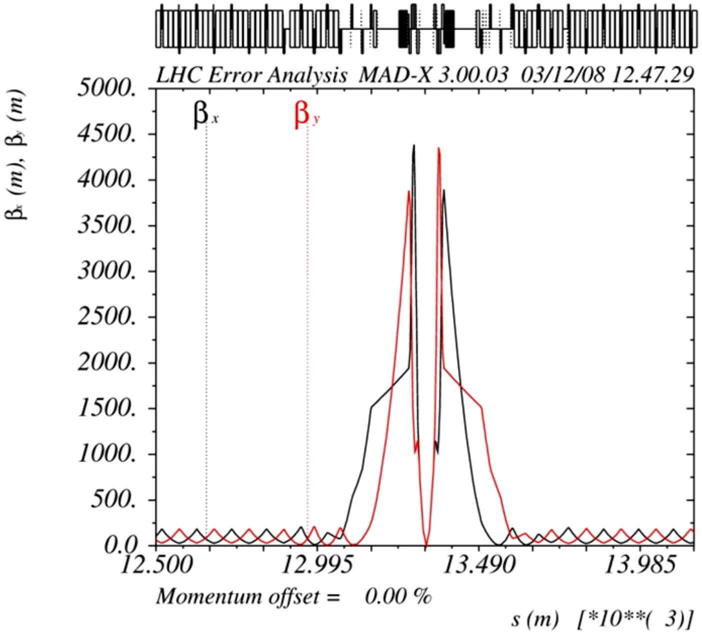
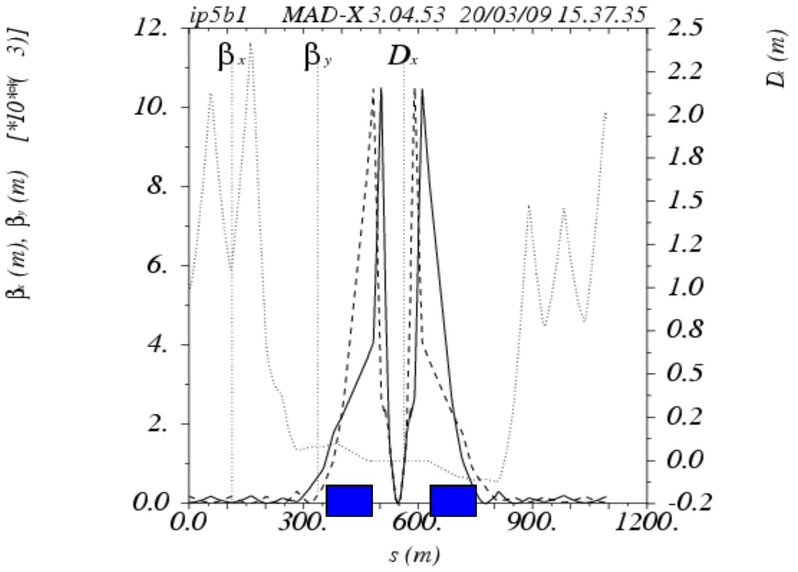
Tracking Calculations and Operational Aspects for the LHC Upgrade
- D1 errors in Collision Optics -

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

LHC Standard Collision Optics ...



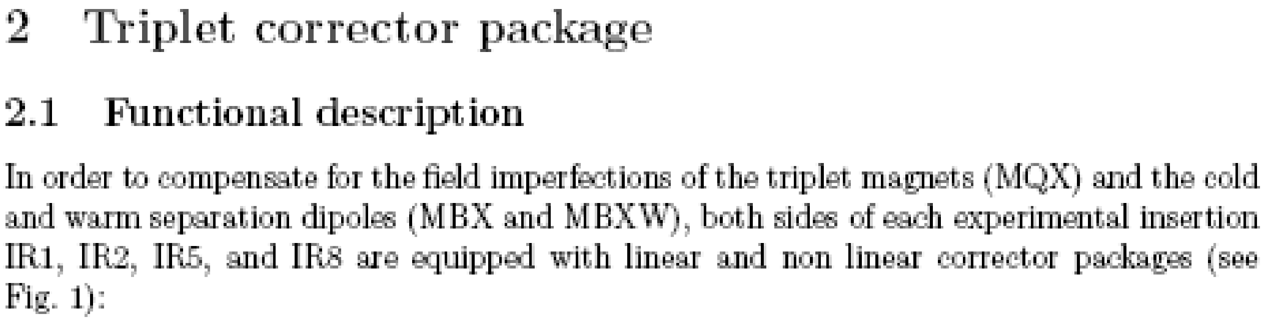
and the Upgrade



critical issues for the DA ???

