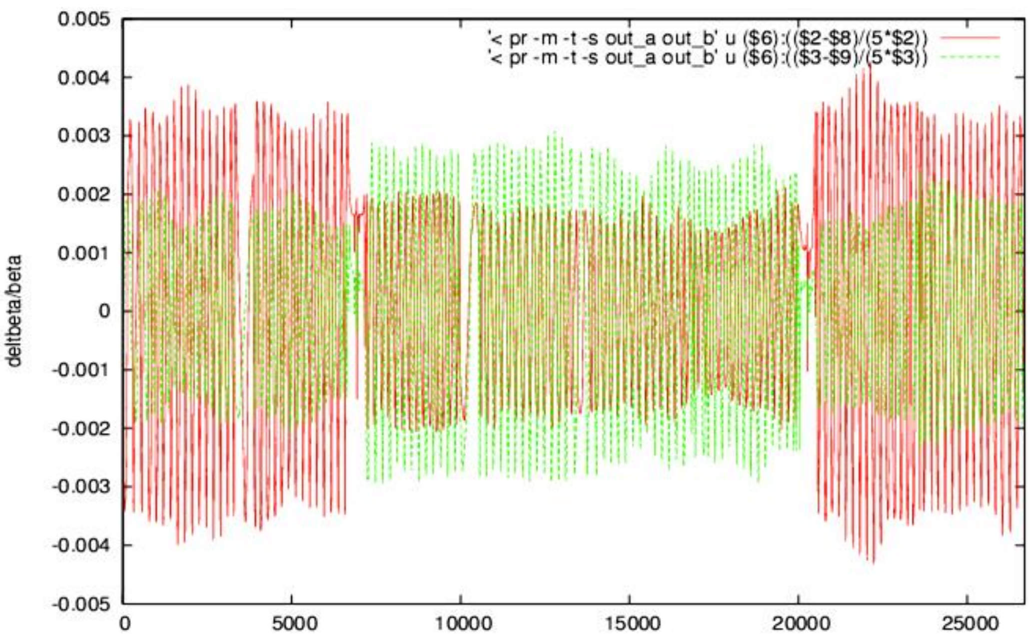
DA with / without errors in the IT Quadrupoles

~ v2 acceptable.

→ room for magnet improvement

Operational Aspects:
Back to Reality ... nothing is perfect

determine feed down effects from crossing angle and non-ideal multipole correctors



calculate optics,
optimise the compensation coil settings,
set a3,b3 correctors → 70 %
correct orbit, Q, Q', coupling

