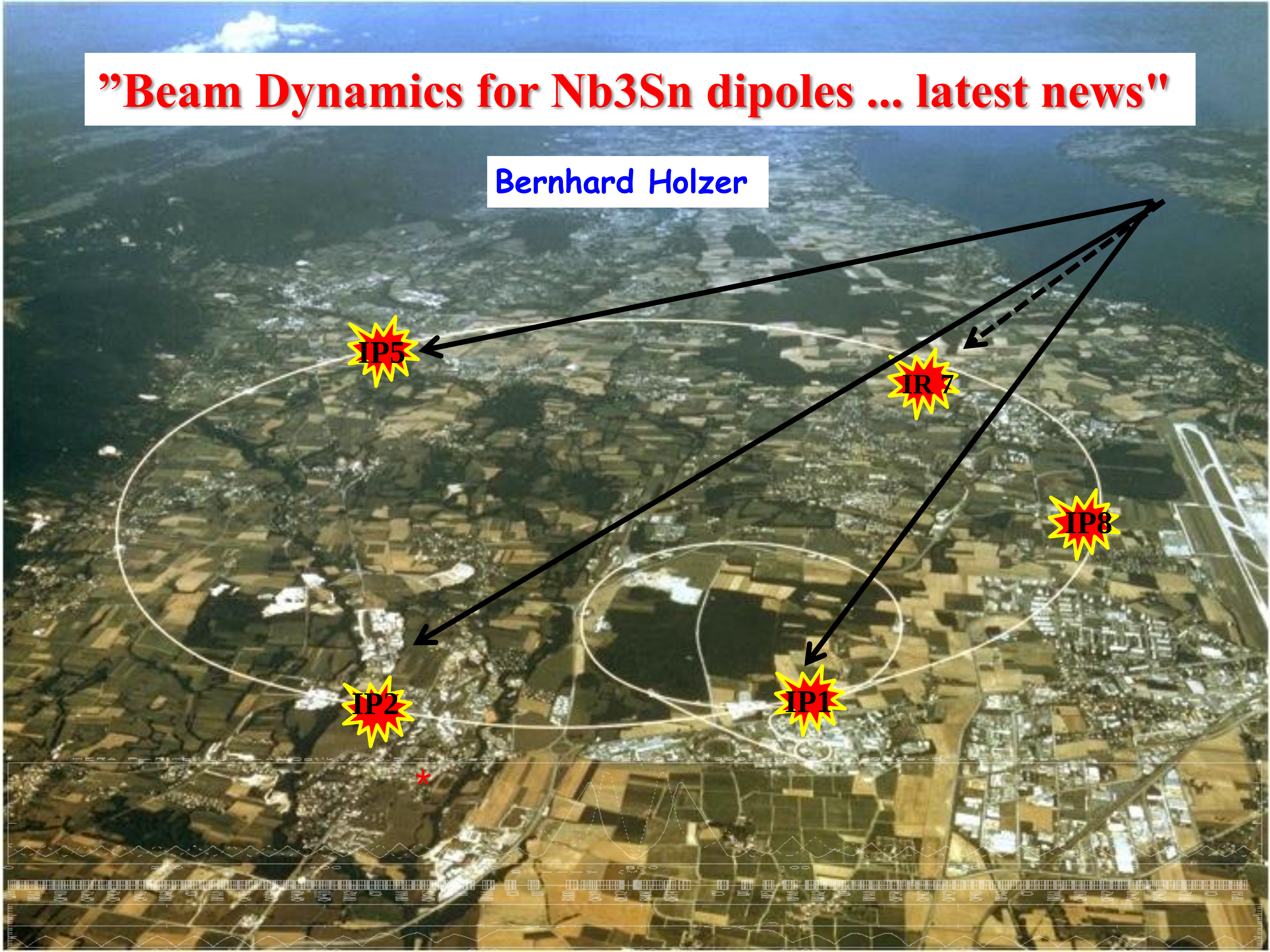
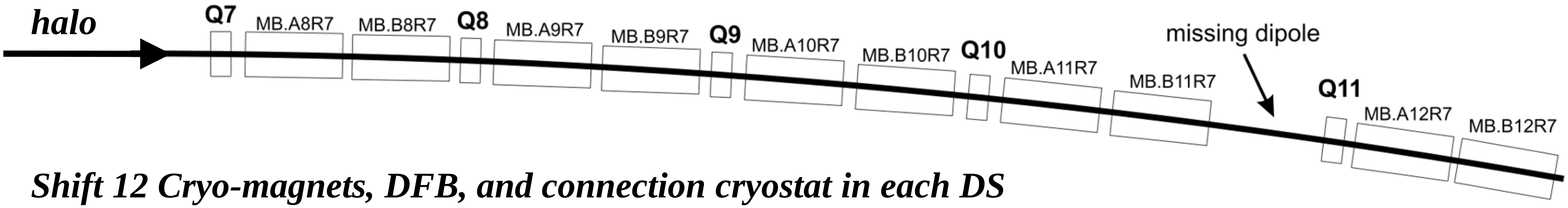
”Beam Dynamics for Nb3Sn dipoles ... latest news"

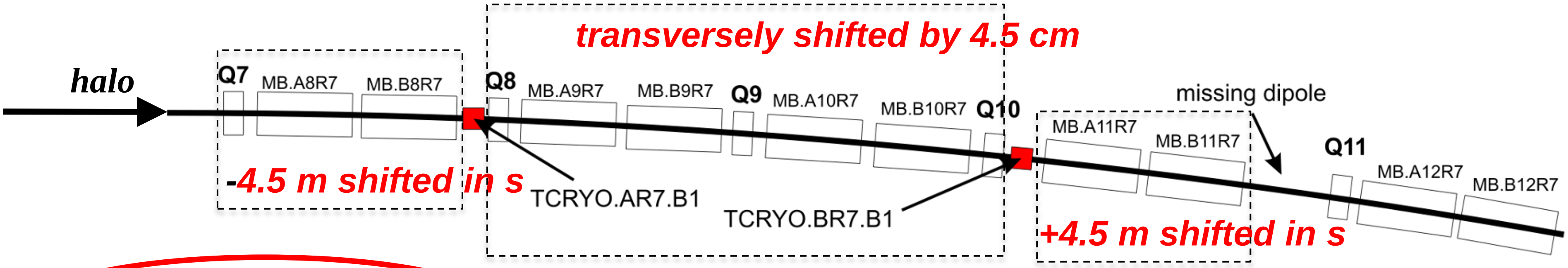
Bernhard Holzer



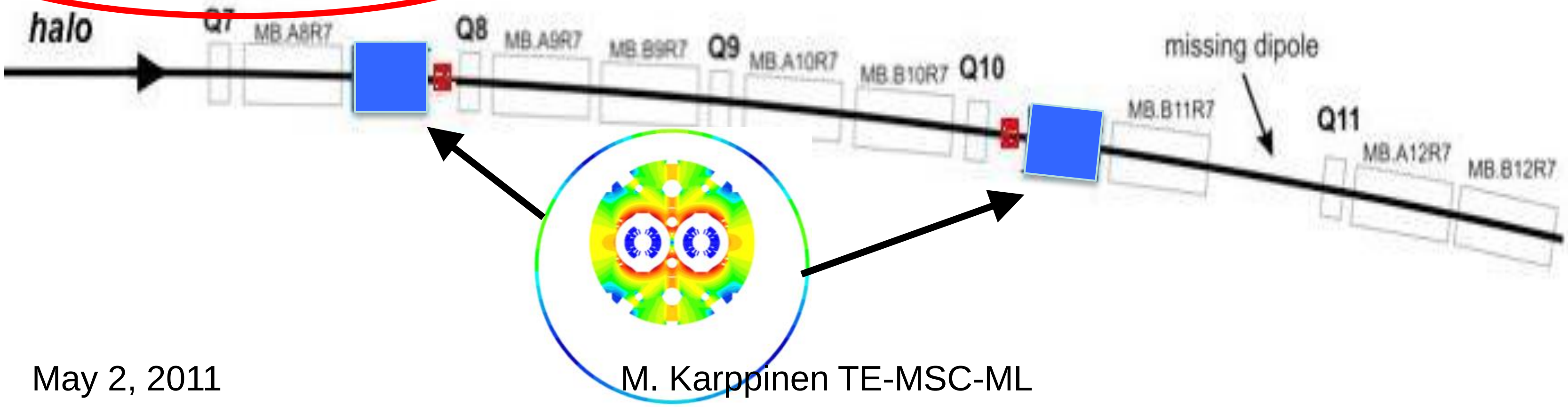
DS Upgrade Scenarios



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



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
distortion of design orbit

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

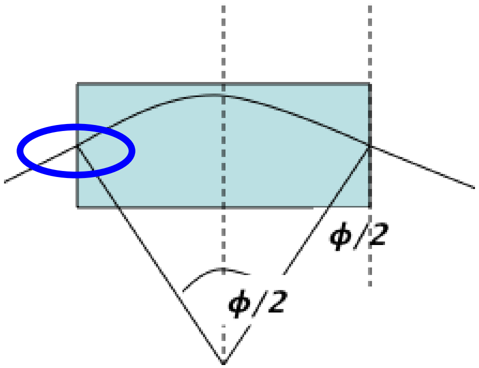
* nonlinar transfer function (3.5 TeV) → distortion of closed orbit
to be corrected locally ??
dedicated corrector coils ??
trim power supply ??

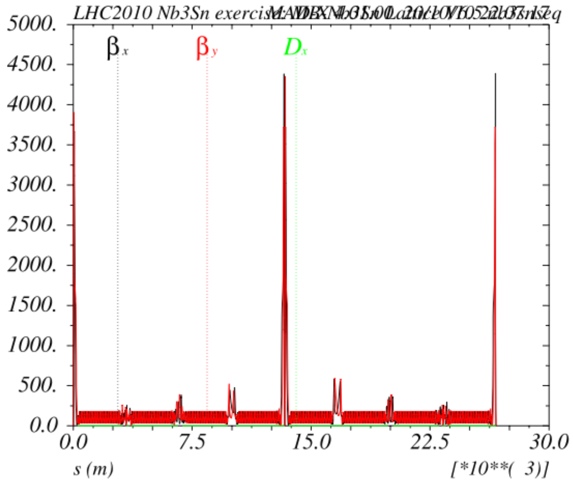
* feed down effects from sagitta ?

* multipole effect on dynamic aperture ?

Sixtrack Tracking Simulations

Problem 1.) Influence on Optics:
Edge Foc Effect





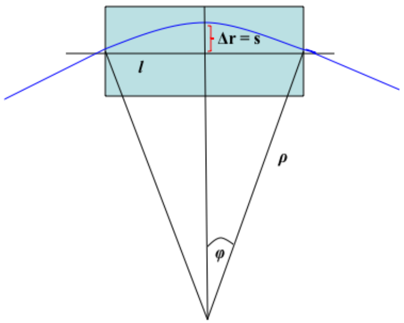
optics distortion

beta beat: $\Delta\beta/\beta < 1*10^{-3}$

tune shift: $\Delta Q_x \approx 9.05*10^{-5}$

$\Delta Q_y \approx 1.33*10^{-4}$

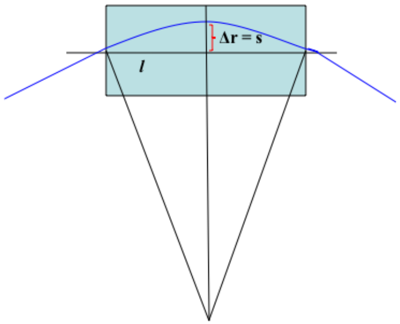
Problem 2.) Influence on Optics:
Sagitta & Feed Down



$$l = 5.5\ m \qquad s = r - \sqrt{r^2 - \frac{l^2}{4}} = 1.7\,mm$$

Influence on Optics and Aperture are quite limited

Problem 3.) Feed Down Effects:



first error estimates: b3 =108 units

Quadrupole Error: $k_1 * l = \Delta x * l * \frac{1}{B\rho} * \frac{2B_0 b_3}{r_0^2}$