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

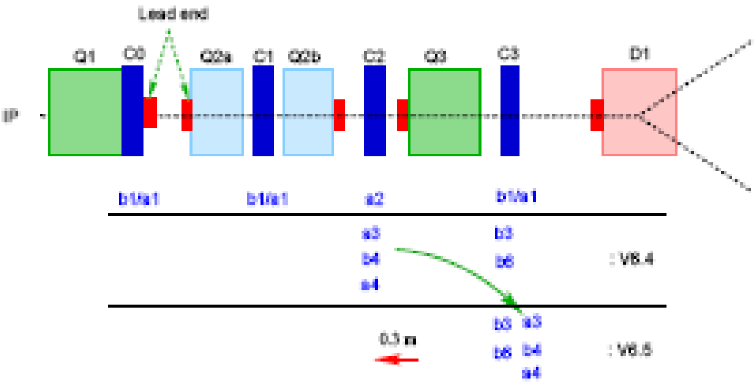
and which multipoles?



2 Triplet corrector package

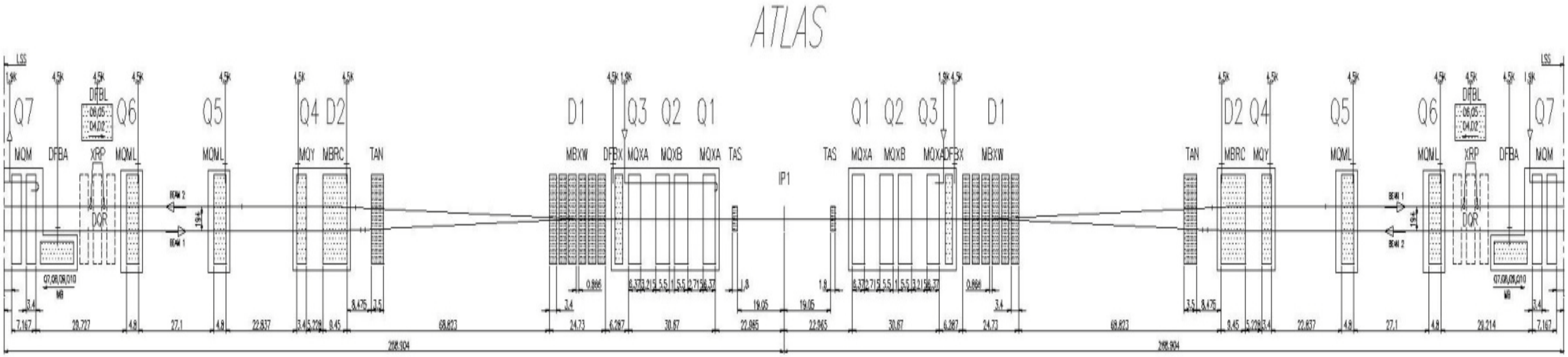
2.1 Functional description

In order to compensate for the field imperfections of the triplet magnets (MQX) and the cold and warm separation dipoles (MBX and MBXW), both sides of each experimental insertion IR1, IR2, IR5, and IR8 are equipped with linear and non linear corrector packages (see Fig. 1):