reduce x-angle by 20 %

re-optimise Q, Q', coupling
determine coupling and Δβ/β

for the latest and most beautiful error table,
for 60 seeds

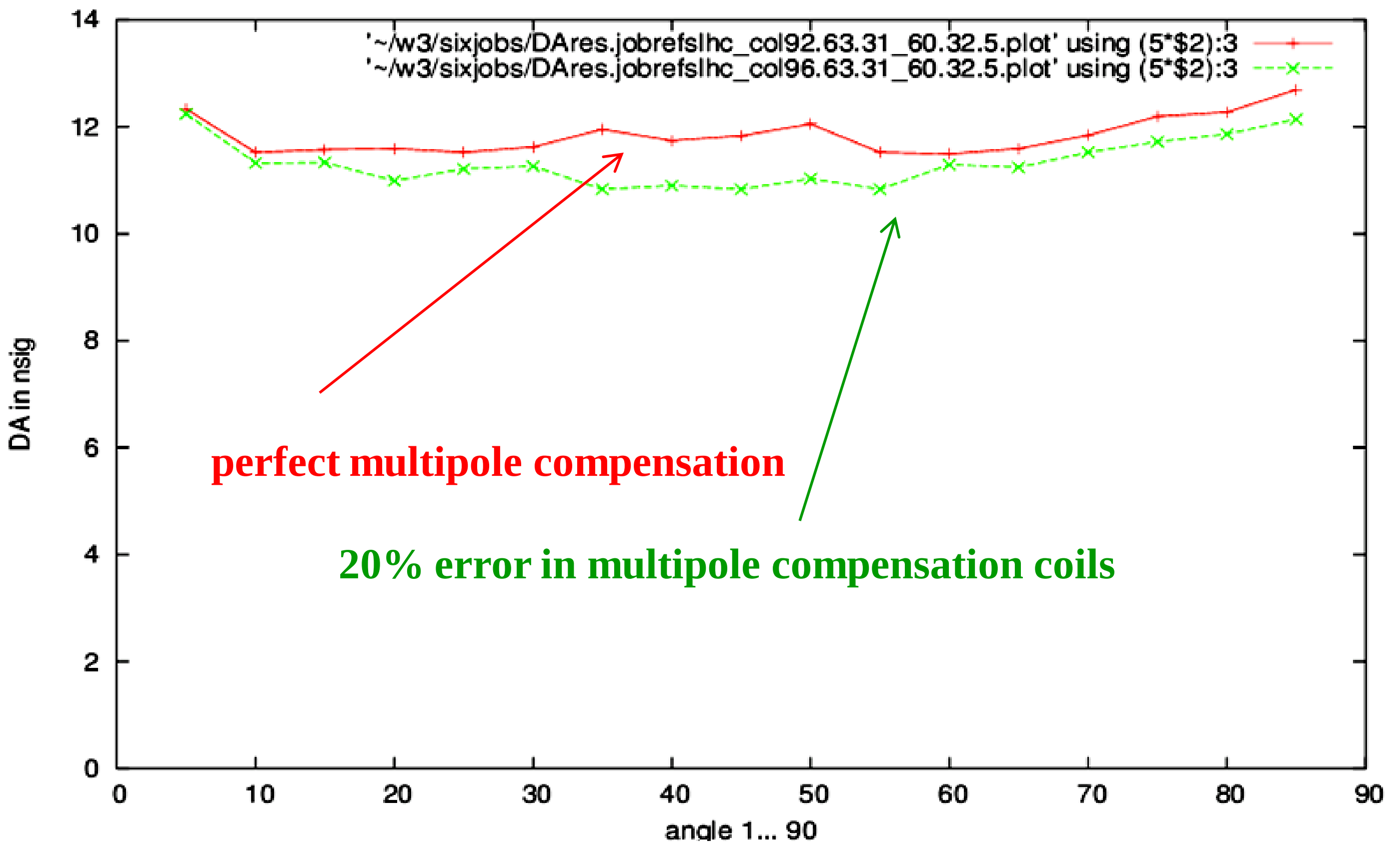
$$\left.\begin{array}{l}\Delta\beta/\beta \le 1.4\% \\ \kappa = 0.88 * 10^{-3}\end{array}\right\}$$

... for the complete machine

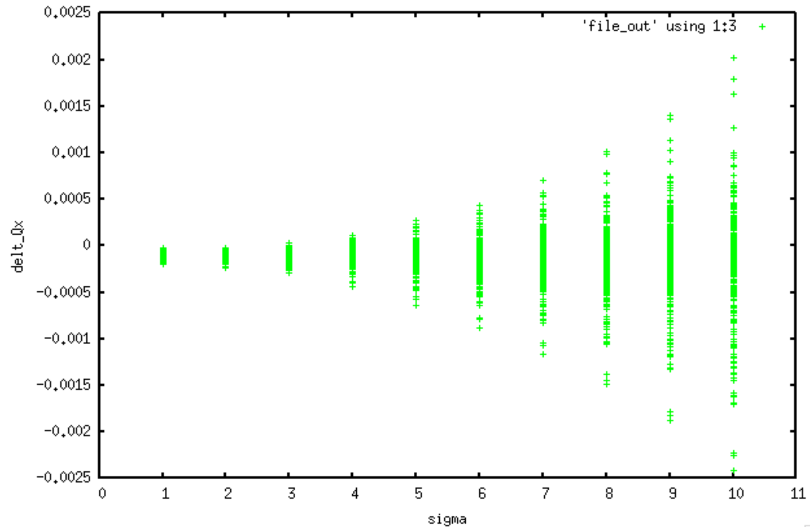
Operational Aspects:
corrector tolerances ... nothing is perfect