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

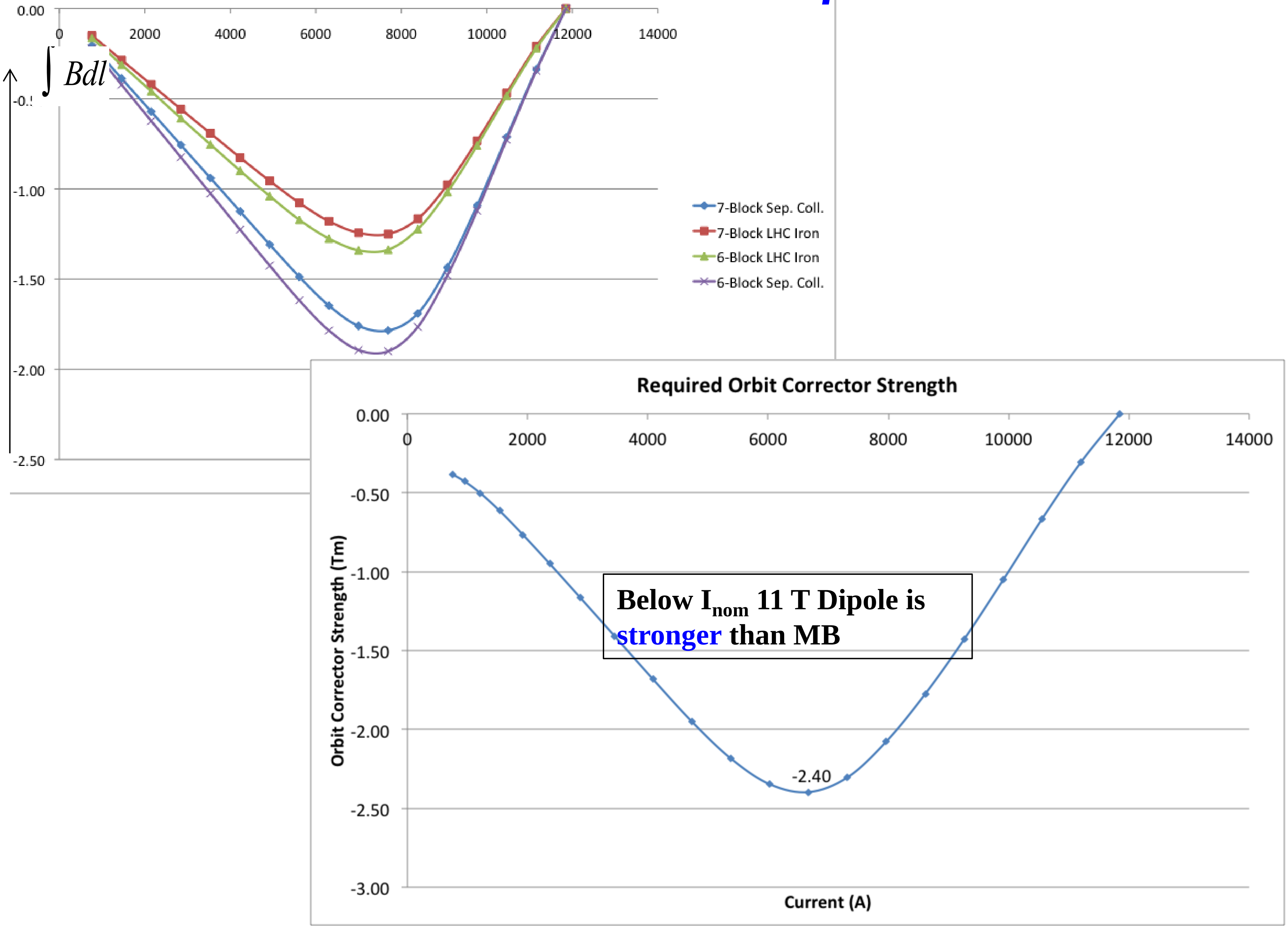
Beta Beat $\frac{\Delta\beta}{\beta} \approx \frac{1}{2\sin 2\pi Q} \int \beta k \, ds$

	$k_1 l$	ΔQ	Δβ/β
450 GeV	$2.79*10^{-3}$	0.031	20%
3.5 TeV	$2.35*10^{-4}$	0.00262	1.76%
7 TeV	$2.41*10^{-4}$	0.00268	1.80%
Phase 1 D1	$b3=3*10^{-4}$	0.0059	3.9%

per Magnet

← **considered as tolerance limit (DA)**

Problem 1: “non-linear” Transfer Function



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

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 ... $\int Bdl = 1.5\ Tm$

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

... 10 seconds for the contemplation:

$$E = 7\ TeV$$

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

$$N = 1232\ Magnets$$

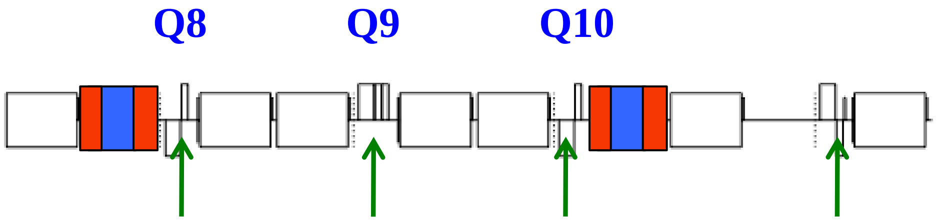
$$\rightarrow \quad 5.1\ mrad \quad per\ dipole$$

Nb3Sn Transferfunction:

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

rough estimate: → Δx ≈ 13 mm

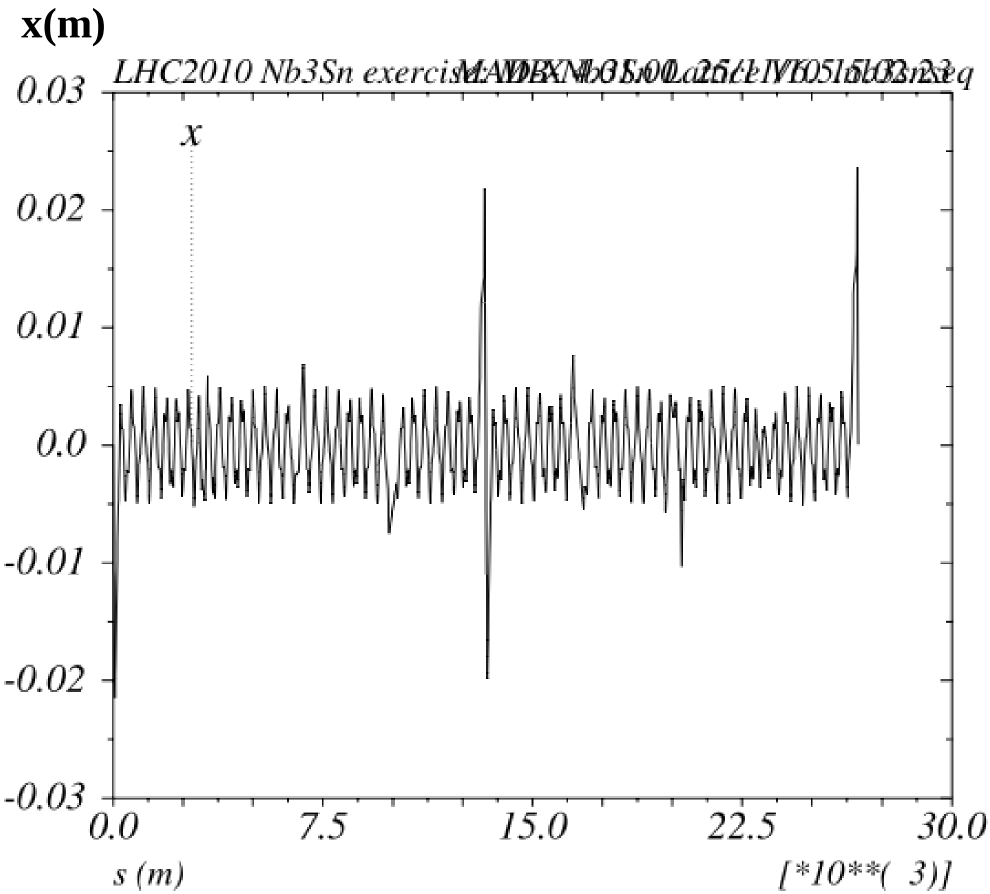
source of the problem: orbit correctors are located at the quadrupoles, with a cell length of 105m.



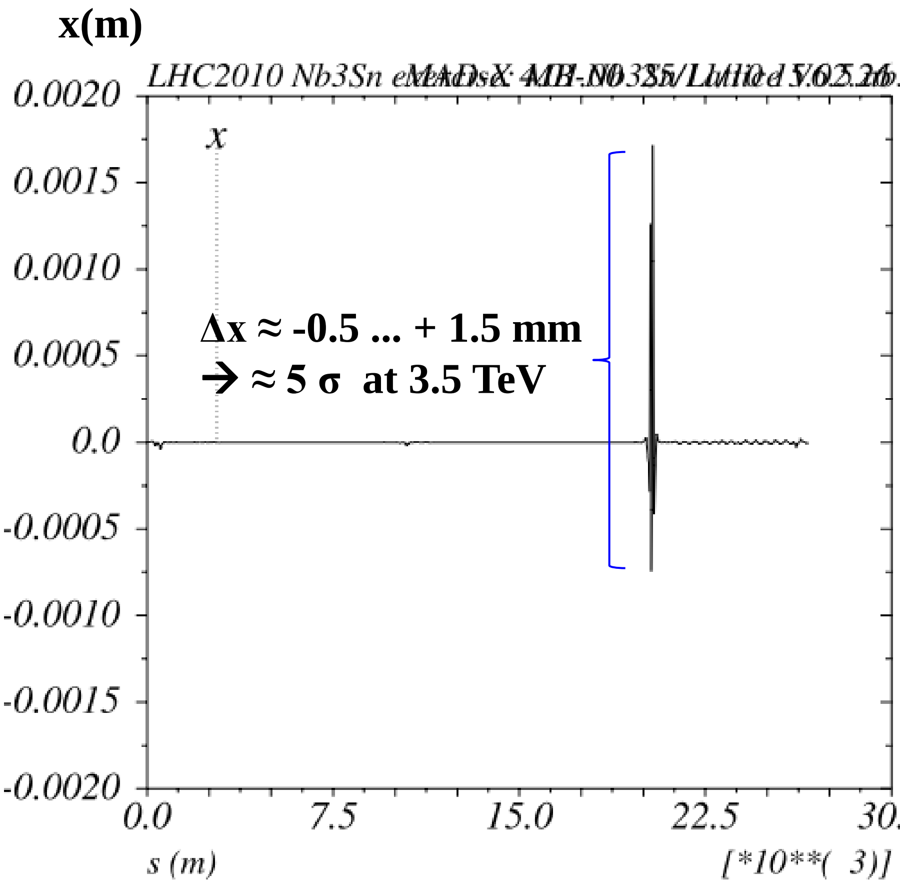
4.) The Story of the Transfer Function ...

