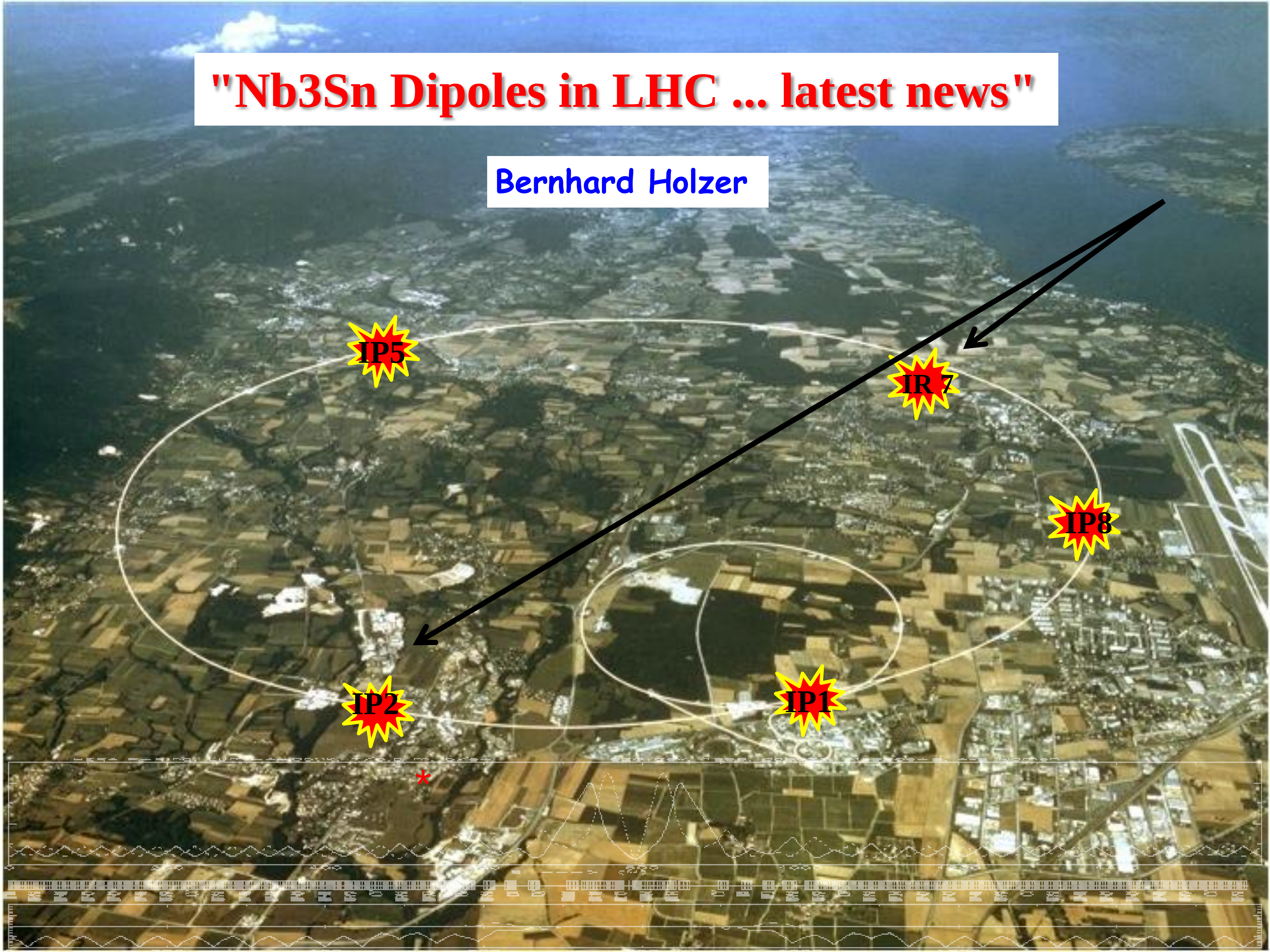
"Nb3Sn Dipoles in LHC ... latest news"

Bernhard Holzer



11 T Dipole for DS

M. Karppinen TE-MSC-ML

On behalf of CERN-FNAL collaboration

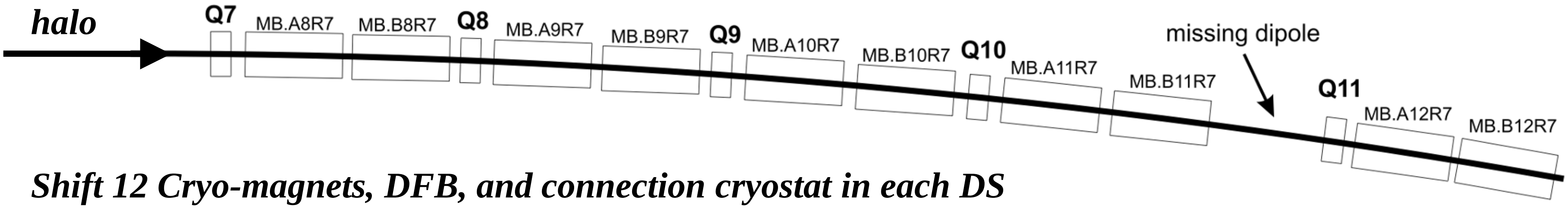
B. Auchmann, L. Bottura , B. Holzer, L. Oberli,
L. Rossi, D. Smekens (CERN)

N, Andreev, G. Apollinari, E. Bartzi, R. Bossert,
F. Nobrega, I. Novitski, A. Zlobin (FNAL)

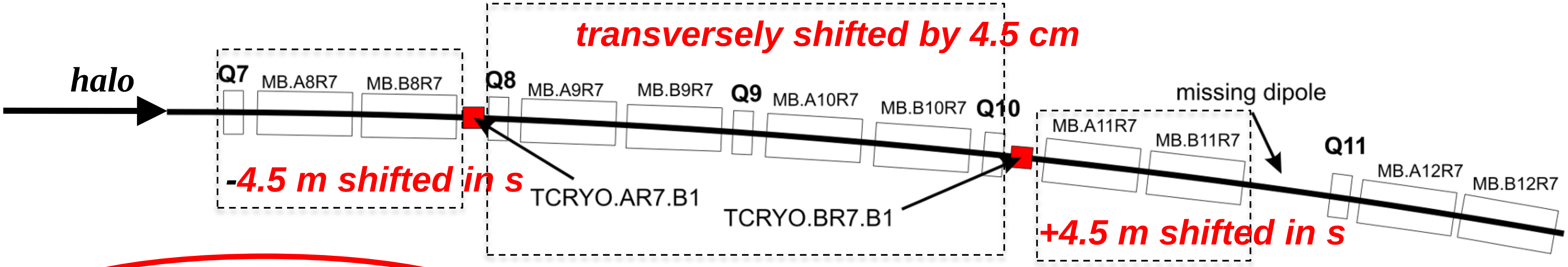
Collimation Phase II Upgrade in DS

- 2013: IR3 (Decision in June)
- 2017: IR7 & IR2 (*IR3?*)
- 2020: IR1,5 as part of HL-LHC
- Base-line is re-location of magnets to create space for 4.5 m long warm collimator
- Cryo-collimator is an R&D project

DS Upgrade Scenarios



Shift 12 Cryo-magnets, DFB, and connection cryostat in each DS

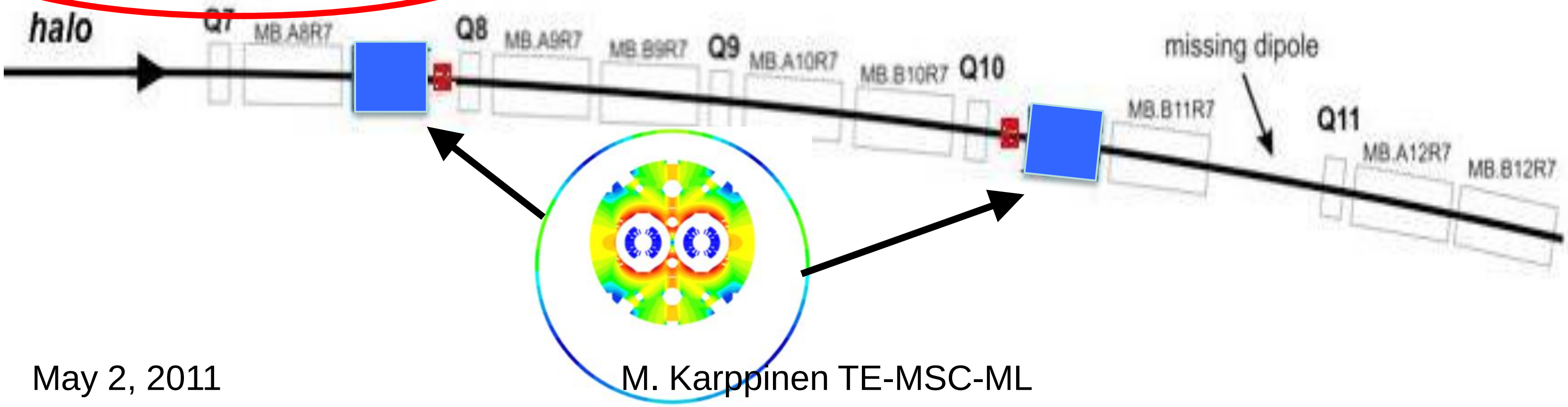


transversely shifted by 4.5 cm

-4.5 m shifted in s

+4.5 m shifted in s

New ~3..3.5 m shorter Nb_3Sn Dipoles (2 per DS)



Effects to be expected:

* magnets are shorter than MB Standards → change of geometry ... ?
may be not !