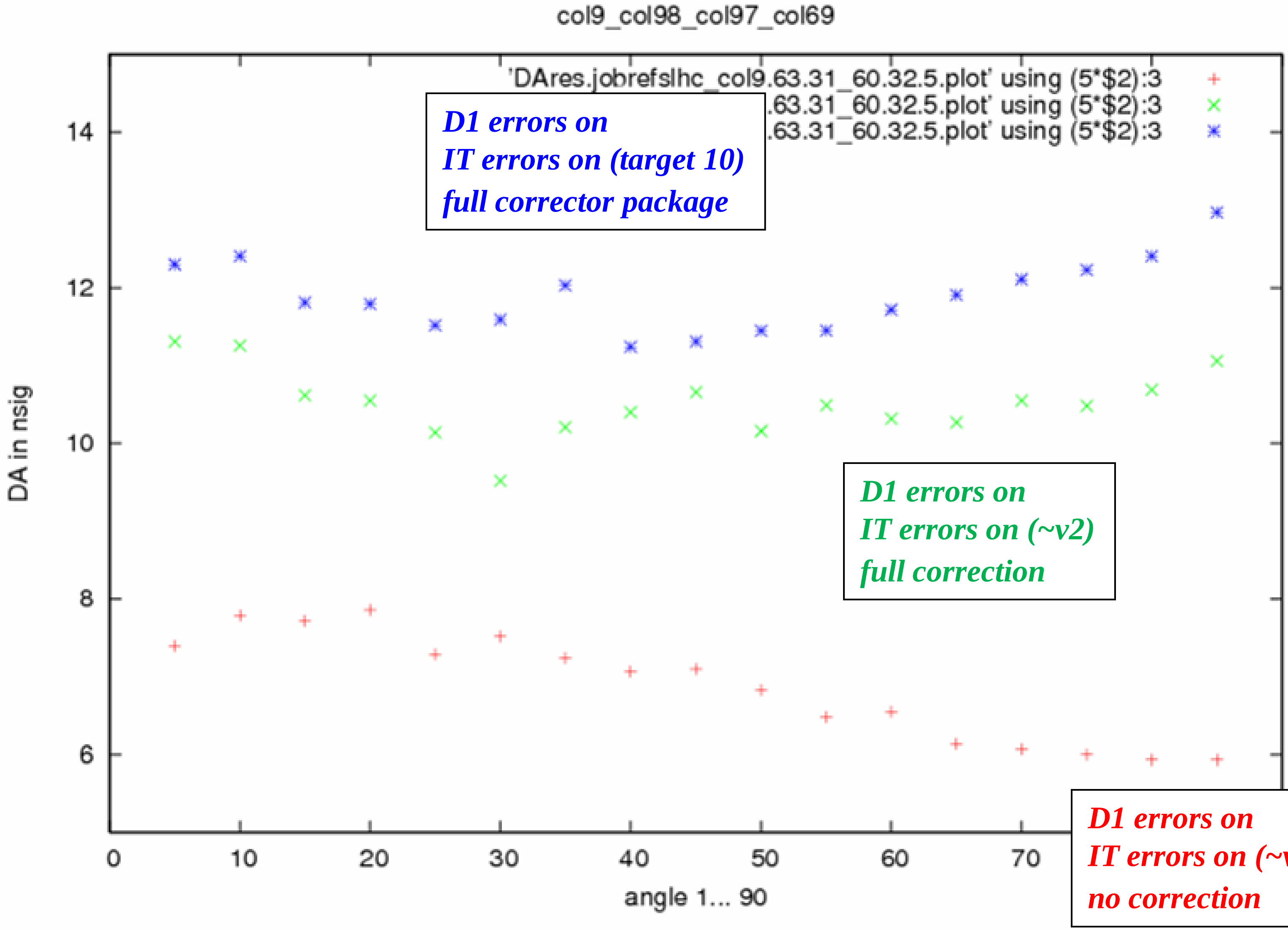
Problem:

multipole coefficients from
Q1, Q2, Q3 & D1 ... and beyond ??
how many multipole correctors do we need ?



SLHC/errors/ ITD1 Error Table_ V2

```
! -----------------------------------------------------------------------
! ************************ Magnet type : MBXAB (new D1) ****
! -----------------------------------------------------------------------

    !                    bn in collision (7500A)
    b1M_MBXAB_col  :=  0.0000 ; b1U_MBXAB_col  :=  0.0000 ; b1R_MBXAB_col  :=  0.0000 ;

    b2M_MBXAB_col  :=  0.0000 ; b2U_MBXAB_col  :=  0.5000 ; b2R_MBXAB_col  :=  0.6000 ;

    b3M_MBXAB_col  :=  0.0000 ; b3U_MBXAB_col  :=  3.0000 ; b3R_MBXAB_col  :=  1.1000 ;

    b4M_MBXAB_col  :=  0.0000 ; b4U_MBXAB_col  :=  0.2000 ; b4R_MBXAB_col  :=  0.1000 ;

    b5M_MBXAB_col  :=  0.0000 ; b5U_MBXAB_col  :=  1.0000 ; b5R_MBXAB_col  :=  0.1000 ;

    b6M_MBXAB_col  :=  0.0000 ; b6U_MBXAB_col  :=  0.0500 ; b6R_MBXAB_col  :=  0.0200 ;

    b7M_MBXAB_col  := -0.2000 ; b7U_MBXAB_col  :=  0.3000 ; b7R_MBXAB_col  :=  0.0200 ;

    b8M_MBXAB_col  :=  0.0000 ; b8U_MBXAB_col  :=  0.0020 ; b8R_MBXAB_col  :=  0.0030 ;

    b9M_MBXAB_col  := -0.0500 ; b9U_MBXAB_col  :=  0.1000 ; b9R_MBXAB_col  :=  0.0030 ;

    b10M_MBXAB_col :=  0.0000 ; b10U_MBXAB_col :=  0.0010 ; b10R_MBXAB_col :=  0.0010 ;

    b11M_MBXAB_col := -0.0200 ; b11U_MBXAB_col :=  0.0200 ; b11R_MBXAB_col :=  0.0003 ;

    b12M_MBXAB_col :=  0.0000 ; b12U_MBXAB_col :=  0.0001 ; b12R_MBXAB_col :=  0.0001 ;

    b13M_MBXAB_col :=  0.0100 ; b13U_MBXAB_col :=  0.0100 ; b13R_MBXAB_col :=  0.0001 ;

    b14M_MBXAB_col :=  0.0000 ; b14U_MBXAB_col :=  0.0001 ; b14R_MBXAB_col :=  0.0001 ;

    b15M_MBXAB_col :=  0.0000 ; b15U_MBXAB_col :=  0.0001 ; b15R_MBXAB_col :=  0.0001 ;
```