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

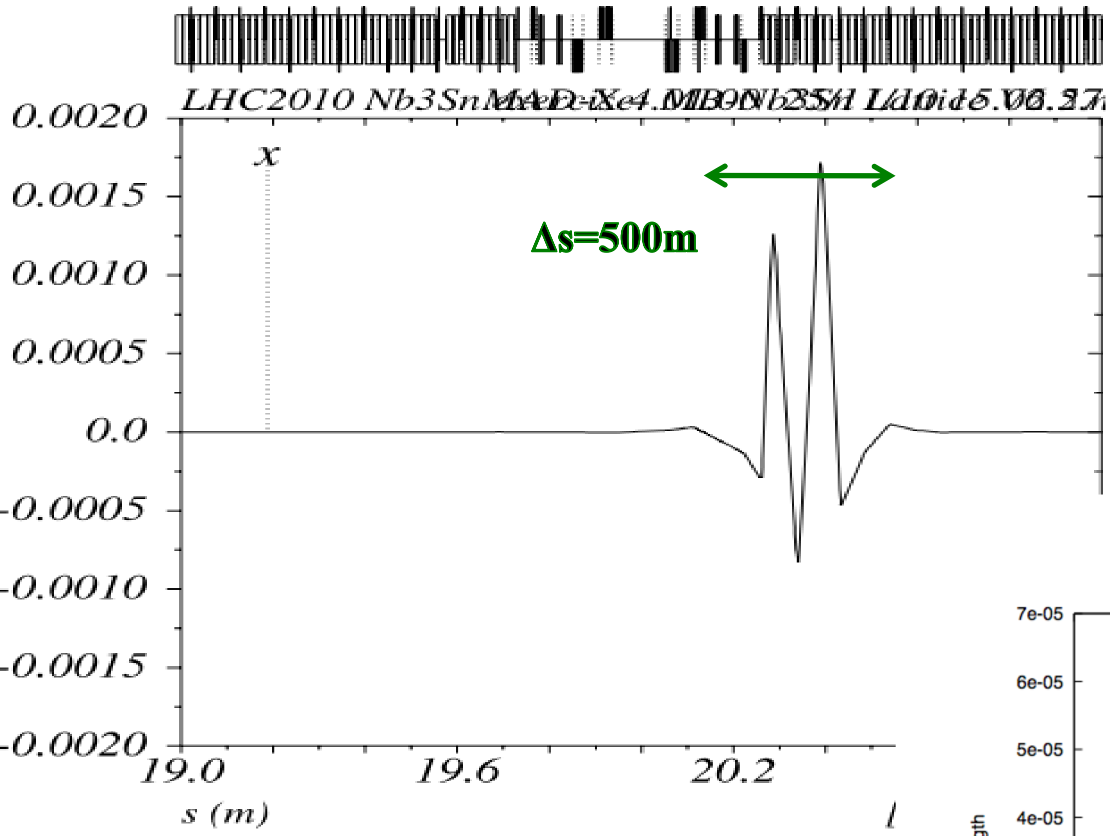
corrected by 20 orbcor dipoles

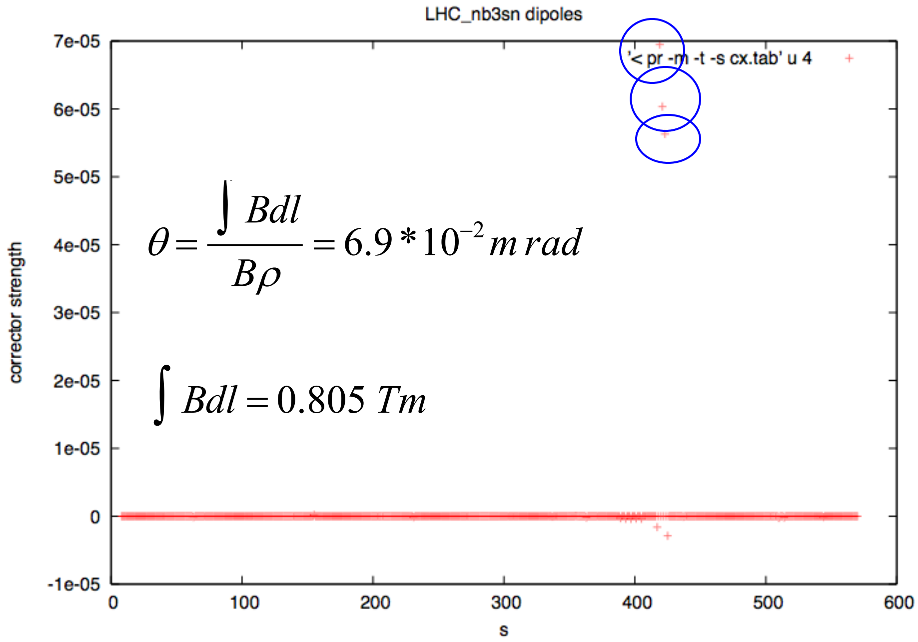
4.) The Story of the Transfer Function ...

a closed orbit problem

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

... local distortion due to
$\Delta\phi \approx 4.545$ phase relation,
closed by MCBH correctors





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

$$\int Bdl = 0.805\ Tm$$

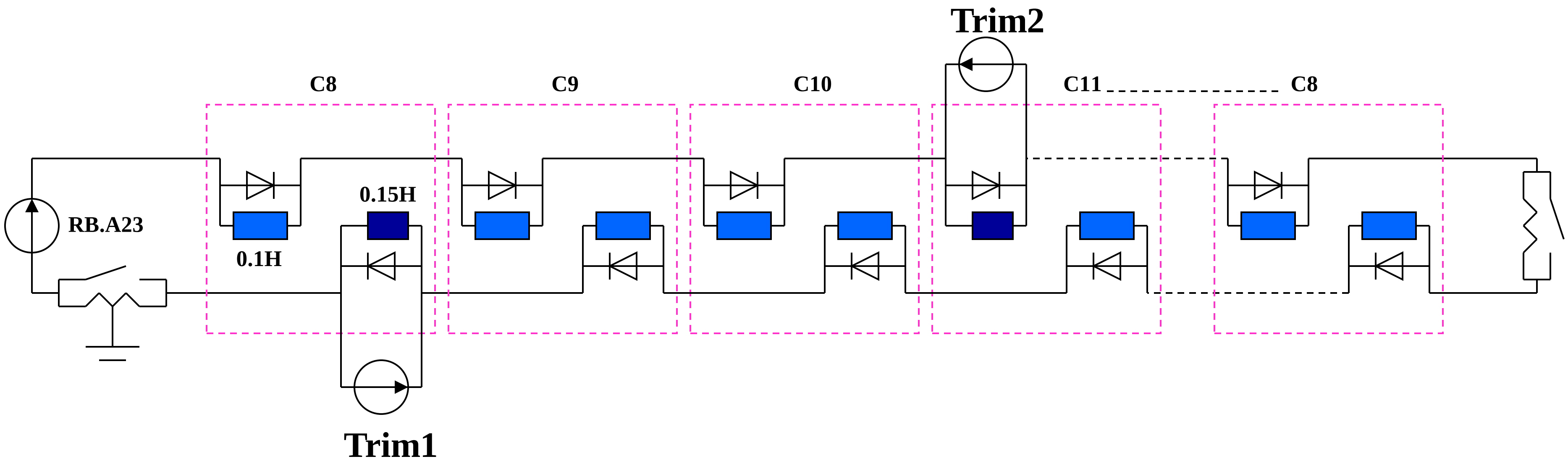
MCBH corrector strength:

available:	**1.900 Tm**
needed:	**0.805 Tm**

!

= 42 %

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

TRIM Power Converters

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

(+)

- **Low current CL for the trim circuits**
- **Size of Trim power converters**

(-)

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

Courtesy of H. Thiessen

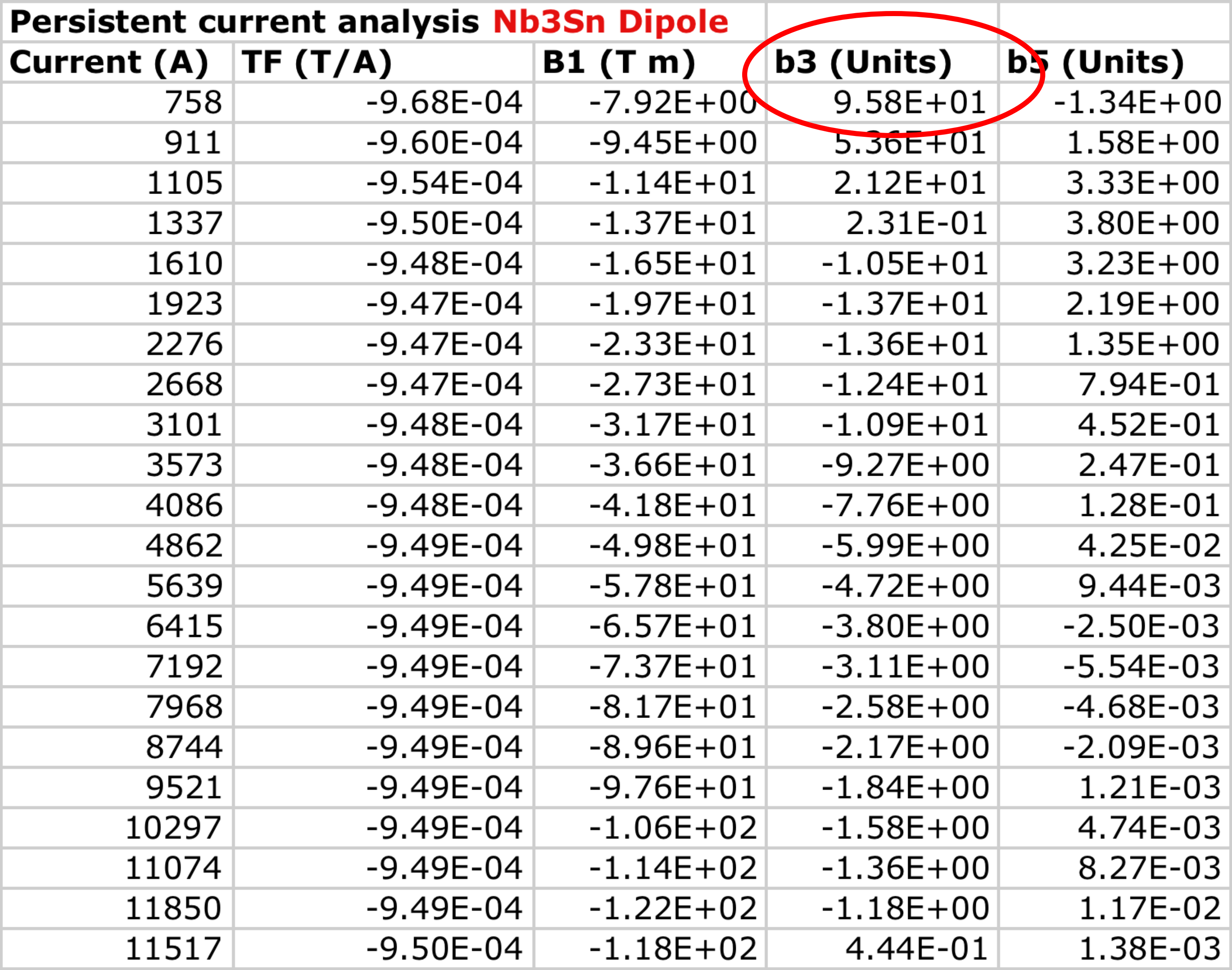
Problem 2: Multipole Errors & Dynamic Aperture in Nb3Sn Dipoles ... *the very first estimates*

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

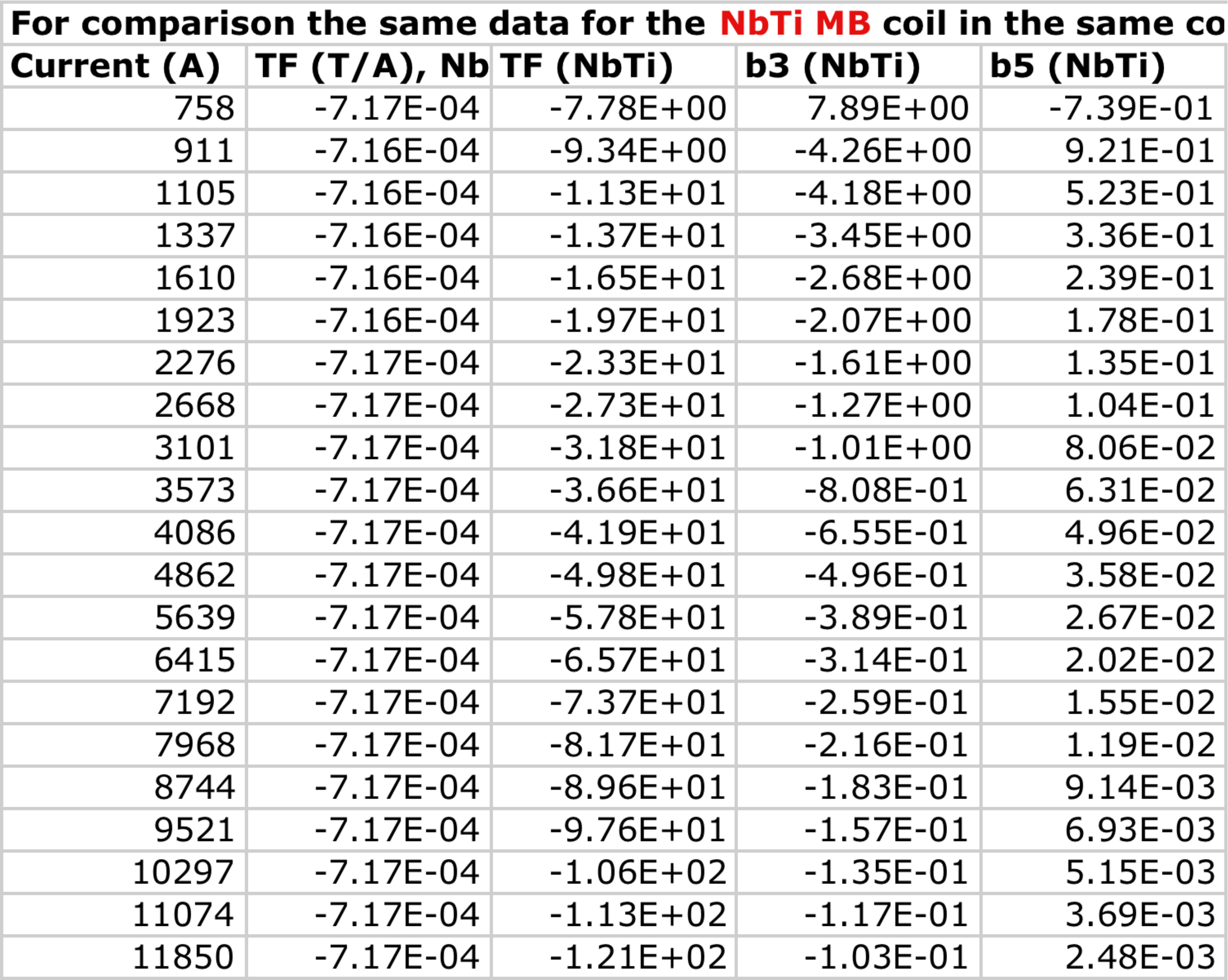
... in the usual units, i.e. 10^{-4} referred to the usual ref radius = 17mm