* R-Bends ←→ S-Bends → edge focusing
distortion of the optics
tune shift, beta beat

* nonlinar transfer function (3.5 TeV) → distortion of closed orbit
to be corrected locally ??
dedicated corrector coils ??
trim power supply ??

* feed down effects from sagitta
* multipole effect on dynamic aperture

Analytical approach / Mad-X / Sixtrack Simulations

4.) The Story of the Transfer Function ...

a closed orbit problem

calculate the ideal (nb3sn) machine

flatten the experiment bumps, switch off LHC-B, ALICE etc

assign field error to nb3sn dipoles

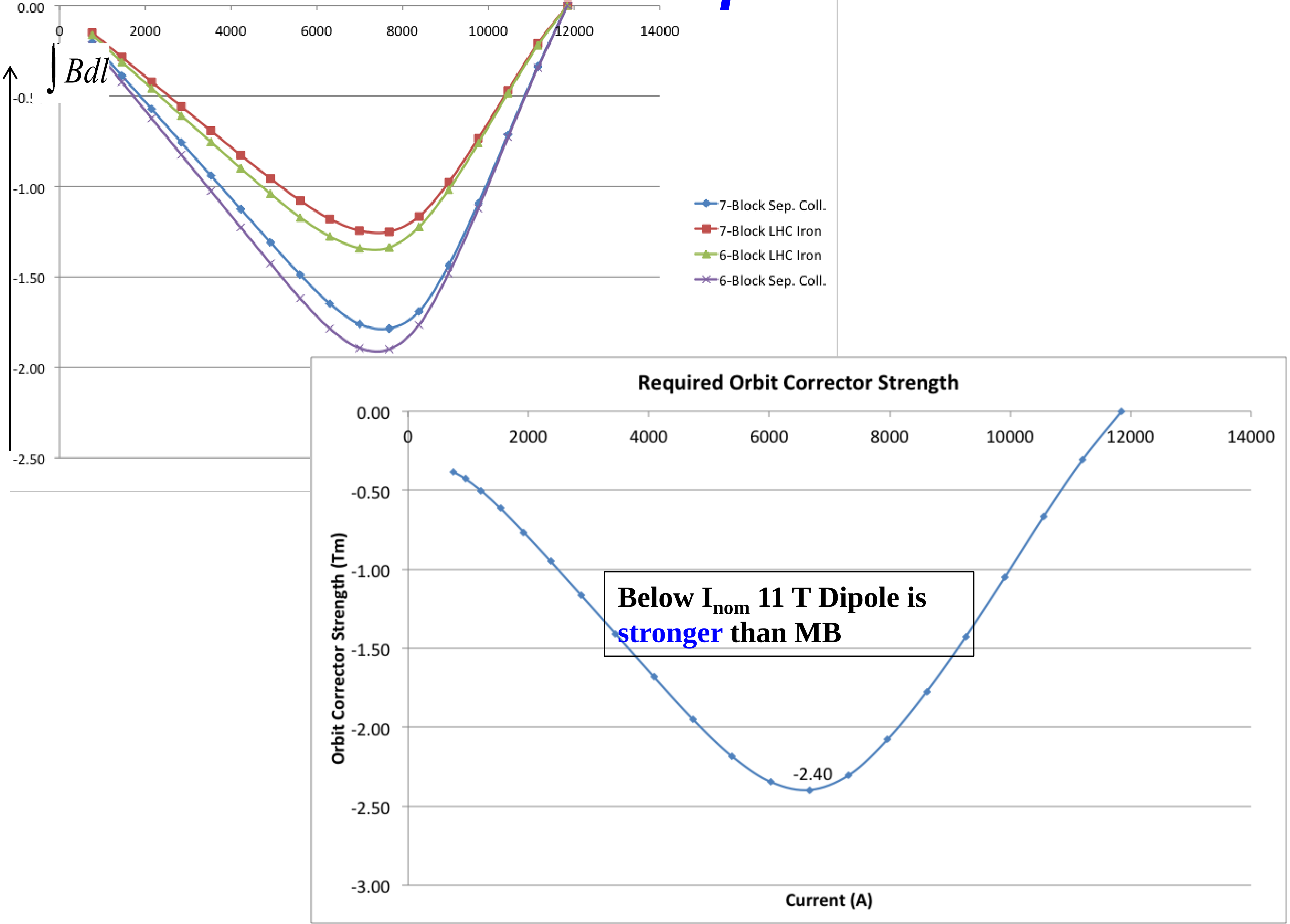
correct the orbit

plot the residual error

what are we talking about ... $\int B dl = 1.5\, Tm$

treated not as a geometrical problem but as a orbit problem → to be corrected.

“non-linear” Transfer Function



Below I_{nom} 11 T Dipole is stronger than MB

again: ... 10 seconds for the contemplation:

$$E = 7\ TeV$$

$$\left.\begin{array}{l} B = 8.33\ T \\ L = 14.3\ m \end{array}\right\} \quad \int B dl = 119\ Tm$$

$$N = 1232\ \ Magnets$$

$$\rightarrow \quad 5.1\ mrad$$

Nb3Sn Transferfunction:

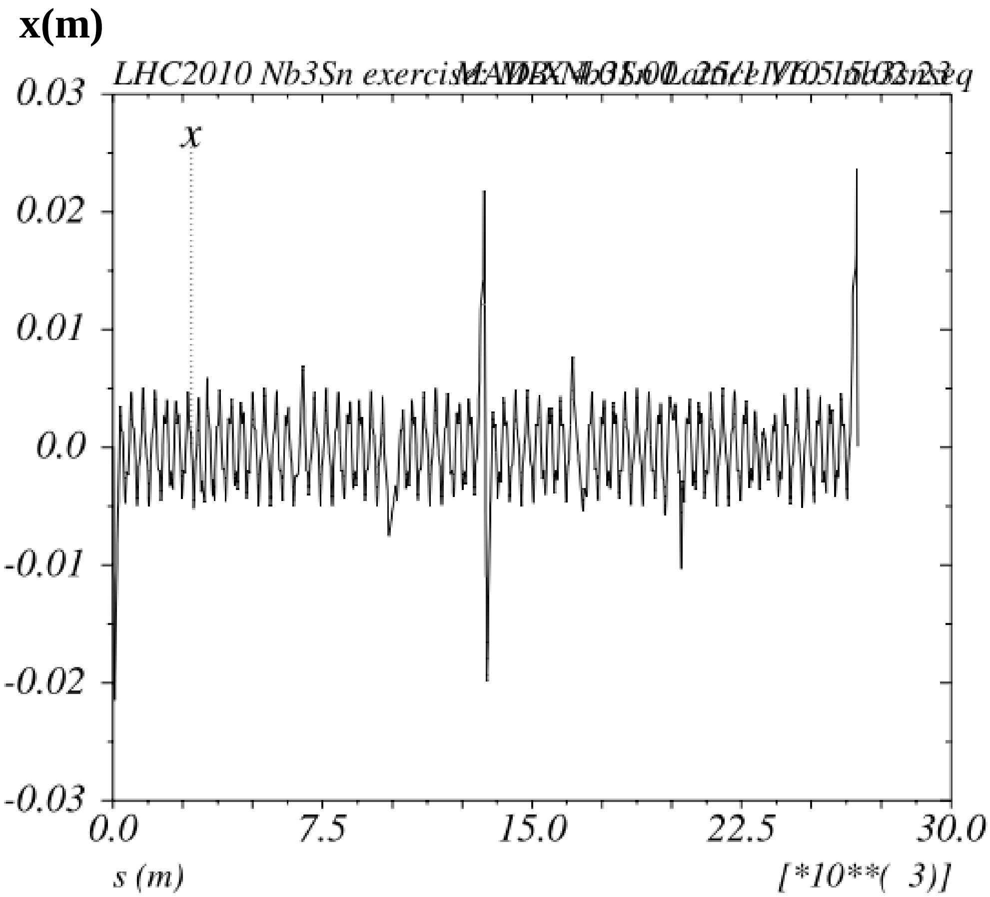
worst case (... around 3.5 TeV) = 2.7% lack in main field