calculate optics,
optimise the compensation coil settings,
set all correctors → 80 % **within a 1 σ gaussian distribution,**
correct orbit, Q, Q', coupling

determine DA

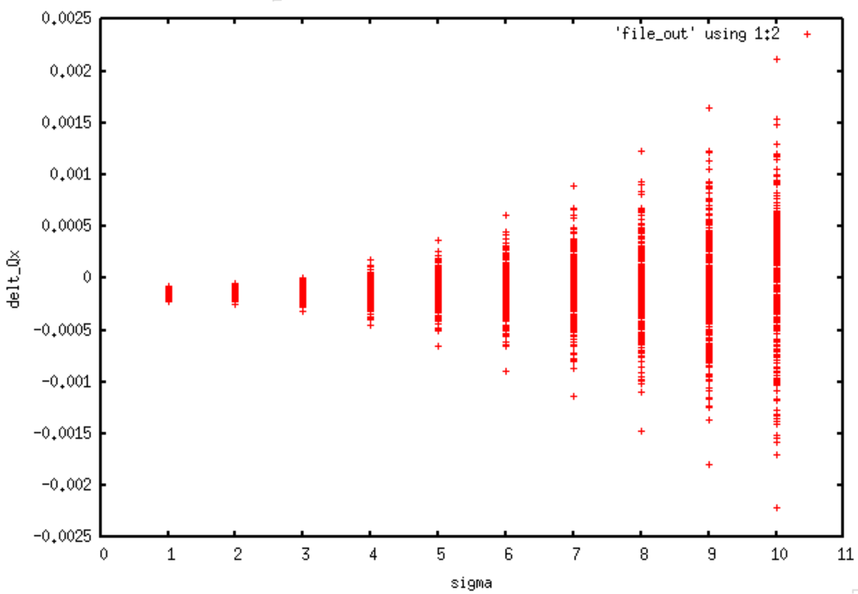


... and back to the start: detuning for new error table all seeds



horizontal detuning

vertical detuning



Error-Tables: Hunting the Mutlipoles

collision, "uncertainty" triplet quadrupoles

bn

~.V2	~target_61
b1U_MQXCD_col := 0.0000	b1U_MQXCD_col := 0.0000
b2U_MQXCD_col := 0.0000	b2U_MQXCD_col := 0.0000
b3U_MQXCD_col := 0.4600	b3U_MQXCD_col := 0.4600
b4U_MQXCD_col := 0.6400	b4U_MQXCD_col := 0.6400
b5U_MQXCD_col := 0.4600	b5U_MQXCD_col := 0.2300
b6U_MQXCD_col := 1.7700	b6U_MQXCD_col := 1.3000
b7U_MQXCD_col := 0.2100	b7U_MQXCD_col := 0.1200
b8U_MQXCD_col := 0.1600	b8U_MQXCD_col := 0.1000
b9U_MQXCD_col := 0.0800	b9U_MQXCD_col := 0.0800
b10U_MQXCD_col := 0.2000	b10U_MQXCD_col := 0.2000
b11U_MQXCD_col := 0.0300	b11U_MQXCD_col := 0.0300
b12U_MQXCD_col := 0.0200	b12U_MQXCD_col := 0.0200
b13U_MQXCD_col := 0.0200	b13U_MQXCD_col := 0.0200
b14U_MQXCD_col := 0.0400	b14U_MQXCD_col := 0.0400
b15U_MQXCD_col := 0.0000	b15U_MQXCD_col := 0.0000