Nb3Sn Dipole: Multipole Errors: ... *the very first estimates*



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

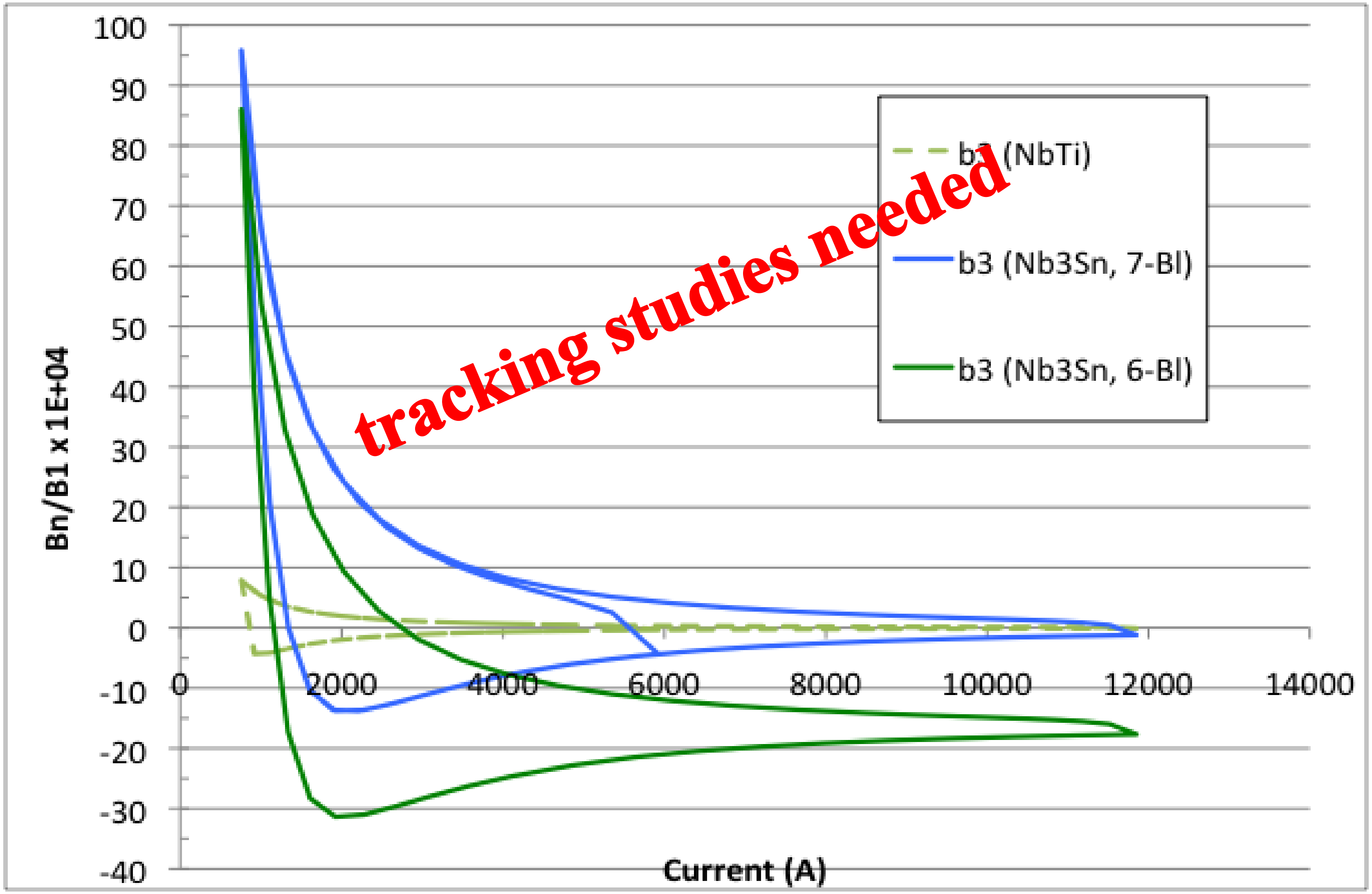
NbTi Dipole: Multipole Errors:



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:

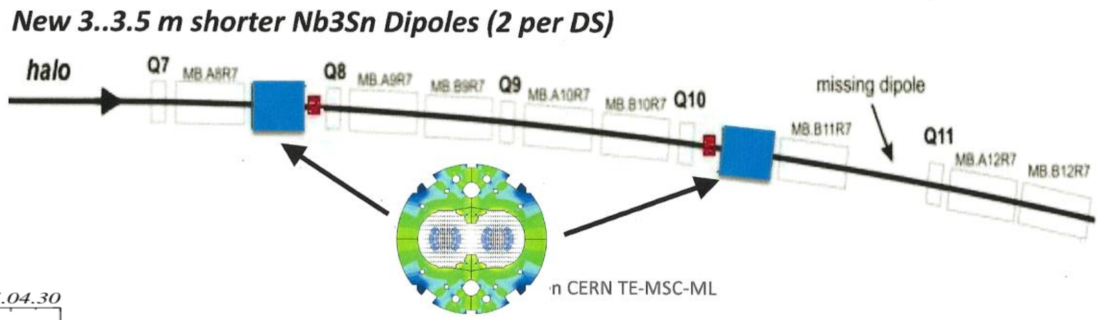


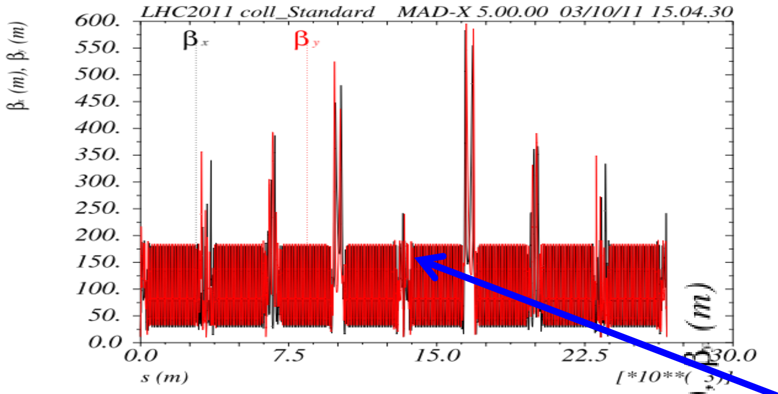
tracking studies needed

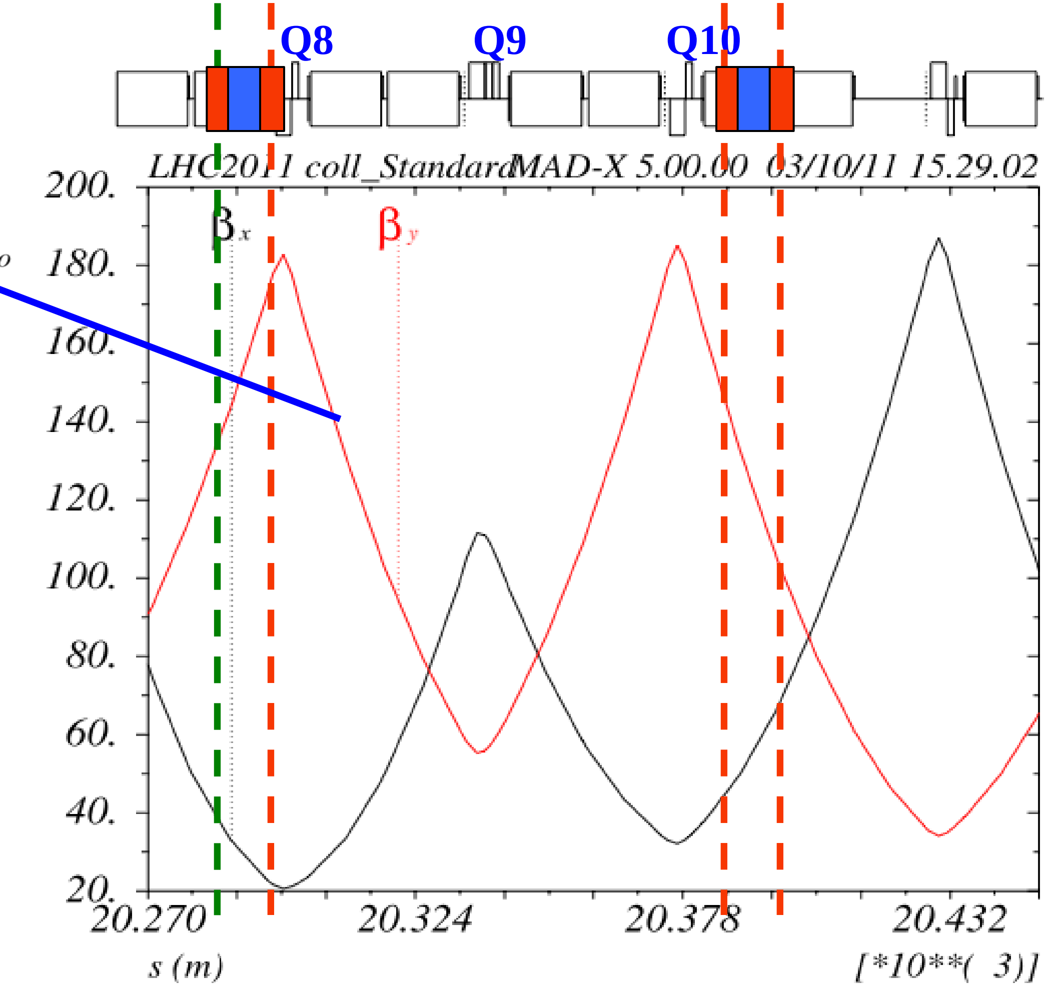
M. Karppinen CERN TE-MSC-ML

Where are we ?