rough estimate: → Δx ≈ 13 mm

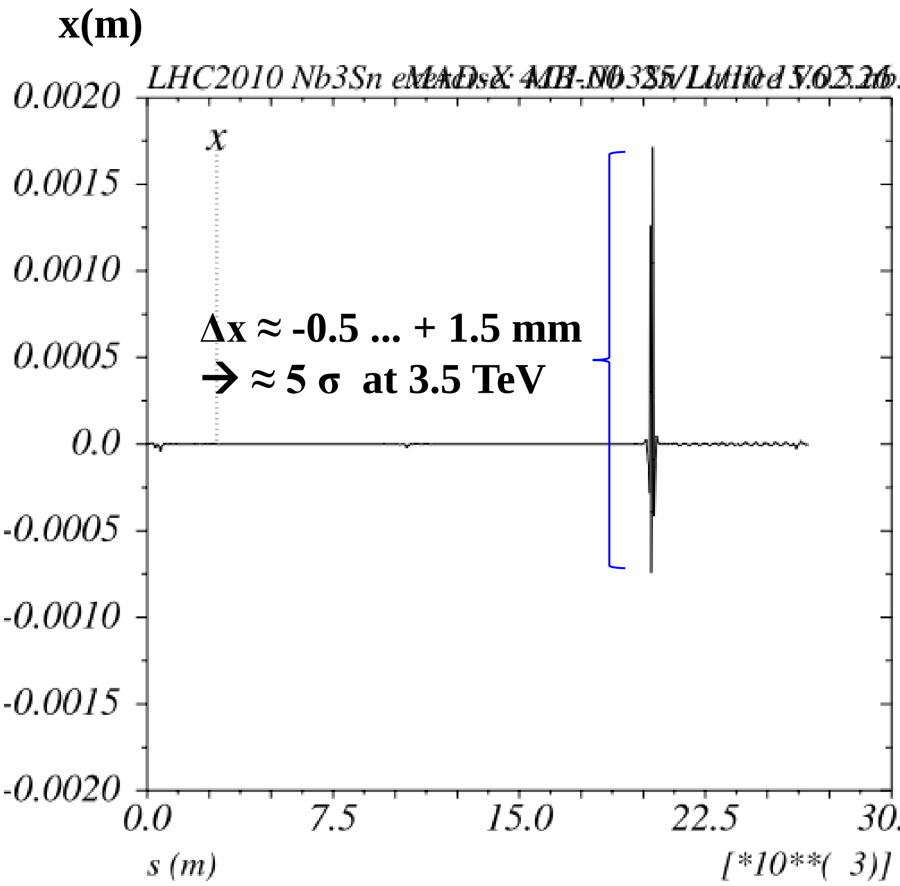
4.) The Story of the Transfer Function ...

a closed orbit problem

effect of nb3sn field error (1.5 Tm)
two dipoles
distorted orbit,
and corrected by the "usual methods"



two Nb3Sn magnets

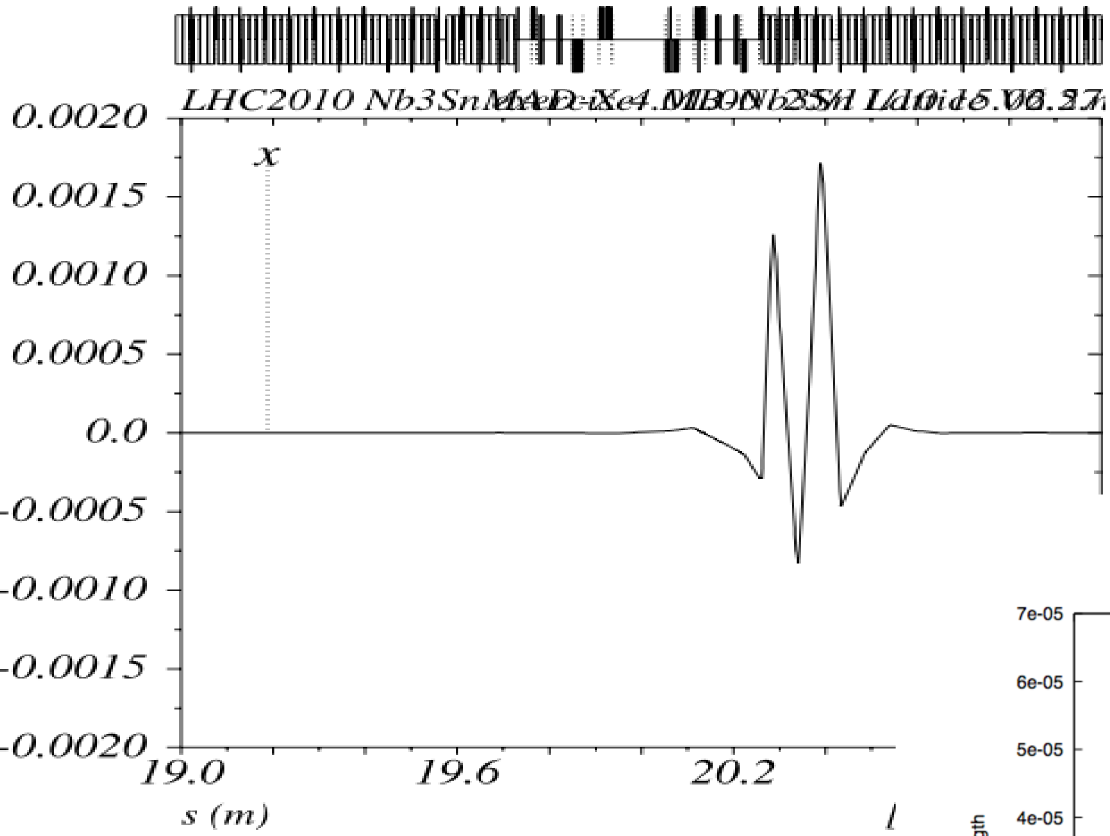


Δx ≈ -0.5 ... + 1.5 mm
→ ≈ 5 σ at 3.5 TeV

corrected by 20 orbcor dipoles

4.) The Story of the Transfer Function ...

a closed orbit problem



field error corrected by 3 (20) most eff. correctors
zooming the orbit distortion

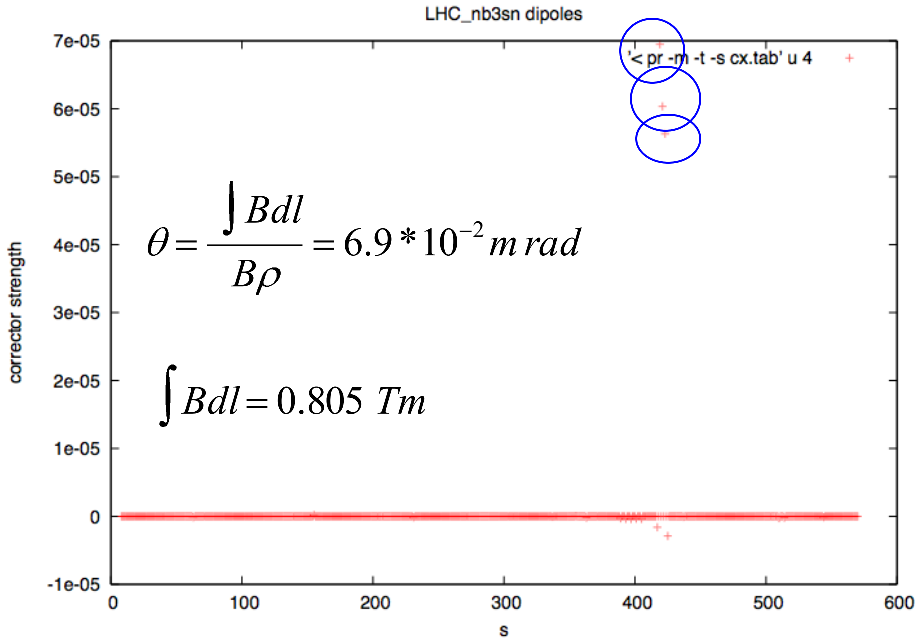
... local distortion due to
Δϕ ≈ 4.545 phase relation,
closed by MCBH correctors

MCBH corrector strength:

available: 1.900 Tm
needed: 0.805 Tm

!