D1 errors on
IT errors on (target 10)
full corrector package

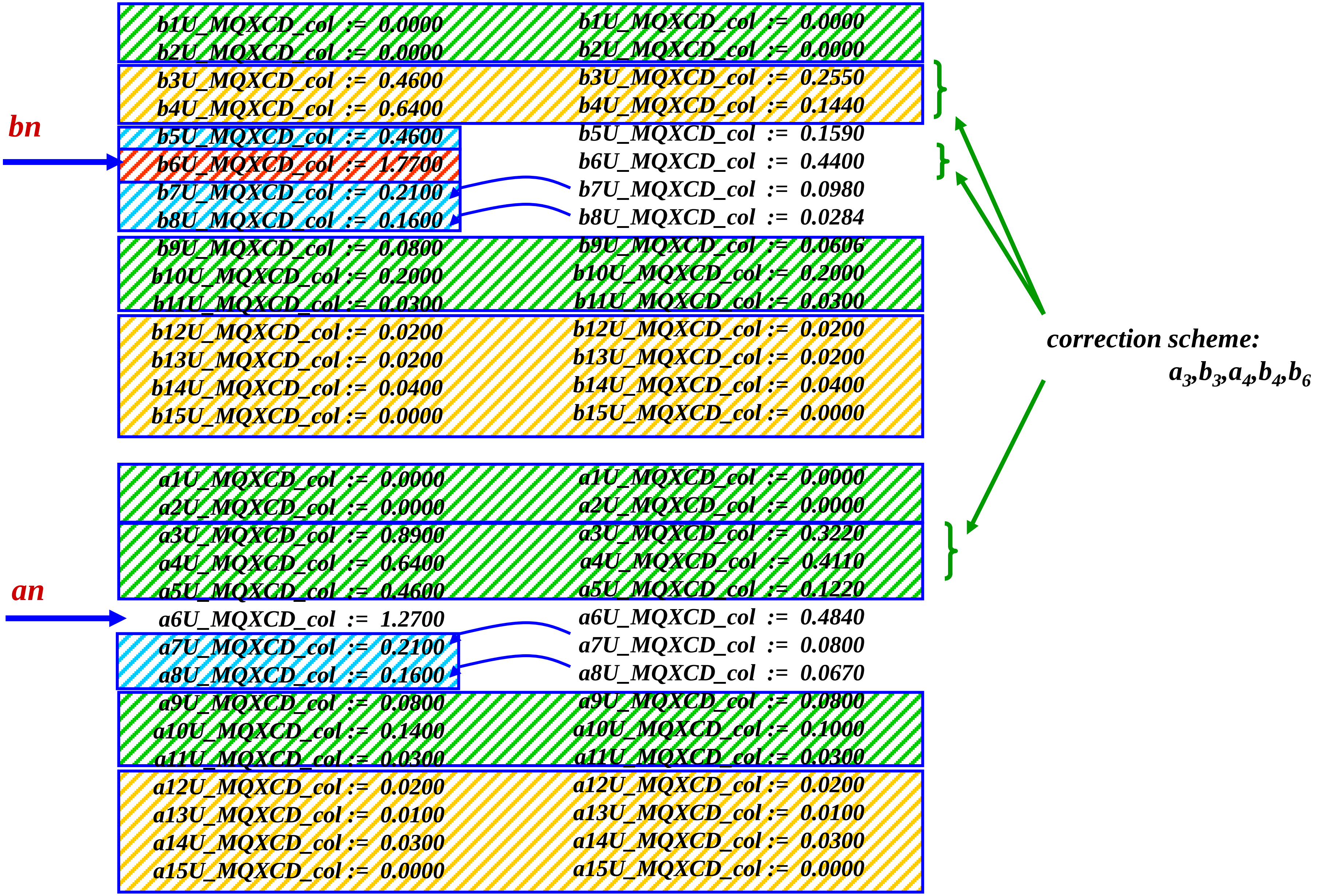
D1 errors on
IT errors on (~v2)
full correction