IP1,2,5,IP7





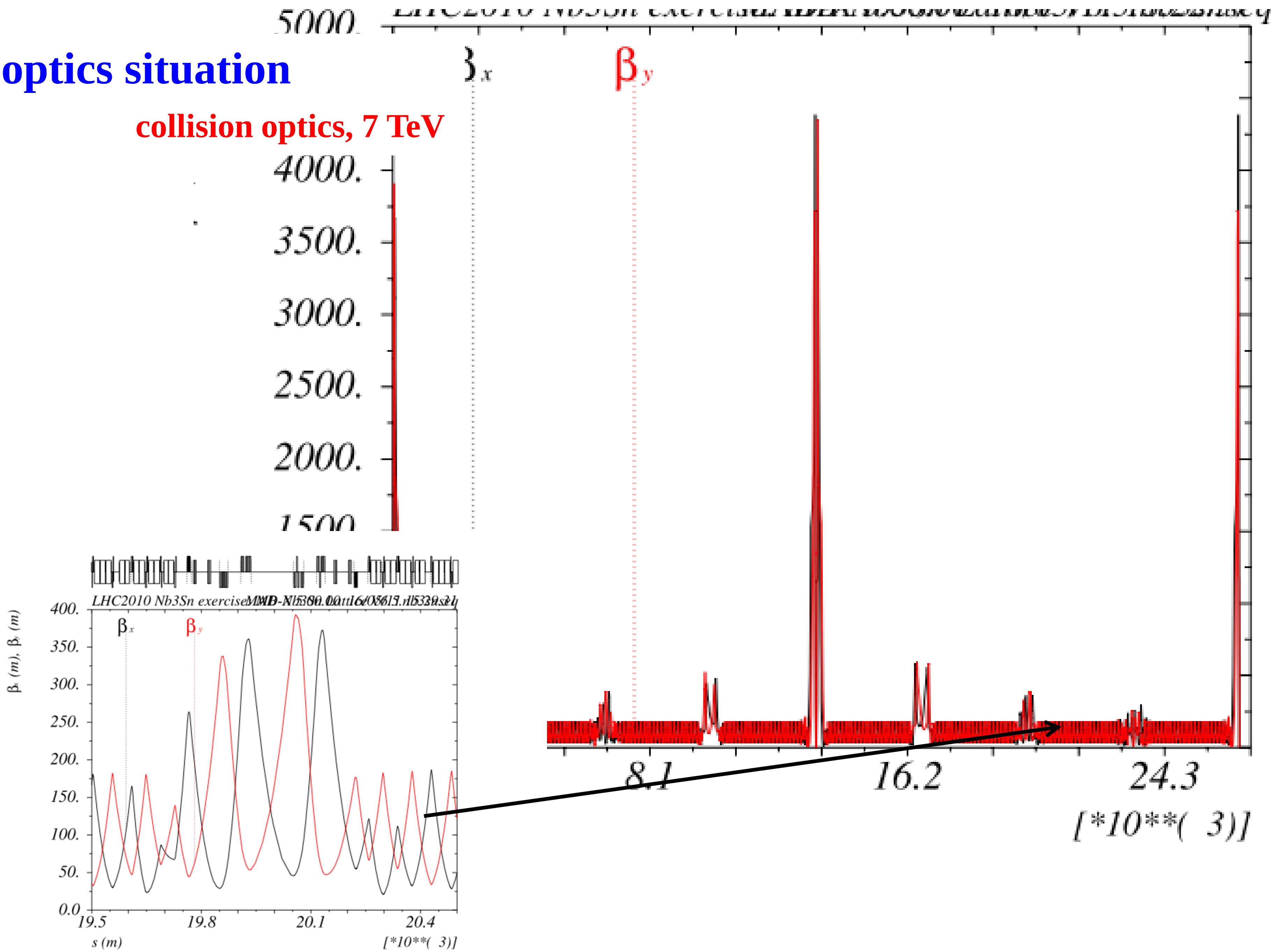


Present Option:

2 x 5.5m Nb3Sn Dipoles separated

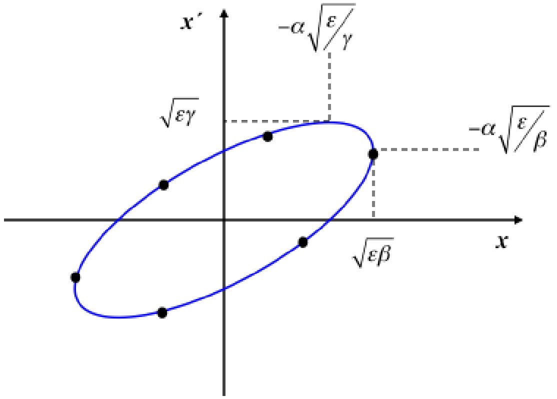
optics situation

collision optics, 7 TeV

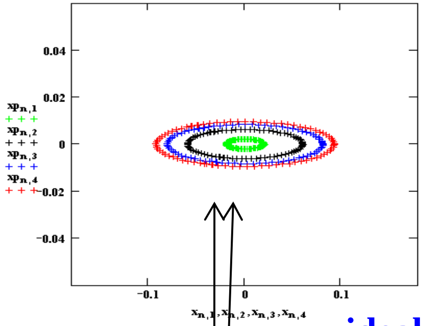


Tracking Studies:

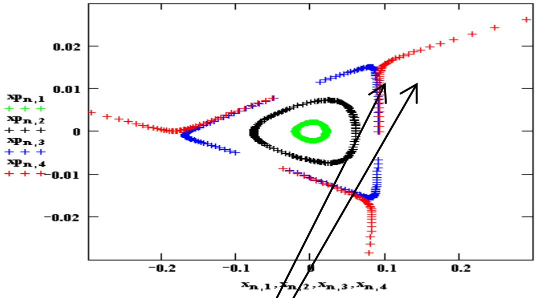
Dynamic Aperture determined via stability / survival time



theory: phase space ellipse defined by optical parameters

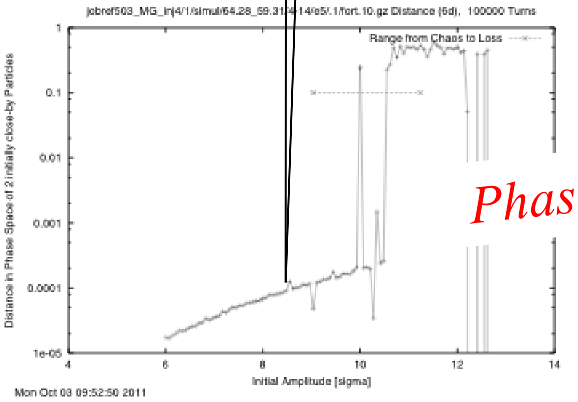


ideal, linear machine

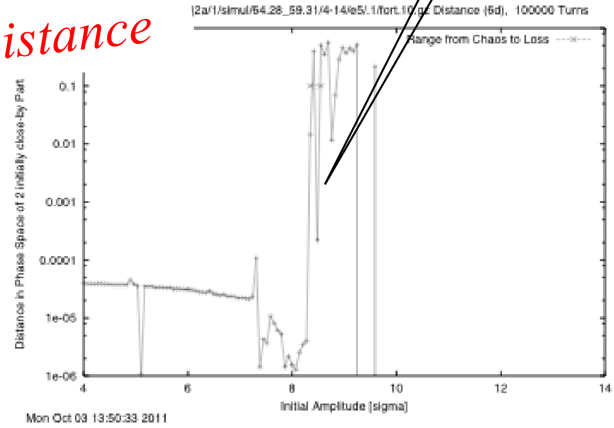


strong b3 multipole

Phase Space Distance



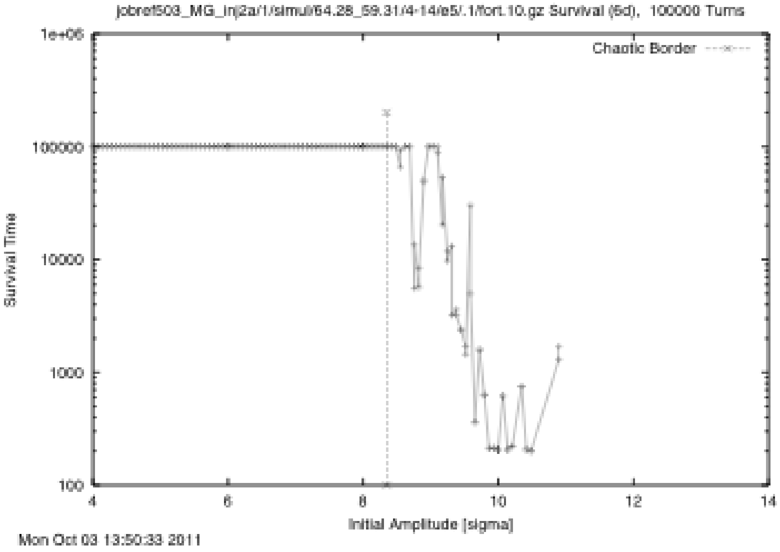
b3 = 98, full & local correction



b3 = 98, no correction

Tracking Studies:

Dynamic Aperture determined via survival time

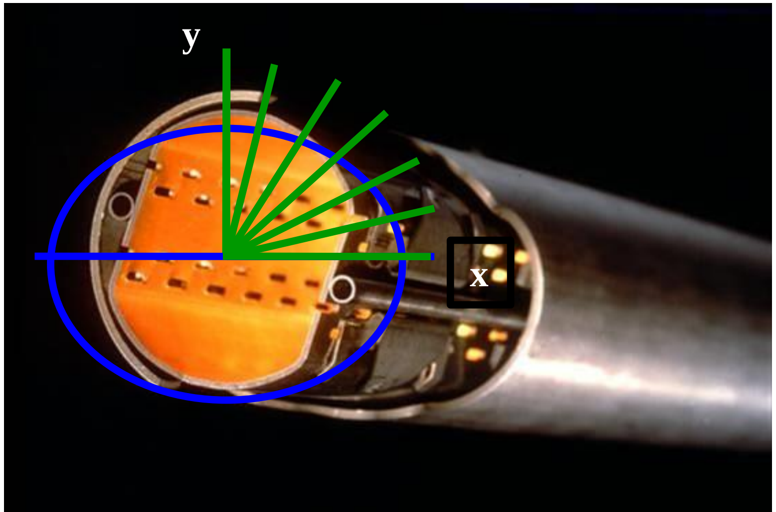


b3 = 98, no correction

survival time ... measured in number of turns
... gives an indication of the influence of the non-linear fields on the (an-) harmonic oscillation of the particles.

For the experts:

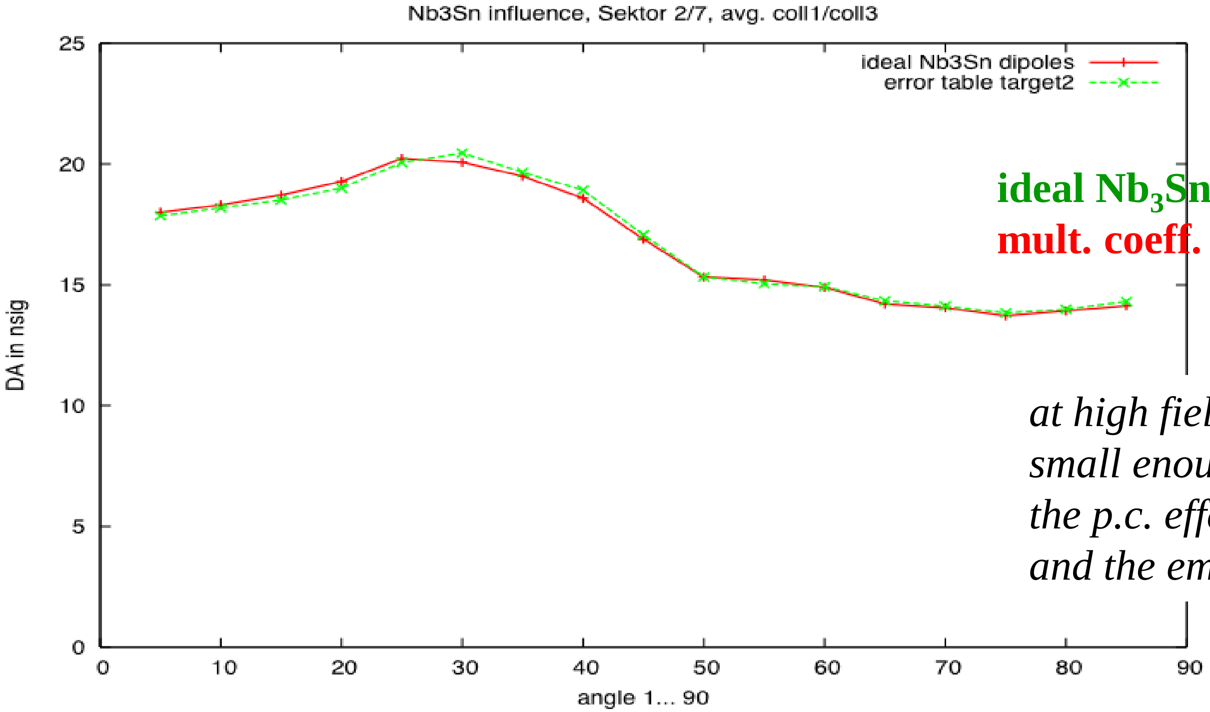
60 seeds,
10^5 turns,
4-18 σ in units of 2,
30 particle pairs,
17 angles



Field Quality: Dynamic Aperture Studies

7 TeV Case, luminosity optics (55cm)

$\varepsilon = 5 * 10^{-10}$ radm ($\varepsilon_n = 3.75 \mu m$)



ideal Nb_3Sn dipoles

mult. coeff. à la error table6

at high field the higher harmonics are small enough,
the p.c. effects disappeared
and the emittance is reduced (Liouville)

Field Quality injection optics, 450 GeV

two options:

1.) introduce a strong local spool piece corrector to accept the large b3

2.) set tolerance limits to b3 to compensate with the standard “mcs”

Option 1.)