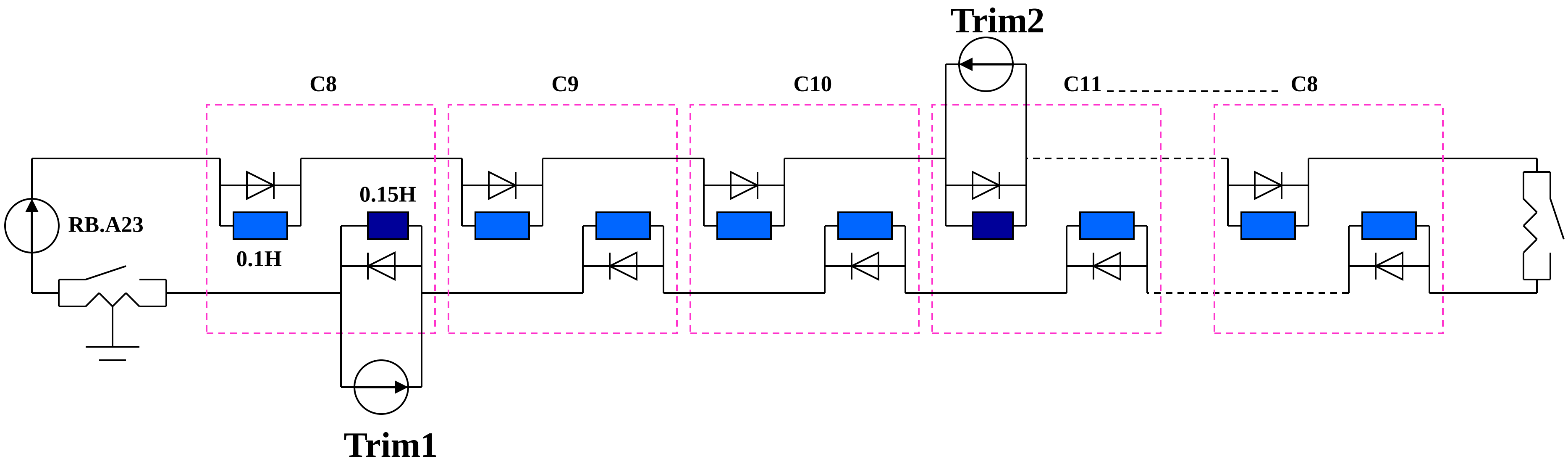
= 42 %



$$\theta = \frac{\int Bdl}{B\rho} = 6.9 * 10^{-2}\, m\, rad$$

$$\int Bdl = 0.805\ Tm$$

New RB Circuit (Type 1)



Main Power Converter

Total inductance: 15.5 H (152x0.1H + 2x0.15H)
Total resistance: 1mΩ
Output current: 13 kA
Output voltage: 190 V

(+)
- Low current CL for the trim circuits
- Size of Trim power converters

TRIM Power Converters

Total inductance: 0.15 H
Total resistance: 1mΩ
RB output current: ±0.6 kA
RB output voltage: ±10 V

(-)
- Protection of the magnets
- Floating Trim PCs (>2 kV)
- coupled circuits

Courtesy of H. Thiessen

5.) Nb3Sn Dipole: Multipole Errors:

Systematic errors

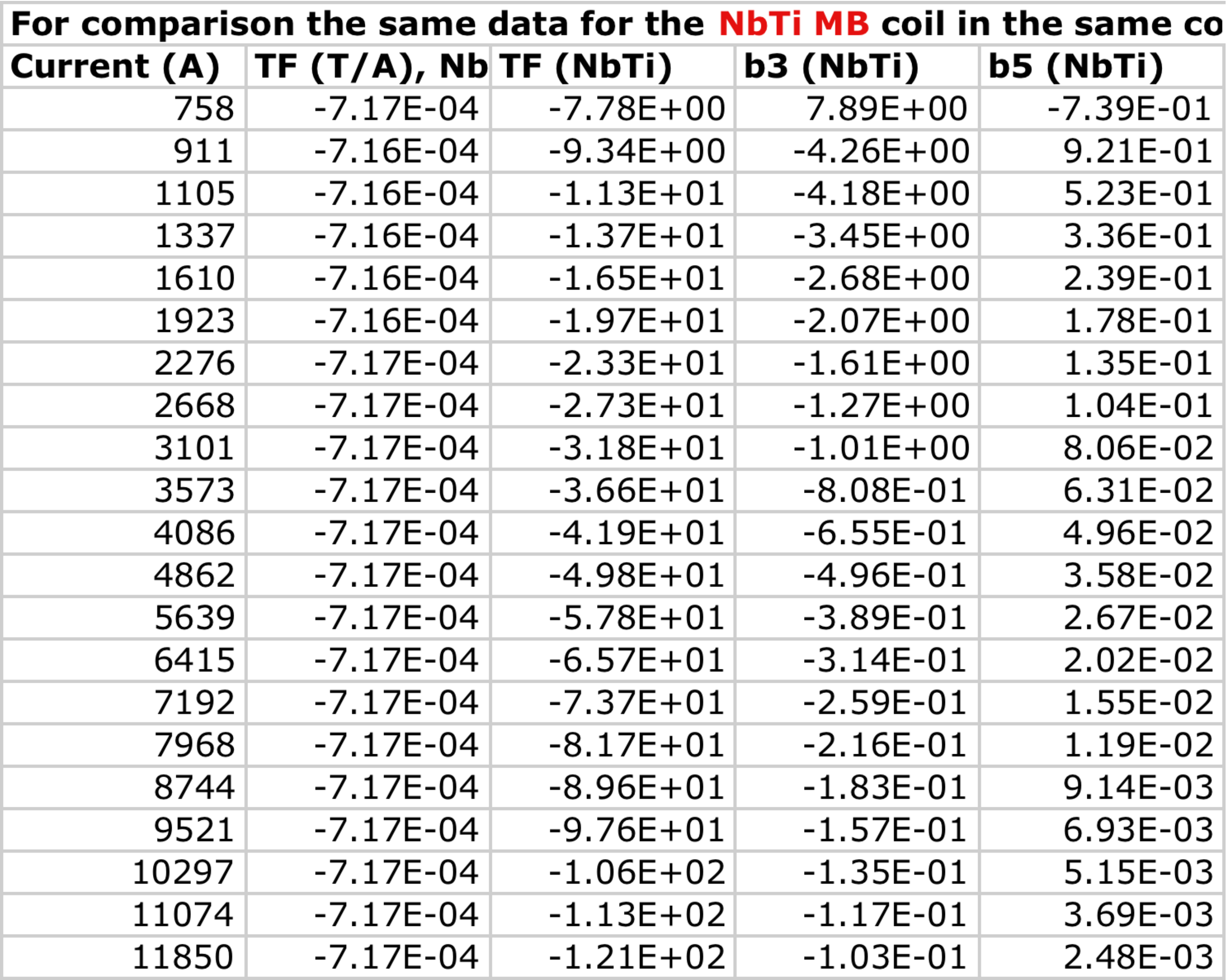
Current (A)	B1	b2	b3	b4	b5	b6	b7
763	-0.7325	2.50	13.96	0.02	-0.24	0.00	0.29
1456	-1.3977	2.50	13.96	0.02	-0.24	0.00	0.29
2149	-2.0628	2.50	13.96	0.02	-0.24	0.00	0.29
2842	-2.7279	2.50	13.96	0.02	-0.24	0.00	0.29
3535	-3.3930	2.50	13.96	0.02	-0.24	0.00	0.29
4228	-4.0581	2.49	13.96	0.02	-0.24	0.00	0.29
4921	-4.7231	2.48	13.97	0.02	-0.24	0.00	0.29
5614	-5.3875	2.45	13.99	0.02	-0.23	0.00	0.29
6307	-6.0499	2.28	14.03	0.01	-0.23	0.00	0.29
7000	-6.7075	1.84	14.15	-0.01	-0.23	0.00	0.29
7692	-7.3565	1.05	14.31	-0.04	-0.21	0.00	0.29
8385	-7.9928	-0.21	14.36	-0.10	-0.18	0.00	0.29
9078	-8.6120	-2.13	14.21	-0.21	-0.17	-0.01	0.29
9771	-9.2204	-4.43	13.97	-0.31	-0.15	-0.01	0.29
10464	-9.8212	-6.94	13.68	-0.41	-0.14	-0.02	0.29
11157	-10.4160	-9.68	13.37	-0.51	-0.13	-0.02	0.30
11850	-11.0060	-12.49	13.06	-0.58	-0.13	-0.02	0.30

... in the usual units, i.e. 10^{-4} referred to the usual ref radius = 17mm

Nb3Sn Dipole: Multipole Errors:

Persistent current analysis Nb3Sn Dipole				
Current (A)	**TF (T/A)**	**B1 (T m)**	**b3 (Units)**	**b5 (Units)**
758	-9.68E-04	-7.92E+00	9.58E+01	-1.34E+00
911	-9.60E-04	-9.45E+00	5.36E+01	1.58E+00
1105	-9.54E-04	-1.14E+01	2.12E+01	3.33E+00
1337	-9.50E-04	-1.37E+01	2.31E-01	3.80E+00
1610	-9.48E-04	-1.65E+01	-1.05E+01	3.23E+00
1923	-9.47E-04	-1.97E+01	-1.37E+01	2.19E+00
2276	-9.47E-04	-2.33E+01	-1.36E+01	1.35E+00
2668	-9.47E-04	-2.73E+01	-1.24E+01	7.94E-01
3101	-9.48E-04	-3.17E+01	-1.09E+01	4.52E-01
3573	-9.48E-04	-3.66E+01	-9.27E+00	2.47E-01
4086	-9.48E-04	-4.18E+01	-7.76E+00	1.28E-01
4862	-9.49E-04	-4.98E+01	-5.99E+00	4.25E-02
5639	-9.49E-04	-5.78E+01	-4.72E+00	9.44E-03
6415	-9.49E-04	-6.57E+01	-3.80E+00	-2.50E-03
7192	-9.49E-04	-7.37E+01	-3.11E+00	-5.54E-03
7968	-9.49E-04	-8.17E+01	-2.58E+00	-4.68E-03
8744	-9.49E-04	-8.96E+01	-2.17E+00	-2.09E-03
9521	-9.49E-04	-9.76E+01	-1.84E+00	1.21E-03
10297	-9.49E-04	-1.06E+02	-1.58E+00	4.74E-03
11074	-9.49E-04	-1.14E+02	-1.36E+00	8.27E-03
11850	-9.49E-04	-1.22E+02	-1.18E+00	1.17E-02
11517	-9.50E-04	-1.18E+02	4.44E-01	1.38E-03