D1 errors on
IT errors on (~v1)
no correction

"full corrector package": a3,b3,a4,b4,b6

Error-Tables: Hunting the Mutlipoles

collision, "uncertainty"
triplet quadrupoles

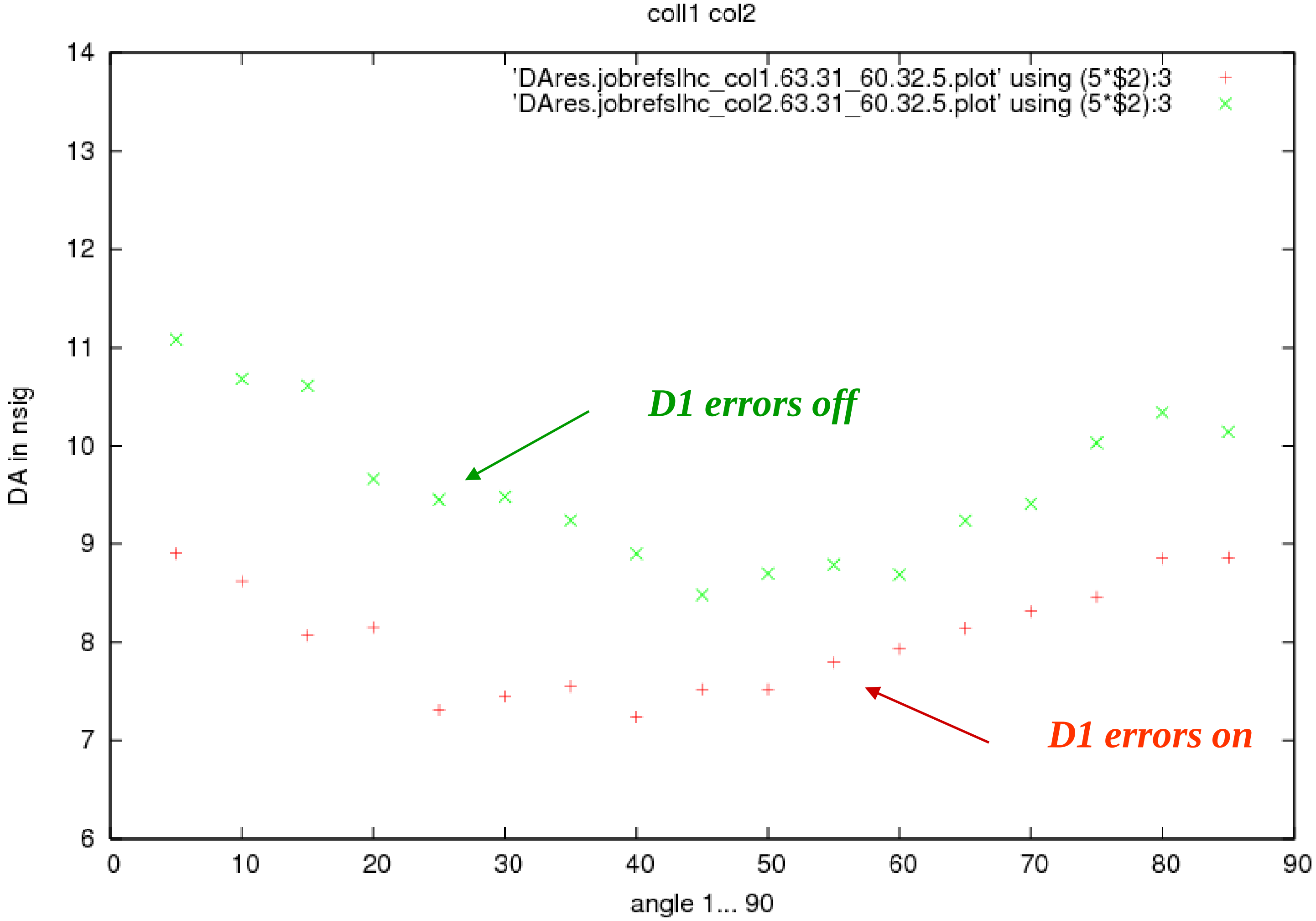


~.V2	~target_0 /
b1U_MQXCD_col := 0.0000	b1U_MQXCD_col := 0.0000
b2U_MQXCD_col := 0.0000	b2U_MQXCD_col := 0.0000
b3U_MQXCD_col := 0.4600	b3U_MQXCD_col := 0.2550
b4U_MQXCD_col := 0.6400	b4U_MQXCD_col := 0.1440
b5U_MQXCD_col := 0.4600	b5U_MQXCD_col := 0.1590
b6U_MQXCD_col := 1.7700	b6U_MQXCD_col := 0.4400
b7U_MQXCD_col := 0.2100	b7U_MQXCD_col := 0.0980
b8U_MQXCD_col := 0.1600	b8U_MQXCD_col := 0.0284
b9U_MQXCD_col := 0.0800	b9U_MQXCD_col := 0.0606
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
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 := 0.3220
a4U_MQXCD_col := 0.6400	a4U_MQXCD_col := 0.4110
a5U_MQXCD_col := 0.4600	a5U_MQXCD_col := 0.1220
a6U_MQXCD_col := 1.2700	a6U_MQXCD_col := 0.4840
a7U_MQXCD_col := 0.2100	a7U_MQXCD_col := 0.0800
a8U_MQXCD_col := 0.1600	a8U_MQXCD_col := 0.0670
a9U_MQXCD_col := 0.0800	a9U_MQXCD_col := 0.0800