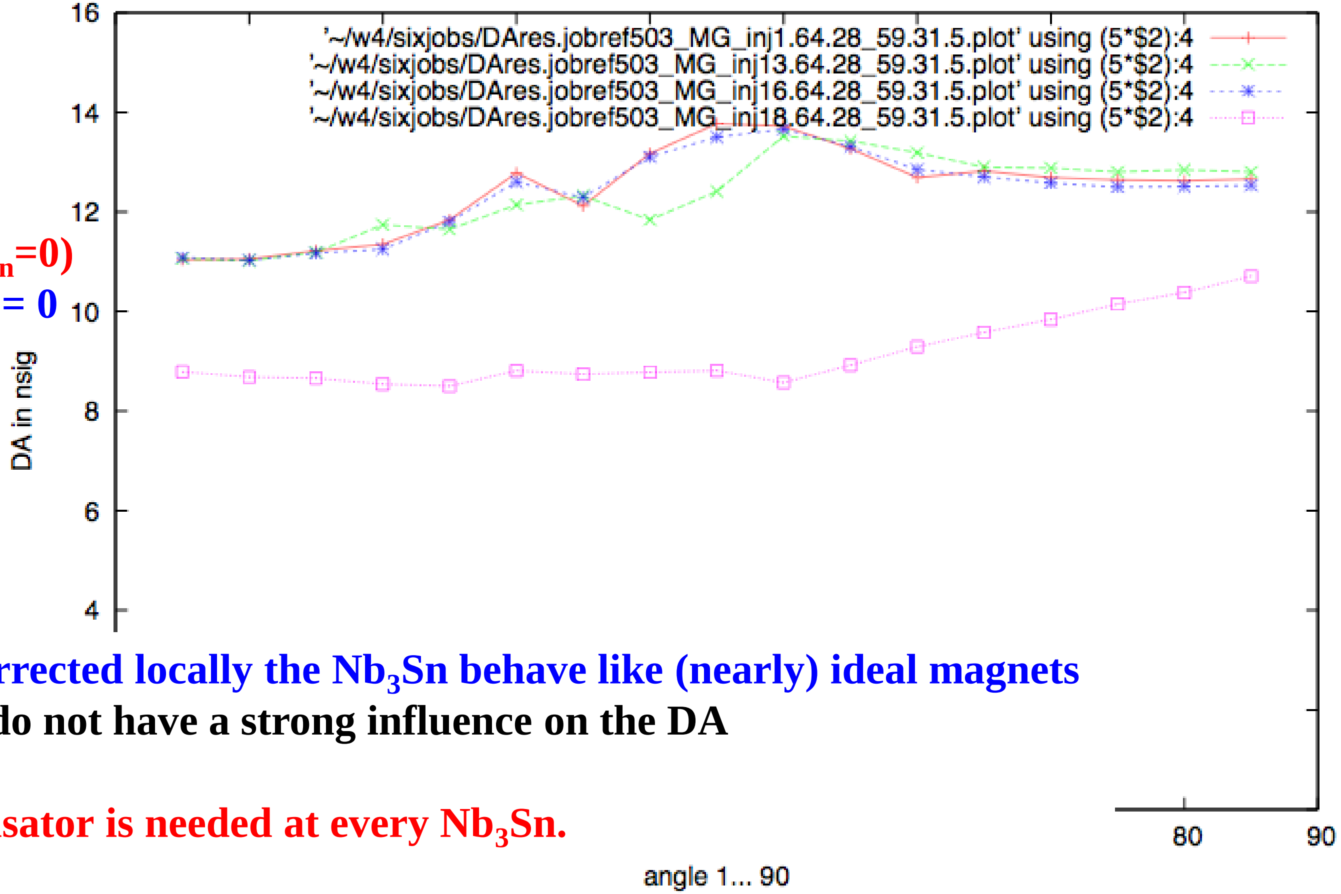
ideal Nb3Sn magnets (a_n=b_n=0)

a_n=b_n=Nb_3Sn values but b_3 = 0

b_3=full, local compensation

b_3 =full, no correction

dyn aperture injection optics, average of 60 seeds



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.

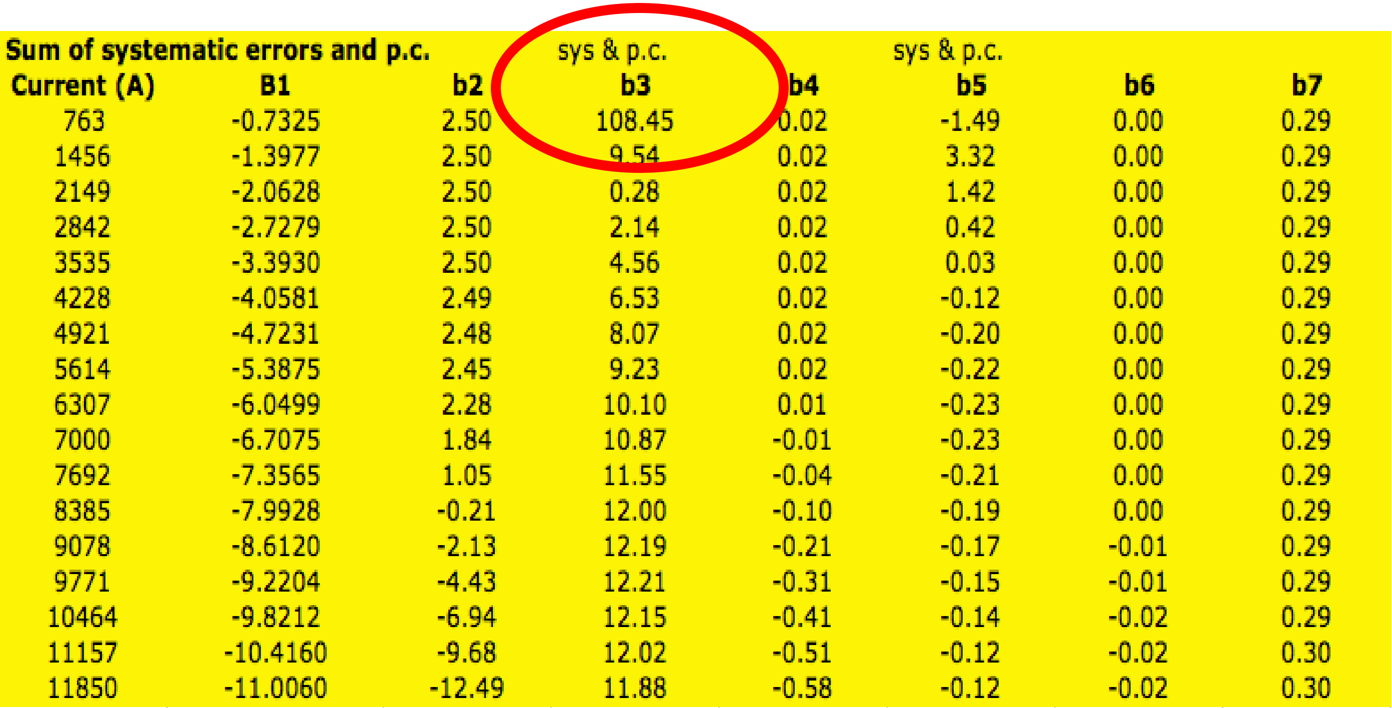
Option 1.)

accept the large b3 and install a local correction

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

Option 2.)

determine tolerance limits for the b3 at injection

... and try to improve the technical design

dynamic aperture for Nb3Sn case:

full error table (red)

b3 reduced to 50% (green)

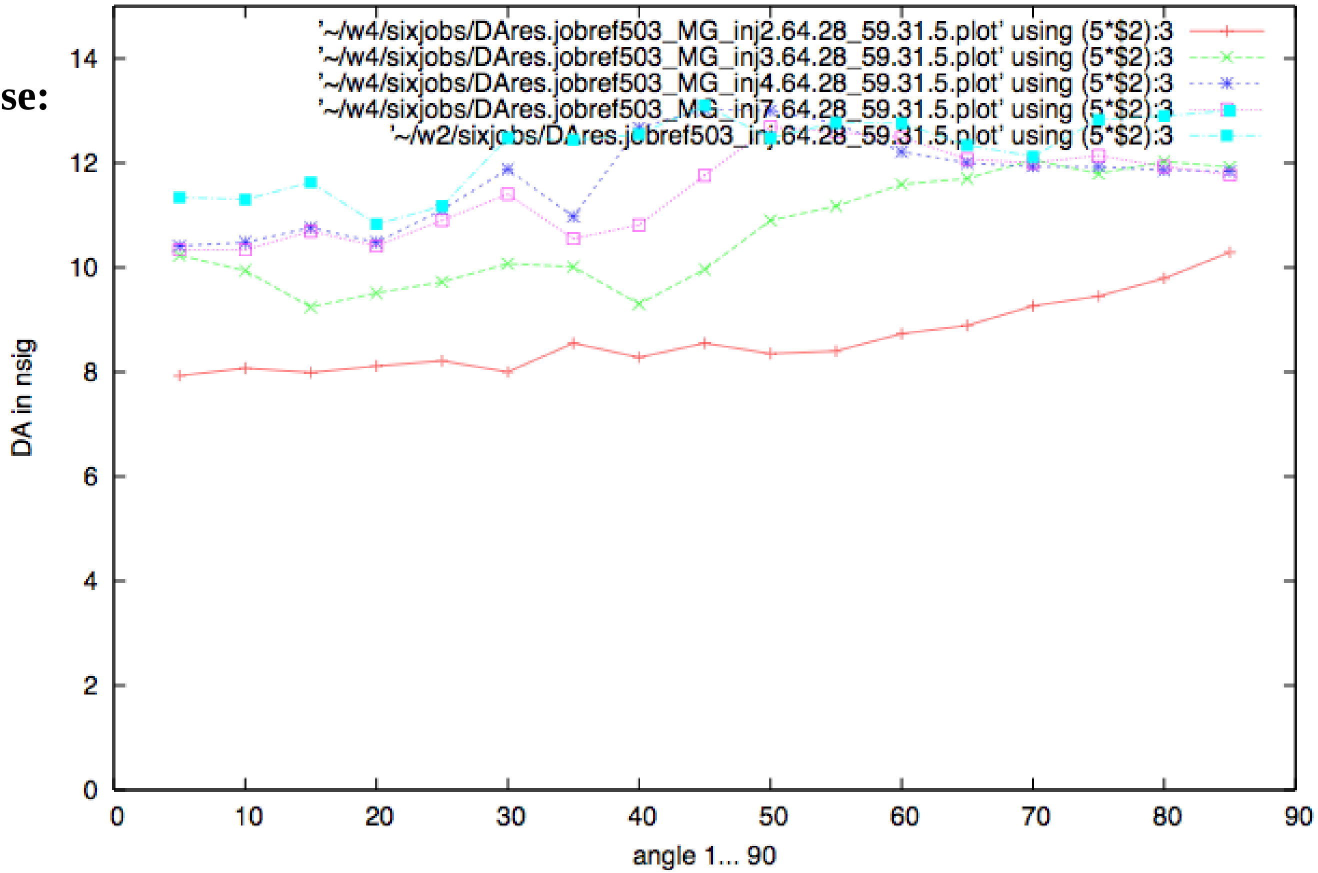
b3 reduced to 25% (violett)

b3 = 0

and to compare with:

present LHC injection

dyn aperture injection optics, minimum of 60 seeds



for the experts: there is not much difference between b3=0 and perfect Nb$_3$Sn magnets !!