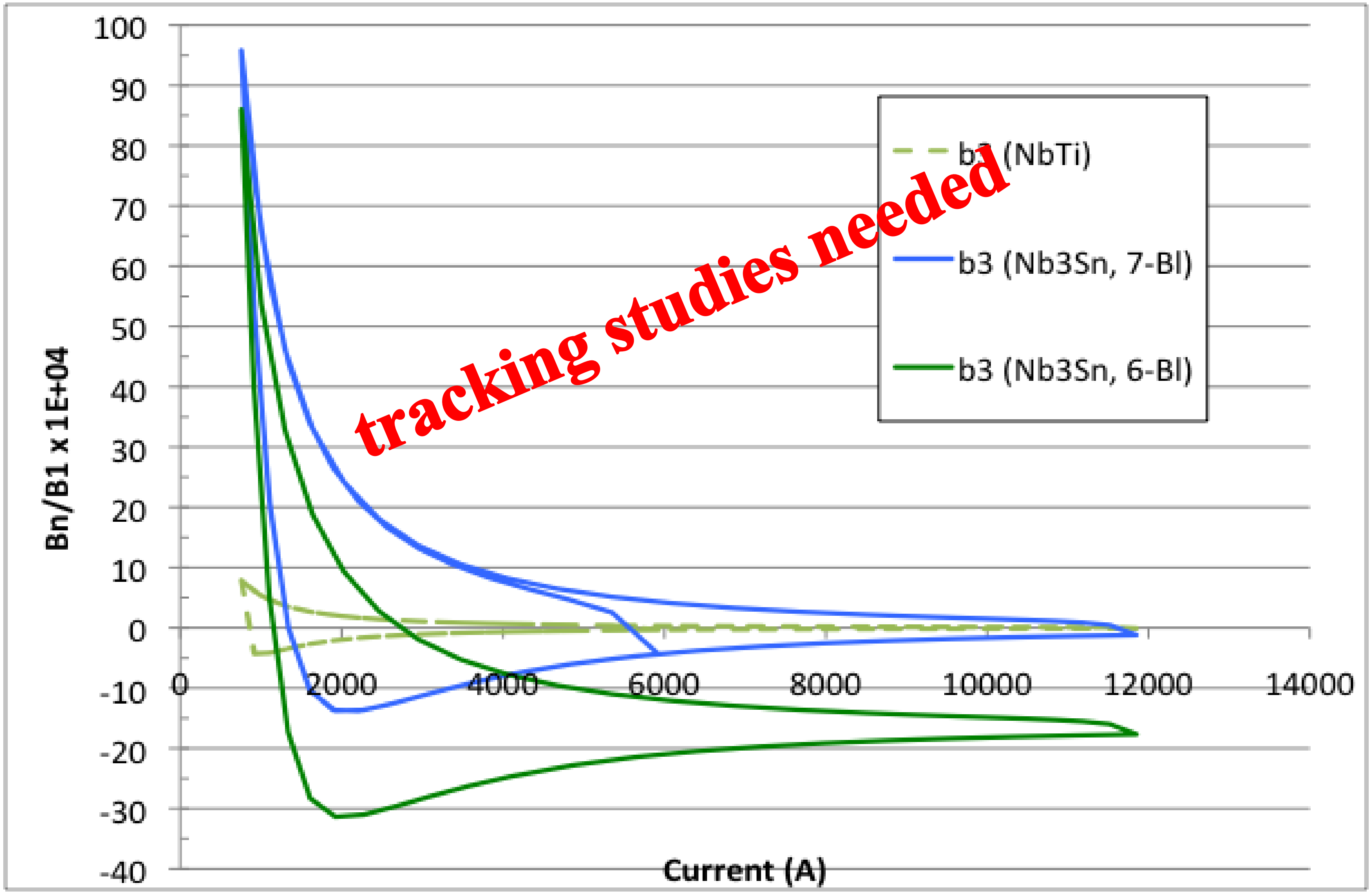
NbTi Dipole: Multipole Errors:



For comparison the same data for the **NbTi MB** coil in the same co

Current (A)	TF (T/A), Nb	TF (NbTi)	b3 (NbTi)	b5 (NbTi)
758	-7.17E-04	-7.78E+00	7.89E+00	-7.39E-01
911	-7.16E-04	-9.34E+00	-4.26E+00	9.21E-01
1105	-7.16E-04	-1.13E+01	-4.18E+00	5.23E-01
1337	-7.16E-04	-1.37E+01	-3.45E+00	3.36E-01
1610	-7.16E-04	-1.65E+01	-2.68E+00	2.39E-01
1923	-7.16E-04	-1.97E+01	-2.07E+00	1.78E-01
2276	-7.17E-04	-2.33E+01	-1.61E+00	1.35E-01
2668	-7.17E-04	-2.73E+01	-1.27E+00	1.04E-01
3101	-7.17E-04	-3.18E+01	-1.01E+00	8.06E-02
3573	-7.17E-04	-3.66E+01	-8.08E-01	6.31E-02
4086	-7.17E-04	-4.19E+01	-6.55E-01	4.96E-02
4862	-7.17E-04	-4.98E+01	-4.96E-01	3.58E-02
5639	-7.17E-04	-5.78E+01	-3.89E-01	2.67E-02
6415	-7.17E-04	-6.57E+01	-3.14E-01	2.02E-02
7192	-7.17E-04	-7.37E+01	-2.59E-01	1.55E-02
7968	-7.17E-04	-8.17E+01	-2.16E-01	1.19E-02
8744	-7.17E-04	-8.96E+01	-1.83E-01	9.14E-03
9521	-7.17E-04	-9.76E+01	-1.57E-01	6.93E-03
10297	-7.17E-04	-1.06E+02	-1.35E-01	5.15E-03
11074	-7.17E-04	-1.13E+02	-1.17E-01	3.69E-03
11850	-7.17E-04	-1.21E+02	-1.03E-01	2.48E-03

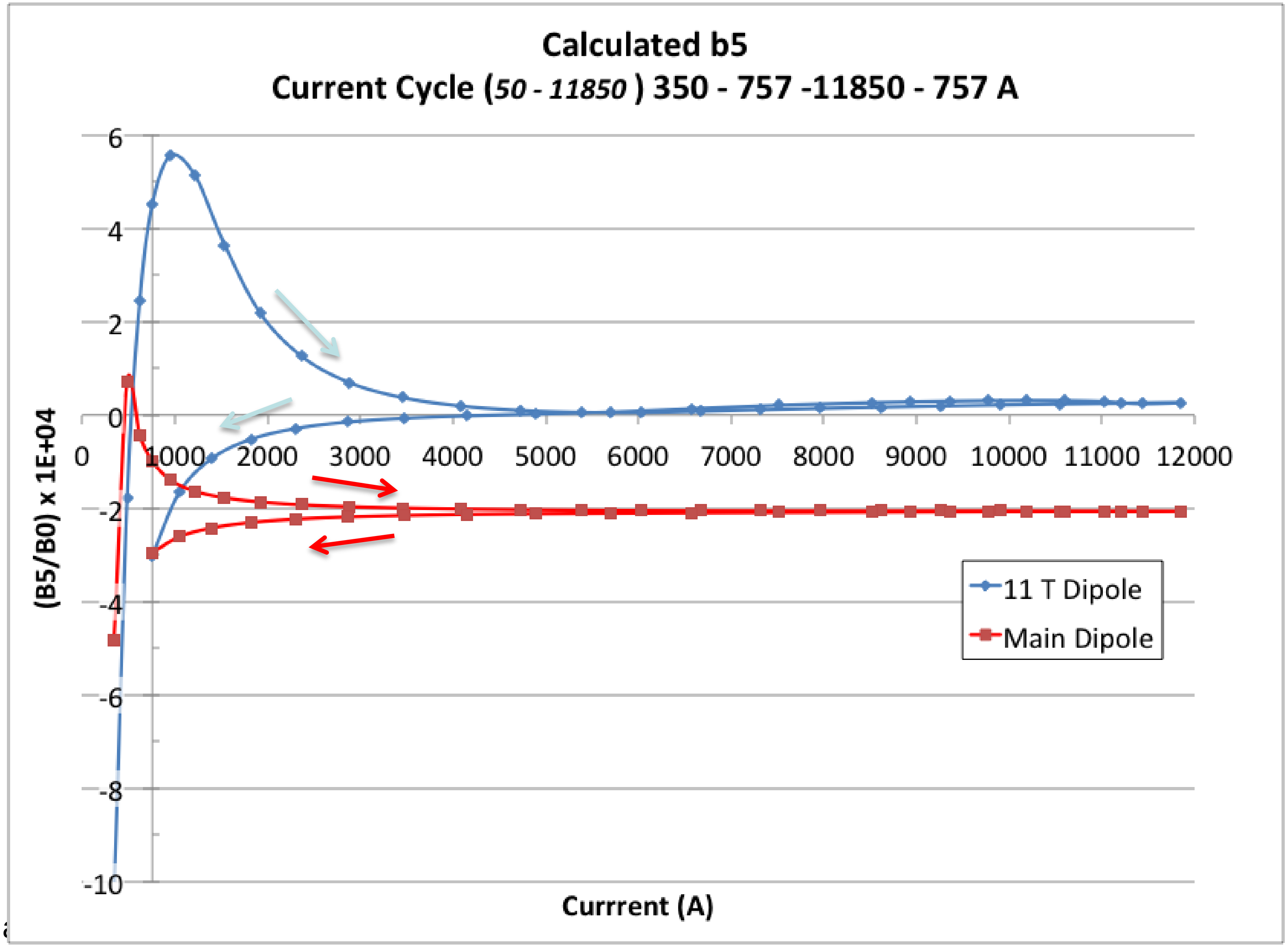
the persistent current problem:



tracking studies needed

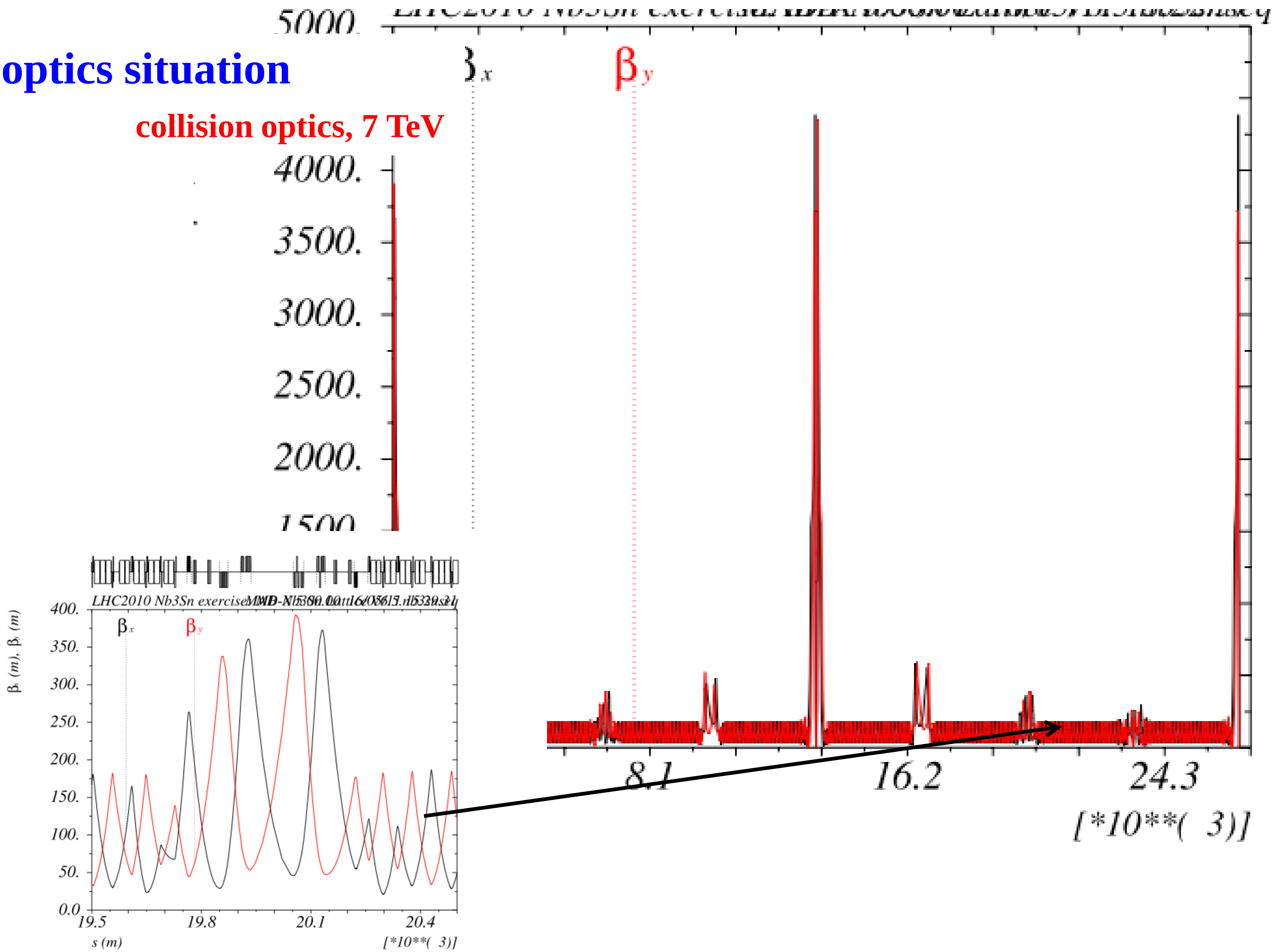
M. Karppinen CERN TE-MSC-ML

Persistent Current Effects



optics situation

collision optics, 7 TeV



Field Quality: Dynamic Aperture Studies

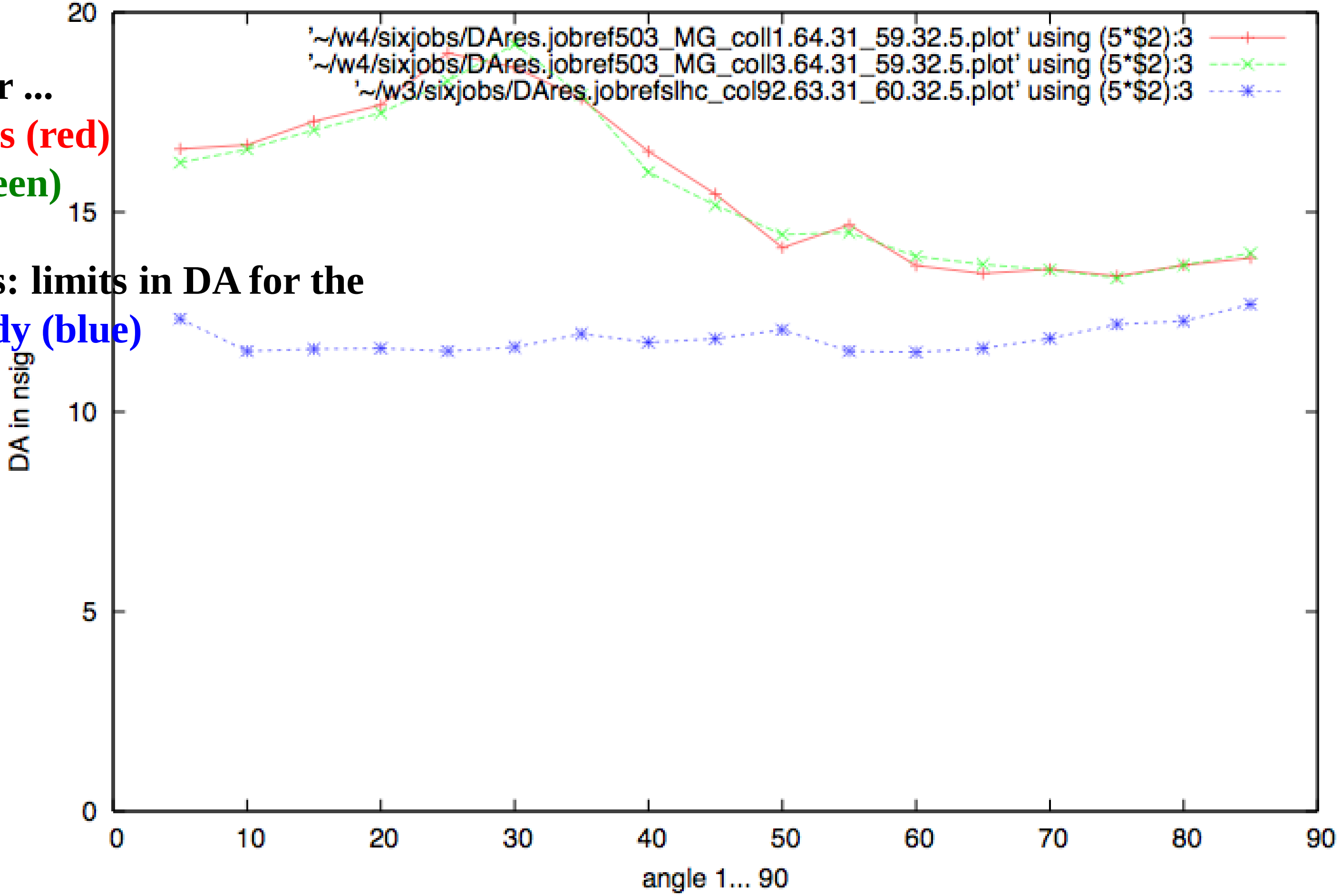
collision optics, 7 TeV

dynamic aperture for ...

ideal Nb3Sn dipoles (red)

full error table (green)

and for completeness: limits in DA for the phase 1 upgrade study (blue)



dyn aperture luminosity optics, 7 TeV, minimum of 60 seeds

for the experts: the plot shows the minimum DA for the 60 error distribution seeds used in the tracking calculations.