a10U_MQXCD_col := 0.1400	a10U_MQXCD_col := 0.1000
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

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



D1 errors off

D1 errors on

... the D1 errors needed special investigation

```
! --------------------------------------------------------------------
! ********************** Magnet type : MBXAB (new D1) *****************
! --------------------------------------------------------------------
```

SLHC/errors/ ITD1 Error Table_ V2

```
                    an in collision (7500 A)
 a1U_MBXAB_col  :=  0.0000 ; a1R_MBXAB_col  :=  0.0000 ;
 a2U_MBXAB_col  :=  3.0000 ; a2R_MBXAB_col  :=  3.5000 ;
 a3U_MBXAB_col  :=  2.0000 ; a3R_MBXAB_col  :=  0.3000 ;
 a4U_MBXAB_col  :=  0.3000 ; a4R_MBXAB_col  :=  0.4000 ;

 !                  bn in collision (7500A)
 b1U_MBXAB_col  :=  0.0000 ; b1R_MBXAB_col  :=  0.0000 ;
 b2U_MBXAB_col  :=  0.5000 ; b2R_MBXAB_col  :=  0.6000 ;
 b3U_MBXAB_col  :=  3.0000 ; b3R_MBXAB_col  :=  1.1000 ;
 b4U_MBXAB_col  :=  0.2000 ; b4R_MBXAB_col  :=  0.1000 ;

  ....
```