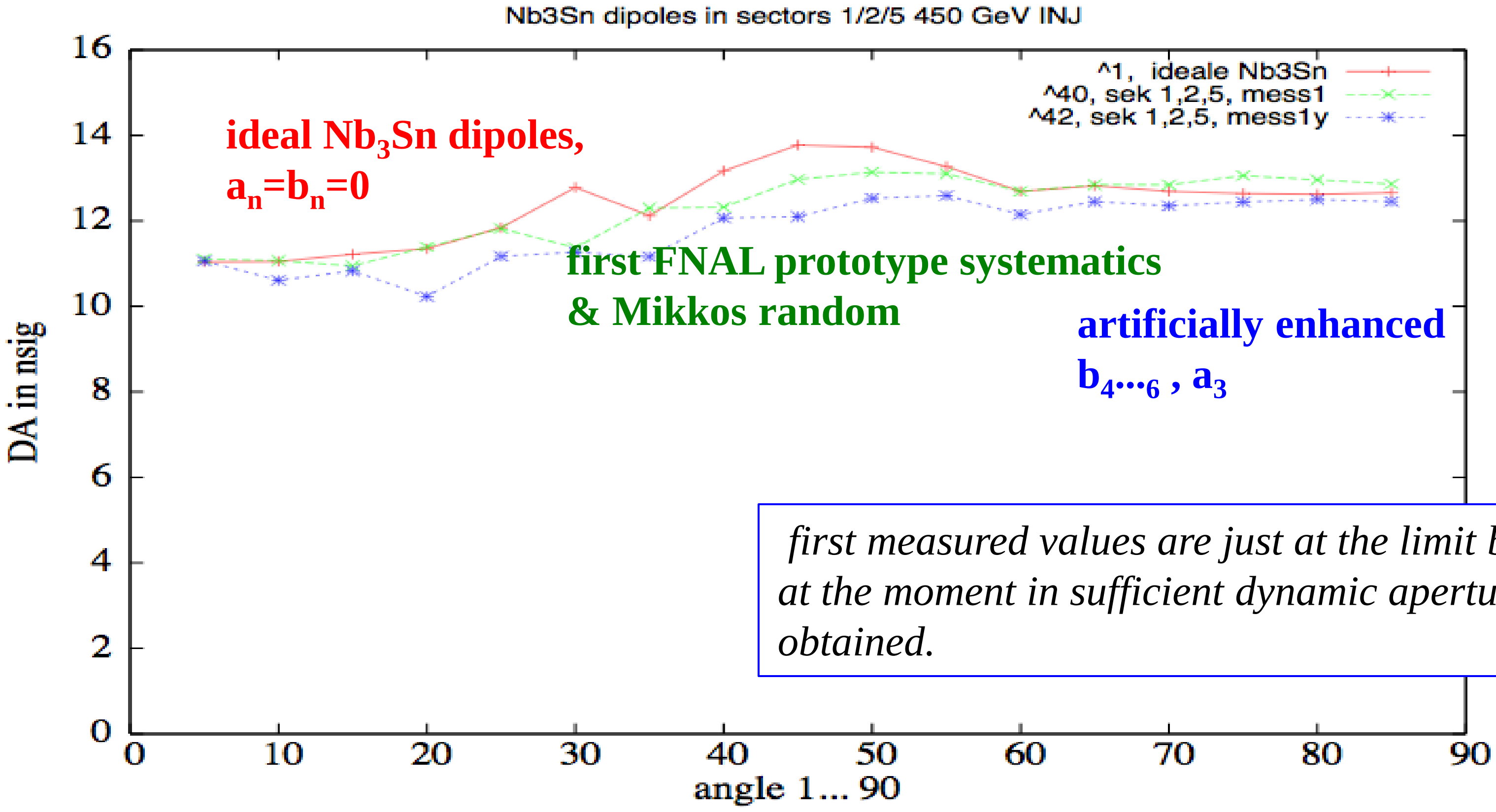
A scan in b$_3$ values has been performed and shows that values up to b$_3$ < 20 units are ok.

Field Quality: First Prototype

Injection Optics, 450 GeV, first measured values: “FNAL-demo-2”

and again the tracking ...

systematics -> FNAL prototype
random -> best guess
uncertainty - > MB standard dipole



ideal Nb_3Sn dipoles, a_n=b_n=0

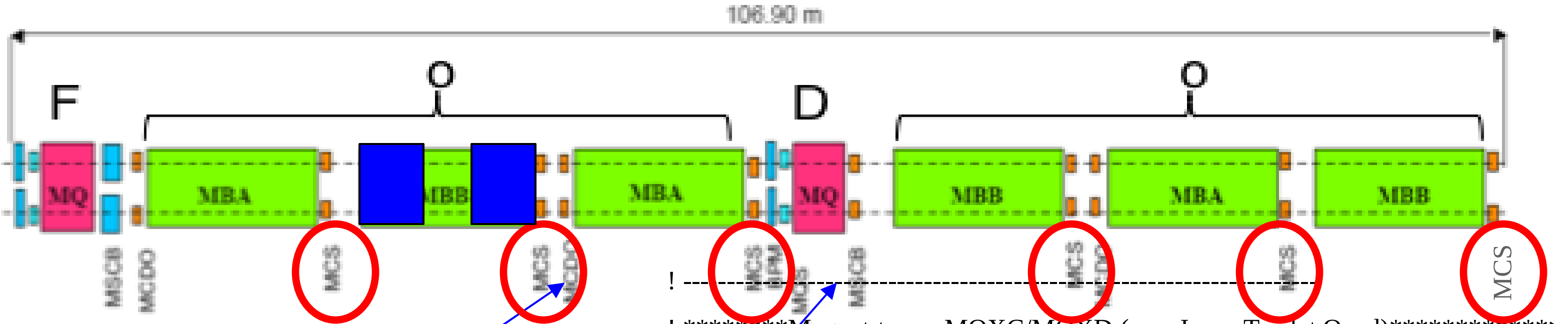
first FNAL prototype systematics & Mikkos random

artificially enhanced $b_{4 \ldots 6}$, a_3

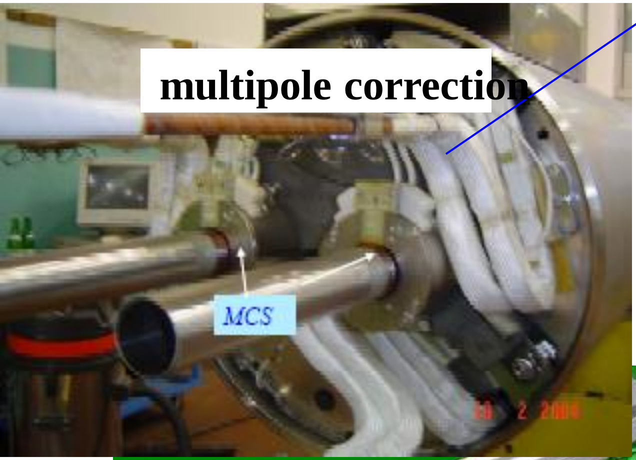
first measured values are just at the limit but at the moment in sufficient dynamic aperture is obtained.

LHC: Basic Layout of the Machine
FoDo and multipole corrector magnets

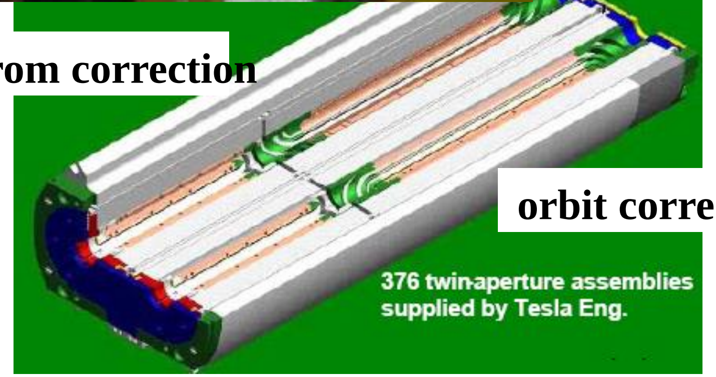
2, 6, 8, 10, 12 pol
skew & trim quad,
chroma 6pol,
landau 8 pole



```
! ------------------------------------------------------------------------------------------
! ********Magnet type : MQXC/MQXD (new Inner Triplet Quad)***************
! ------------------------------------------------------------------------------------------
                 bn in collision
b1M_MQXCD_col  :=  0.0000 ;   b1U_MQXCD_col  :=  0.0000 ; b1R_MQXCD_col  :=  0.0000 ;
b2M_MQXCD_col  :=  0.0000 ;   b2U_MQXCD_col  :=  0.0000 ; b2R_MQXCD_col  :=  0.0000 ;
b3M_MQXCD_col  :=  0.0000 ;   b3U_MQXCD_col  :=  0.4600 ; b3R_MQXCD_col  :=  0.8900 ;
b4M_MQXCD_col  :=  0.0000 ;   b4U_MQXCD_col  :=  0.6400 ; b4R_MQXCD_col  :=  0.6400 ;
b5M_MQXCD_col  :=  0.0000 ;   b5U_MQXCD_col  :=  0.4600 ; b5R_MQXCD_col  :=  0.4600 ;
b6M_MQXCD_col  :=  0.0000 ;   b6U_MQXCD_col  :=  1.7700 ; b6R_MQXCD_col  :=  1.2800 ;
b7M_MQXCD_col  :=  0.0000 ;   b7U_MQXCD_col  :=  0.2100 ; b7R_MQXCD_col  :=  0.2100 ;
b8M_MQXCD_col  :=  0.0000 ;   b8U_MQXCD_col  :=  0.1600 ; b8R_MQXCD_col  :=  0.1600 ;
b9M_MQXCD_col  :=  0.0000 ;   b9U_MQXCD_col  :=  0.0800 ; b9R_MQXCD_col  :=  0.0800 ;
b10M_MQXCD_col :=  0.0000 ;   b10U_MQXCD_col :=  0.2000 ; b10R_MQXCD_col :=  0.0600 ;
   M_MQXCD_col :=  0.0000 ;   b11U_MQXCD_col :=  0.0300 ; b11R_MQXCD_col :=  0.0300 ;
   M_MQXCD_col :=  0.0000 ;   b12U_MQXCD_col :=  0.0200 ; b12R_MQXCD_col :=  0.0200 ;
b13M_MQXCD_col :=  0.0000 ;   b13U_MQXCD_col :=  0.0200 ; b13R_MQXCD_col :=  0.0100 ;
b14M_MQXCD_col :=  0.0000 ;   b14U_MQXCD_col :=  0.0400 ; b14R_MQXCD_col :=  0.0100 ;
b15M_MQXCD_col :=  0.0000 ;   b15U_MQXCD_col :=  0.0000 ; b15R_MQXCD_col :=  0.0000 ;
```



multipole correction



chrom correction

orbit correction

376 twin-aperture assemblies supplied by Tesla Eng.

Magnets for the LHC, total budget, every magnet has a role in the optics design

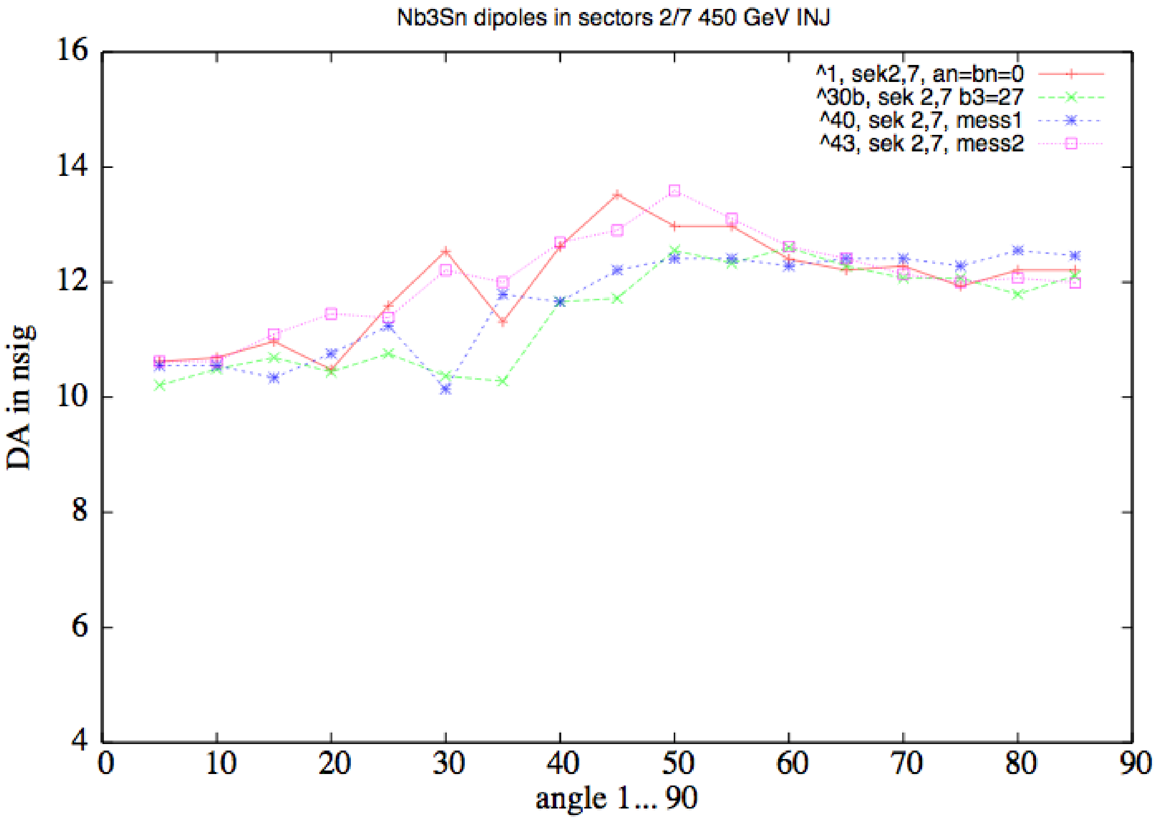
Name	**Quantity**	**Purpose**
MB	1232	Main dipoles
MQ	400	Main lattice quadrupoles
MSCB	376	Combined chromaticity/ closed orbit correctors
MCS	2464	Dipole spool sextupole for persistent currents at injection
MCDO	1232	Dipole spool octupole/decapole for persistent currents
MO	336	Landau octupole for instability control
MQT	256	Trim quad for lattice correction
MCB	266	Orbit correction dipoles
MQM	100	Dispersion suppressor quadrupoles
MQY	20	Enlarged aperture quadrupoles

In total 6628 cold magnets ...