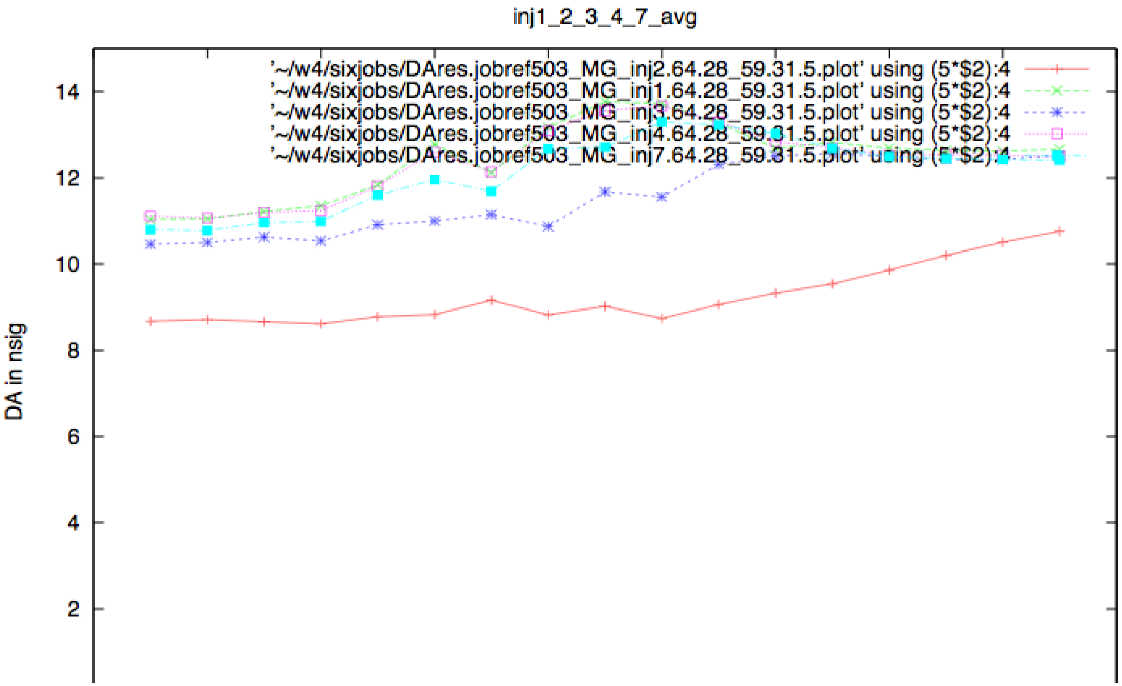
Field Quality: no local b_3 correction

injection optics, 450 GeV, scan of b_3

dyn aperture injection optics, average of 60 seeds

dynamic aperture for Nb3Sn case:

full error table
b3 = 50%
b3 = 25%
b3 reduced to 0%
ideal Nb3Sn magnets (all a_n = b_n =0)



for the experts: there is not much difference between b3=0
and perfect Nb_3Sn magnets !!

A scan in b_3 values has been performed and shows that values up to $b_3 < 20$ units are ok.

Alternative solution: strong local spool piece corrector ... which is being studied at the very moment.

Field Quality: local b_3 correction

injection optics, 450 GeV, special spool piece correctors for the Nb_3Sn

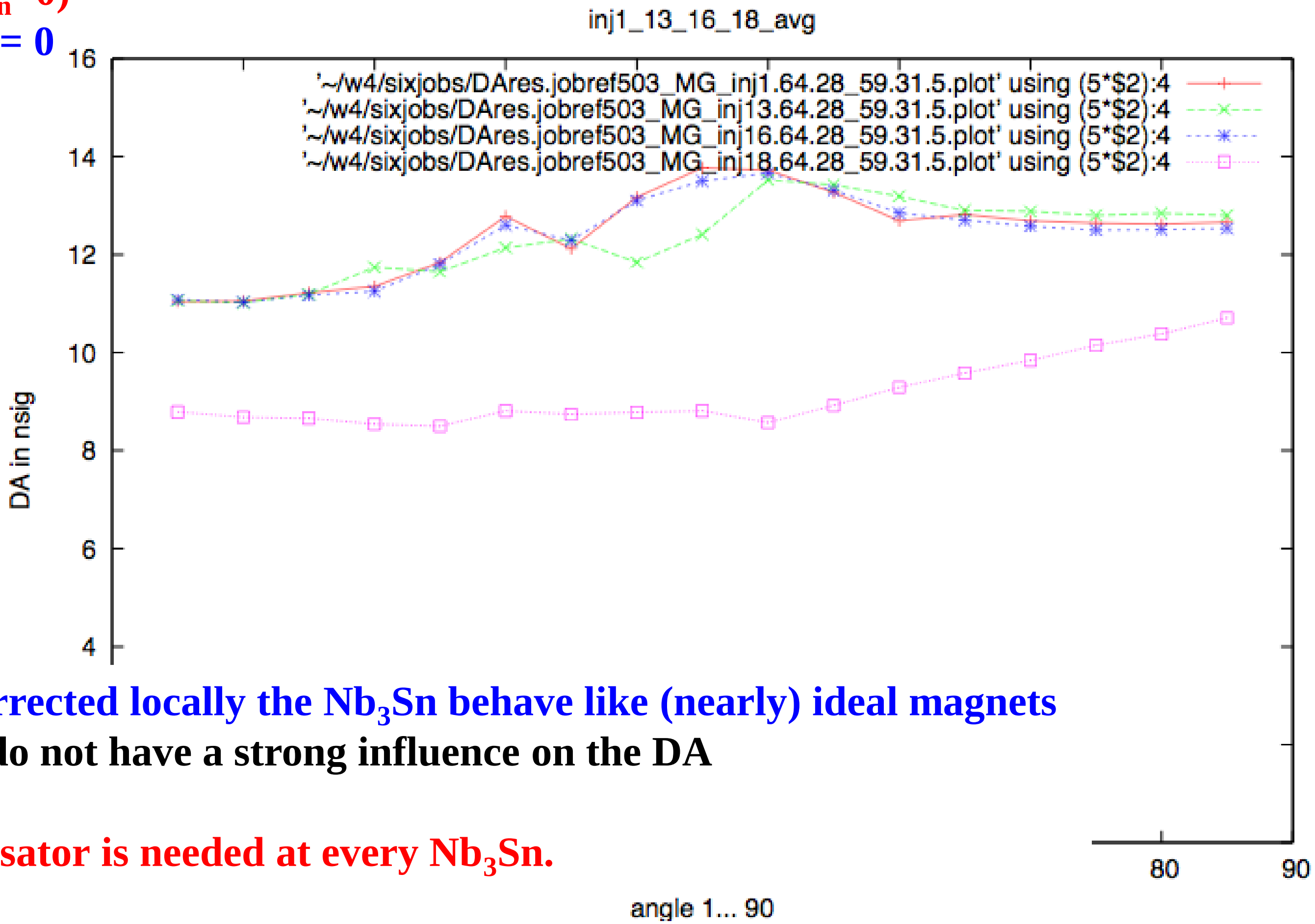
dyn aperture injection optics, average of 60 seeds

ideal Nb3Sn magnets (a_n=b_n=0)

a_n=b_n=Nb_3Sn values but b_3 = 0

b_3=full, local compensation

b_3 =full, no correction



for the experts: if b_3 is corrected locally the Nb_3Sn behave like (nearly) ideal magnets

Higher order multipoles do not have a strong influence on the DA

A strong mcs like compensator is needed at every Nb_3Sn.