remember: for the worst case we have to expect $a_{total} = aU + 3*aR$

Error Table_ target_10

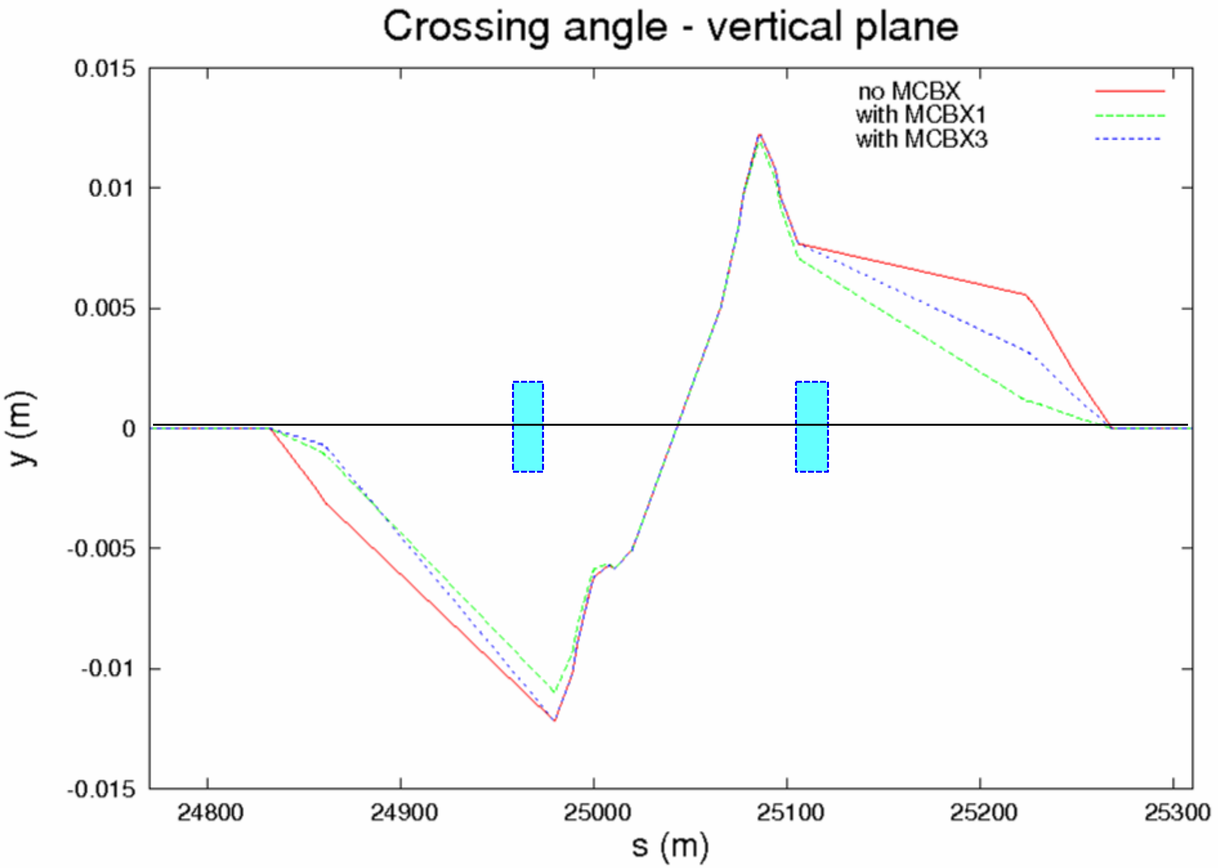
```
                    an in collision (7500 A)
 a1U_MBXAB_col  :=  0.0000 ; a1R_MBXAB_col  :=  0.0000 ;
 a2U_MBXAB_col  :=  1.5000 ; a2R_MBXAB_col  :=  1.7000 ;
 a3U_MBXAB_col  :=  1.0000 ; a3R_MBXAB_col  :=  0.3000 ;
 a4U_MBXAB_col  :=  0.3000 ; a4R_MBXAB_col  :=  0.4000 ;
  ....
 b1U_MBXAB_col  :=  0.0000 ; b1R_MBXAB_col  :=  0.0000 ;
 b2U_MBXAB_col  :=  0.5000 ; b2R_MBXAB_col  :=  0.6000 ;
 b3U_MBXAB_col  :=  1.5000 ; b3R_MBXAB_col  :=  0.5000 ;
 b4U_MBXAB_col  :=  0.2000 ; b4R_MBXAB_col  :=  0.1000 ;
```

Are there – beyond the dynamic aperture – more aspects that we have to consider ???

D1 Magnet: *to make it even more interesting*

large beam offset due to crossing angle

Φ/2 = 205 µrad



Operational Aspects of the low order D1 multipole errors

** identify the most critical multipoles (DA)*

** define tolerance limits*

** include analytical approach*

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 ...

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

$$\int Bdl = 30Tm$$

$$B\rho = 23000Tm$$

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

Example I: direct effect from b2

$$B_y + iB_x = B_{ref} * \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{r_0} \right)^{n-1}$$

The normal quadrupole field at reference radius $r_0 = 40mm$

$$\mathrm{B_y(r)} = \mathrm{B_0} * b_2 \frac{r}{r_0}$$

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

will cause an optics distortion of

$$\left.\begin{aligned} \Delta Q &\approx \frac{1}{4\pi}\beta\,\Delta k\, l = \frac{1*10^{-6}/m^2*7.4m*10000m}{4\pi} = \underline{\underline{5.8*10^{-3}}} \\ \frac{\Delta\beta}{\beta} &\approx \frac{1*10^{-6}/m^2*7.4m*10000m}{2*\sin(2\pi Q)} = \underline{\underline{4\ \%}} \end{aligned}\right\}$$

per D1 magnet !!!

Remember: phase advance over a mini beta section ≈π

-> the effects left & right of the IP add up

Example II: in-direct effect via feed down from b3

$$\mathrm{B_y(r) = B_0} * b_3 \left(\frac{r}{r_0}\right)^2$$

normal sextupole field at reference radius $r_0 = 40mm$

$$\mathrm{k}_2 = \frac{\partial^2 B}{\partial r^2}\frac{1}{B\rho} = 2B_0 b_3 \frac{1}{r_0^2}\frac{1}{B\rho}$$

quadrupole error due to feed down:

$$\mathrm{k}_1 L = \frac{2B_0 b_3 \Delta x L}{r_0^2}\frac{1}{B\rho} = \frac{2*30Tm*15mm*3*10^{-4}}{(40mm)^2}\frac{1}{2.3*10^4 Tm}$$

and as effect on the optics we get $\Delta\mathrm{Q} \approx 5.9*10^{-3}$ $\frac{\Delta\beta}{\beta} \approx 3.9\,\%$

per D1 magnet !!!