an

~.V2	~target_61
a1U_MQXCD_col := 0.0000	a1U_MQXCD_col := 0.0000
a2U_MQXCD_col := 0.0000	a2U_MQXCD_col := 0.0000
a3U_MQXCD_col := 0.8900	a3U_MQXCD_col := 0.8900
a4U_MQXCD_col := 0.6400	a4U_MQXCD_col := 0.6400
a5U_MQXCD_col := 0.4600	a5U_MQXCD_col := 0.4600
a6U_MQXCD_col := 1.2700	a6U_MQXCD_col := 0.8700
a7U_MQXCD_col := 0.2100	a7U_MQXCD_col := 0.1450
a8U_MQXCD_col := 0.1600	a8U_MQXCD_col := 0.1135
a9U_MQXCD_col := 0.0800	a9U_MQXCD_col := 0.0800
a10U_MQXCD_col := 0.1400	a10U_MQXCD_col := 0.1400
a11U_MQXCD_col := 0.0300	a11U_MQXCD_col := 0.0300
a12U_MQXCD_col := 0.0200	a12U_MQXCD_col := 0.0200
a13U_MQXCD_col := 0.0100	a13U_MQXCD_col := 0.0100
a14U_MQXCD_col := 0.0300	a14U_MQXCD_col := 0.0300
a15U_MQXCD_col := 0.0000	a15U_MQXCD_col := 0.0000

correction scheme: a_3, b_3, a_4, b_4, b_6

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b2R_MQXCD_col := 0.0000	b2R_MQXCD_col := 0.0000
b3R_MQXCD_col := 0.8900	b3R_MQXCD_col := 0.8900
b4R_MQXCD_col := 0.6400	b4R_MQXCD_col := 0.6400
b5R_MQXCD_col := 0.4600	b5R_MQXCD_col := 0.3030
b6R_MQXCD_col := 1.2800	b6R_MQXCD_col := 0.9600
b7R_MQXCD_col := 0.2100	b7R_MQXCD_col := 0.2001
b8R_MQXCD_col := 0.1600	b8R_MQXCD_col := 0.1600
b9R_MQXCD_col := 0.0800	b9R_MQXCD_col := 0.0800
b10R_MQXCD_col := 0.0600	b10R_MQXCD_col := 0.0600
b11R_MQXCD_col := 0.0300	b11R_MQXCD_col := 0.0300
b12R_MQXCD_col := 0.0200	b12R_MQXCD_col := 0.0200
b13R_MQXCD_col := 0.0100	b13R_MQXCD_col := 0.0100
b14R_MQXCD_col := 0.0100	b14R_MQXCD_col := 0.0100
b15R_MQXCD_col := 0.0000	b15R_MQXCD_col := 0.0000

an

~.V2	~target_61
a1R_MQXCD_col := 0.0000	a1R_MQXCD_col := 0.0000
a2R_MQXCD_col := 0.0000	a2R_MQXCD_col := 0.0000
a3R_MQXCD_col := 0.8900	a3R_MQXCD_col := 0.8900
a4R_MQXCD_col := 0.6400	a4R_MQXCD_col := 0.640
a5R_MQXCD_col := 0.4600	a5R_MQXCD_col := 0.1980
a6R_MQXCD_col := 0.3300	a6R_MQXCD_col := 0.3300
a7R_MQXCD_col := 0.2100	a7R_MQXCD_col := 0.2000
a8R_MQXCD_col := 0.1600	a8R_MQXCD_col := 0.1600
a9R_MQXCD_col := 0.0800	a9R_MQXCD_col := 0.0800
a10R_MQXCD_col := 0.0600	a10R_MQXCD_col := 0.0600
a11R_MQXCD_col := 0.0300	a11R_MQXCD_col := 0.0300
a12R_MQXCD_col := 0.0200	a12R_MQXCD_col := 0.0200
a13R_MQXCD_col := 0.0100	a13R_MQXCD_col := 0.0100
a14R_MQXCD_col := 0.0100	a14R_MQXCD_col := 0.0100
a15R_MQXCD_col := 0.0000	a15R_MQXCD_col := 0.0000

correction scheme: a_3, b_3, a_4, b_4, b_6

Tracking Calculations and Operational Aspects for the LHC Upgrade
- IT errors in Collision Optics -

after 96 studies, 61 target error tables, 157 liter coffee

... the job is done.

more details - including the full multipole specification – can be found in two SLHC reports:

“Linear imperfections and Operational Aspects Induced by the D1 Multipole Errors for the LHC Upgrade Phase-1”

“Dynamic Aperture Studies and Field Quality Specifications for the Triplet Quadrupoles of the LHC Phase-1 Upgrade”

and I can concentrate on additional tasks ...