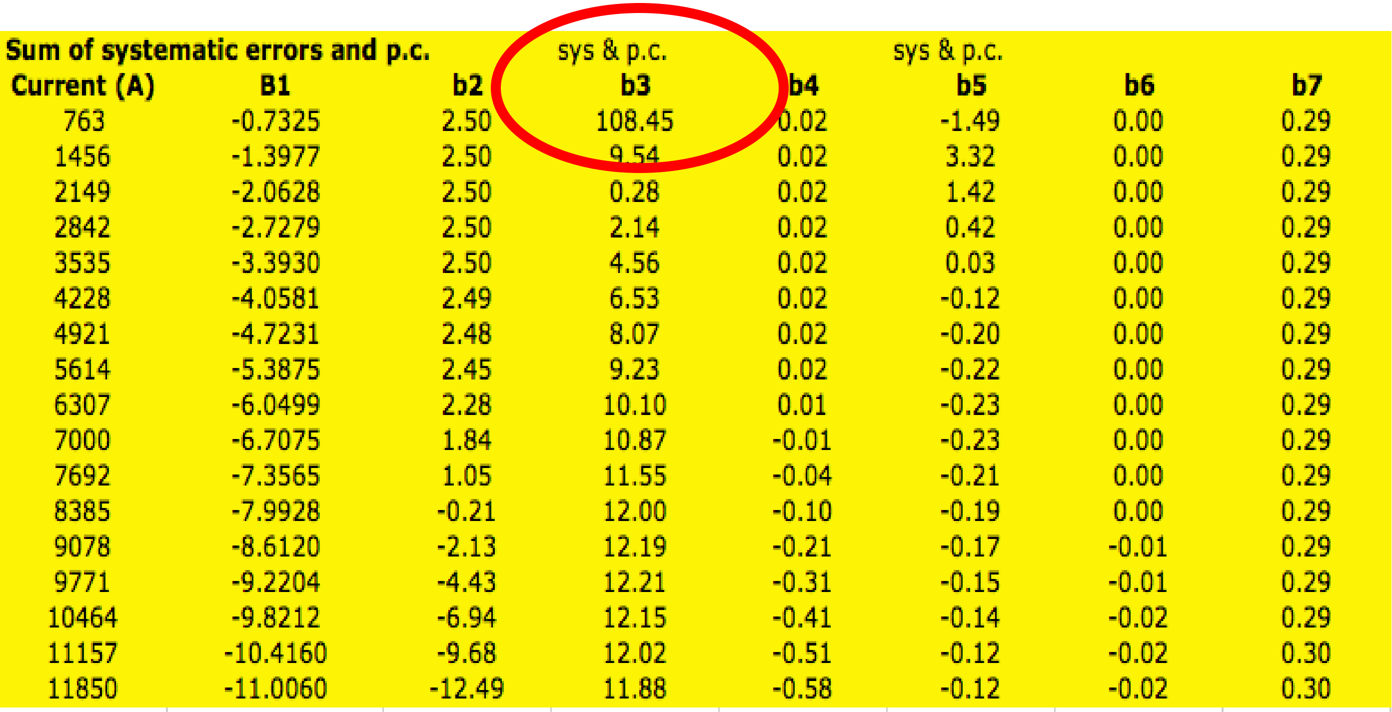
local b_3 correction

some numbers to confuse the audience

Standard MCS: $l = 110$ mm
$g_2 = 1630$ T/m^2

Standard pc contribution: NbTi $b_3 = 7.9$ units

pc contribution: Nb_3Sn $b_3 = 108$ units,
compensation via MCS: $k_2 l = 0.412$ /m^2
$g_2 = 5618$ T/m^2 *... without snap back contribution*



Sum of systematic errors and p.c.			sys & p.c.		sys & p.c.		
Current (A)	**B1**	**b2**	**b3**	**b4**	**b5**	**b6**	**b7**
763	-0.7325	2.50	108.45	0.02	-1.49	0.00	0.29
1456	-1.3977	2.50	9.54	0.02	3.32	0.00	0.29
2149	-2.0628	2.50	0.28	0.02	1.42	0.00	0.29
2842	-2.7279	2.50	2.14	0.02	0.42	0.00	0.29
3535	-3.3930	2.50	4.56	0.02	0.03	0.00	0.29
4228	-4.0581	2.49	6.53	0.02	-0.12	0.00	0.29
4921	-4.7231	2.48	8.07	0.02	-0.20	0.00	0.29
5614	-5.3875	2.45	9.23	0.02	-0.22	0.00	0.29
6307	-6.0499	2.28	10.10	0.01	-0.23	0.00	0.29
7000	-6.7075	1.84	10.87	-0.01	-0.23	0.00	0.29
7692	-7.3565	1.05	11.55	-0.04	-0.21	0.00	0.29
8385	-7.9928	-0.21	12.00	-0.10	-0.19	0.00	0.29
9078	-8.6120	-2.13	12.19	-0.21	-0.17	-0.01	0.29
9771	-9.2204	-4.43	12.21	-0.31	-0.15	-0.01	0.29
10464	-9.8212	-6.94	12.15	-0.41	-0.14	-0.02	0.29
11157	-10.4160	-9.68	12.02	-0.51	-0.12	-0.02	0.30
11850	-11.0060	-12.49	11.88	-0.58	-0.12	-0.02	0.30

? what about higher multipoles

?? what about the skews

??? what about reality

Resume: Nb3Sn dipoles in the cold collimation part

have (nearly) no effect on the beam optic

have (nearly) no effect on the LHC global geometry
local geometry has to be discussed

have a strong influence on the orbit that can be corrected outside the dipole pair
using a considerable fraction of the available corrector strength

a relatively large orbit distortion (5σ) remains between the dipole pairs

would be a great idea to install trim power supply to compensate the effect and forget about the problems !!!

multipoles are enormous (mainly b3):
They have only small impact at high energy,
At 450 GeV injection they are too strong and have to be either reduced to roughly 20 units or compensated by strong spool piece correctors.

Field Quality: Dynamic Aperture Studies

injection optics, 450 GeV, scan of b_3

dynamic aperture for Nb3Sn case:

full error table (red)

b3 reduced to 50% (green)

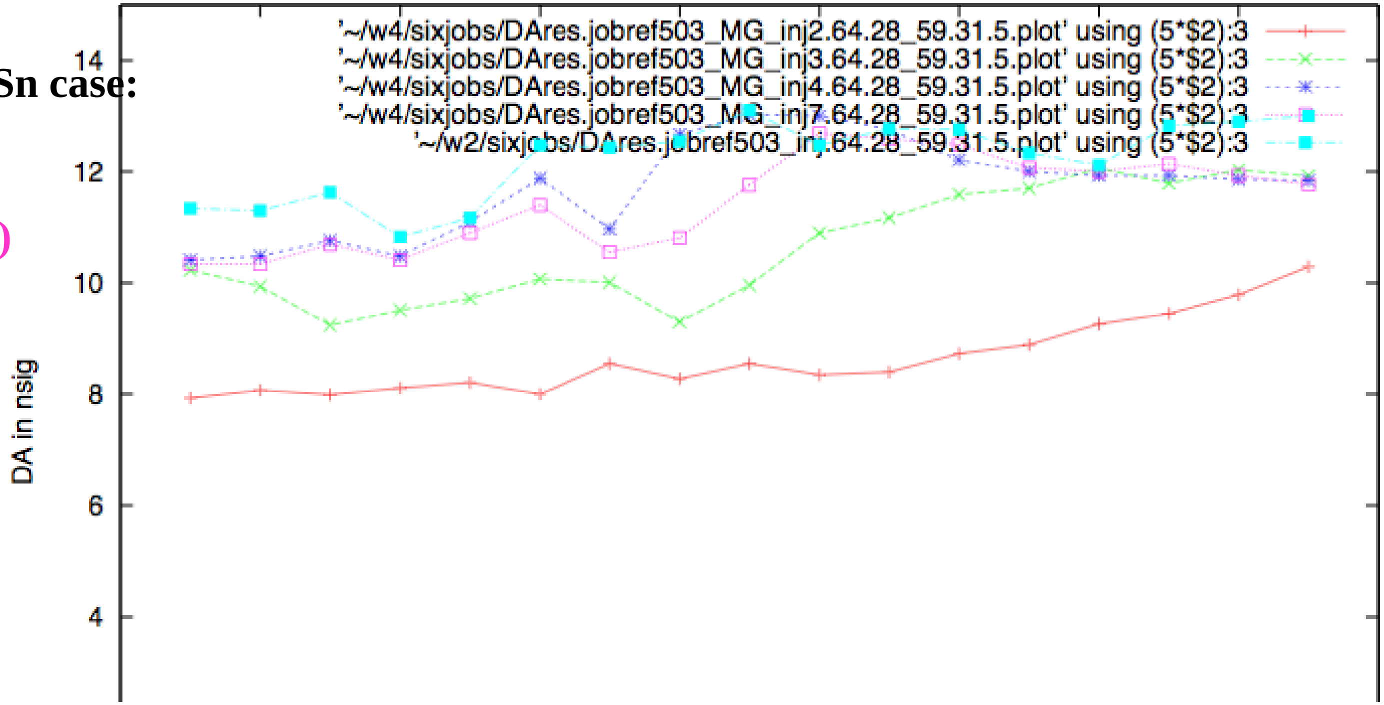
b3 reduced to 25% (violett)

b3 = 0

and to compare with:

present LHC injection

dyn aperture injection optics, minimum of 60 seeds



for the experts: unlike to the collision case: at injection the b3 of the Nb3Sn dipoles is the driving force to the limit in dynamic aperture.

A scan in b3 values has been performed and shows that values up to b3 ≈ 20 units are ok.

Alternative solution: strong local spool piece corrector ... which is being studied at the very moment.