Nota bene:

1.) The effect on the machine parameters due to feed down from n=3 is in the same range as the direct influence from the n=2 multipoles.

2.) But as it depends on the beam position it is subject to variations during machine operation.

3.) et vice versa for the a3 and vertical plane.

Example III: coupling

$$a_{2\,\mathrm{total}} = a_2 u + 3 * a_2 r$$

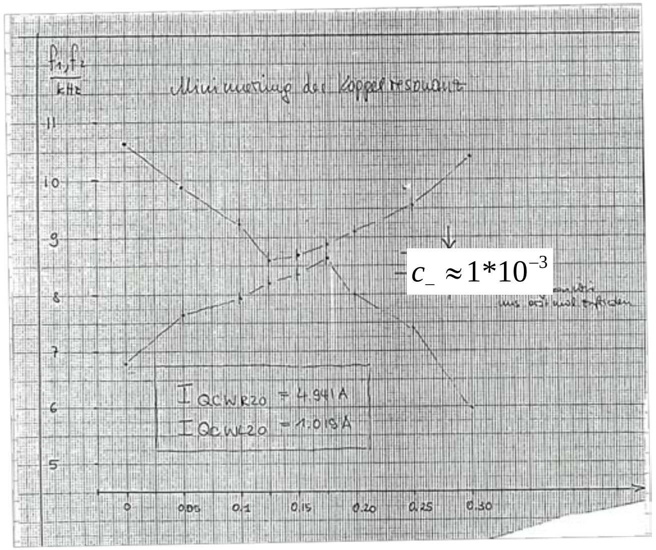
coupling due to a skew field

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

$$c_{-}(a2) = 2.2 * 10^{-2}$$

$$c_{-}(a3) = 4.6 * 10^{-3}$$

$$c_{-}(b3) = 7.4 * 10^{-3}$$



$c_{-} \approx 1 * 10^{-3}$

Scaling and Comparisons ...

we assume that the effect of the multipoles is compensated by the local correction scheme.
we assume however a

non-effectivity of the compensation
un-reproducibility of the machine
a variation from run to run
operational changes in vertex, position / crossing angle ...
of 30 %.

considering therefore the following limits as reasonable
if caused by a single multipole of one magnetic element !!!

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

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

target values for the D1 multipoles

multipole	Limits in 10^{-4}
b2	1.2
a2	3.0
b3	1.2
a3	1.2

Scaling and Comparisons ...

so sorry, what about the present machine ???

	target values upgrade-D1	*sc D1 magnet (MBX) at IR 2 & 8*	*nc D1 magnet MBXW) at IR 1 & 5*
reference radius	*40 mm*	*17 mm*	*17 mm*
b 2	*1.2*	*1.106*	*0.437*
a 2	*3.0*	*4.774*	*-0.564*
b 3	*1.2*	*1.265*	*0.921*
a 3	*1.2*	*-0.180*	*0.034*

we are already there … if we presume the magent quality that is presently installed in the tunnel

A SCALING LAW FOR FIELD ERRORS
(E. Todesco, LHC project report 1010)

"Let us consider a quadrupole of aperture *Φ*, coil thickness *w*, characterized by a set of random field components σ, generated by a random movement of coil blocks with r.m.s. *d*. We set the reference radius *Rref as 1/3* of the aperture diameter. (…) therefore one has i.e., the multipole spread scales with the inverse of the aperture radius."

$$\sigma(b_n, a_n, \alpha\phi, d, \alpha R_{ref}) = \frac{1}{\alpha} * \sigma(b_n, a_n, \phi, d, R_{ref})$$

	target values D1 (aperture = 180 mm)	*sc D1 magnet (MBX) scaled to 180 mm aperture*
reference radius	*60 mm*	*60 mm*
b 2	*1.8*	*0.768*
a 2	*4.5*	*3.32*
b 3	*2.7*	*1.37*
a 3	*2.7*	*0.190*

Conclusion

D1 errors are large
even compared to the triplett errors

we need the full corrector package (a3, b3, a4, b4, b6)

a reduction of 50 % of the prominent multipoles already helps A LOT

using the full correction scheme the effect of the D1 on operation still is considerable ...

do we need a further improvement ?

Off Records:

	~V2 values upgrade-D1	*target_10 values upgrade-D1*	*target values operation upgrade -D1*
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*	*3.0*
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*