Field Quality: Second Prototype

Injection Optics, 450 GeV

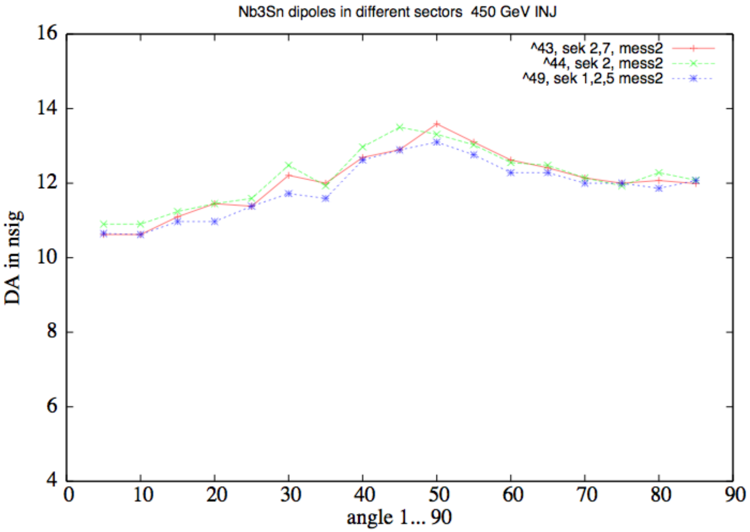
Sec 2/7, min values



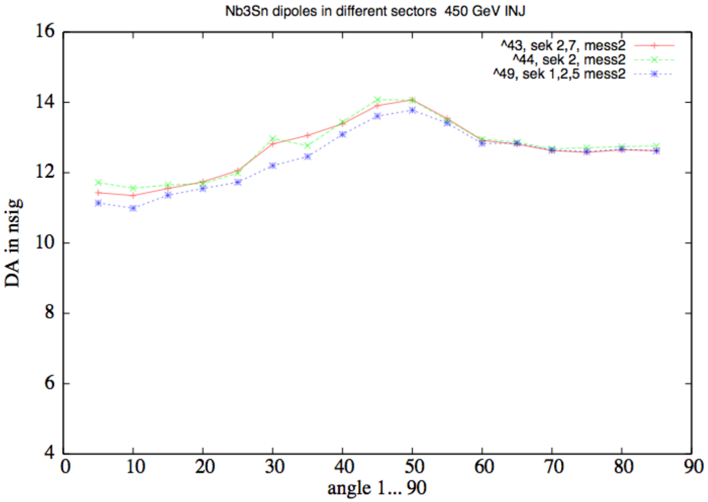
second prototype gives better DA than the first prototype ... and considerably better DA than the b3 tolerance limit

Field Quality: Second Prototype Nb_3 Sn in different sectors

Injection Optics, 450 GeV, standard mcs correection, second prototype



different sectors: #2, #2/7, #1,2,5
min values

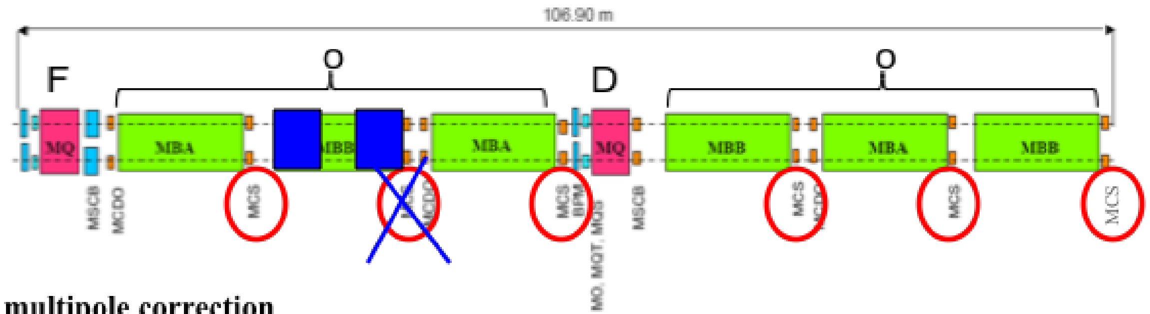


different sectors: #2, #2/7, #1,2,5
min values

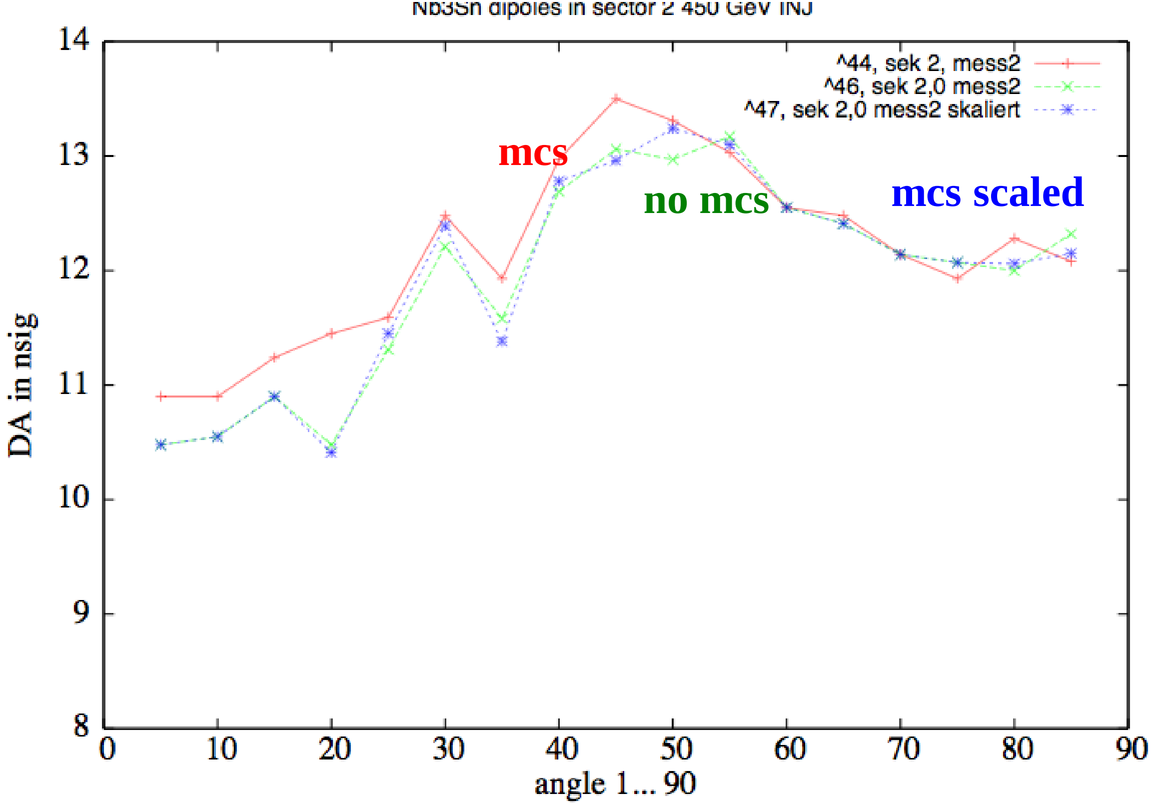
As long as standard mcs compensation is used, the number of sectors is not very relevant

Field Quality: Second Prototype, no mcs

??? can we remove the standard mcs ??? ... a dangerous approach ...



multipole correction



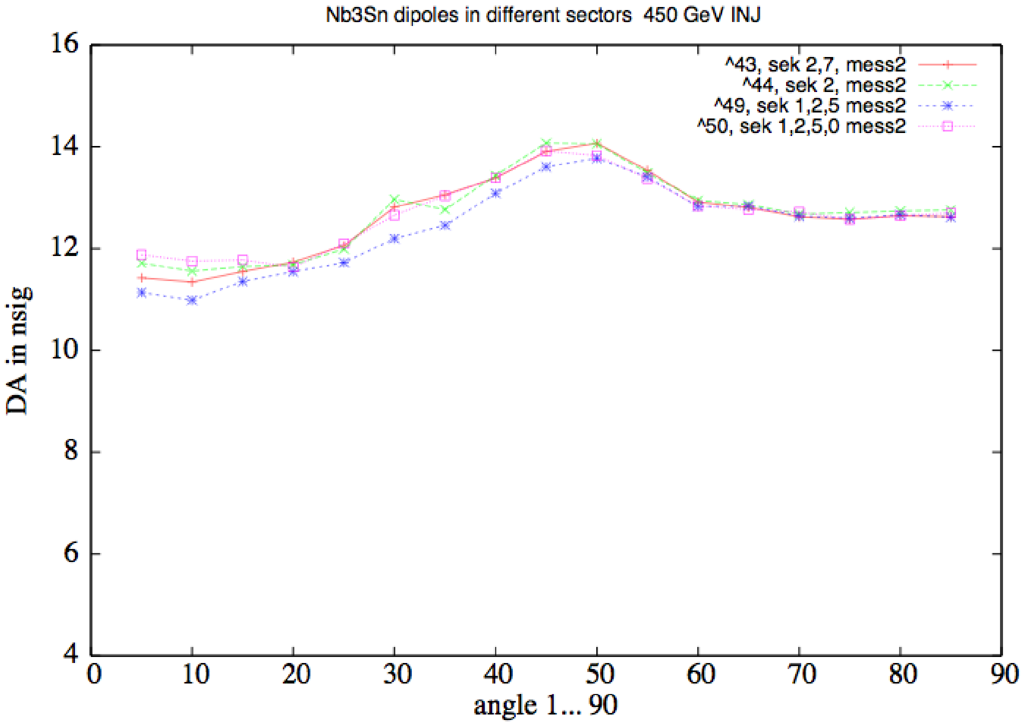
One sector,
compare Sec 2
with / without
mcs
scaled and not

"scaled" => increase the
mcs in the corresponding
sector by 154/152

removing mcs dos not improve the situation scaled or un-scaled.

Field Quality: Second Prototype, no mcs

??? can we remove the standard mcs ??? ... a dangerous approach ...



Different sectors,

compare

sec #2

sec #2,7

sec #1,2,5

sec #1,2,5 with scaled mcs correction (avg).

As long as we stay within the tolerance limits for the second prototype a correction of the b3 seems possible if the remaining mcs are scaled up.

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
Installation trim power supply to compensate seems the ideal solution

Multipoles are an issue: driving problem: b3
They have only small impact at high energy,
At 450 GeV injection they were too strong in first field estimates
they could however be reduced considerably in the 2nd prototype
The b3 has – and can - to be compensated by the mcs standard spool pieces

A correction scheme without local mcs seems possible, leads however in some cases to a reduced DA.