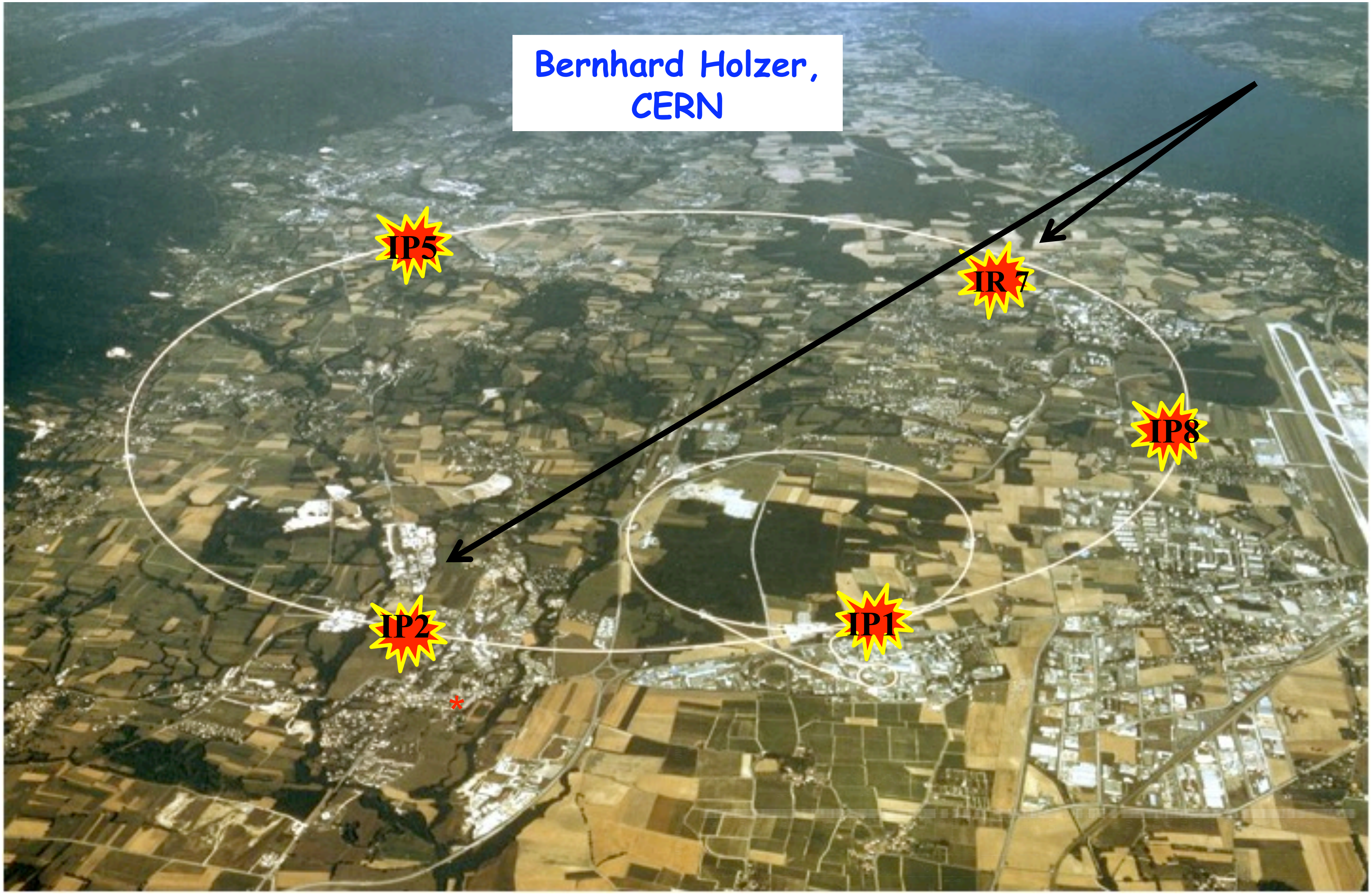
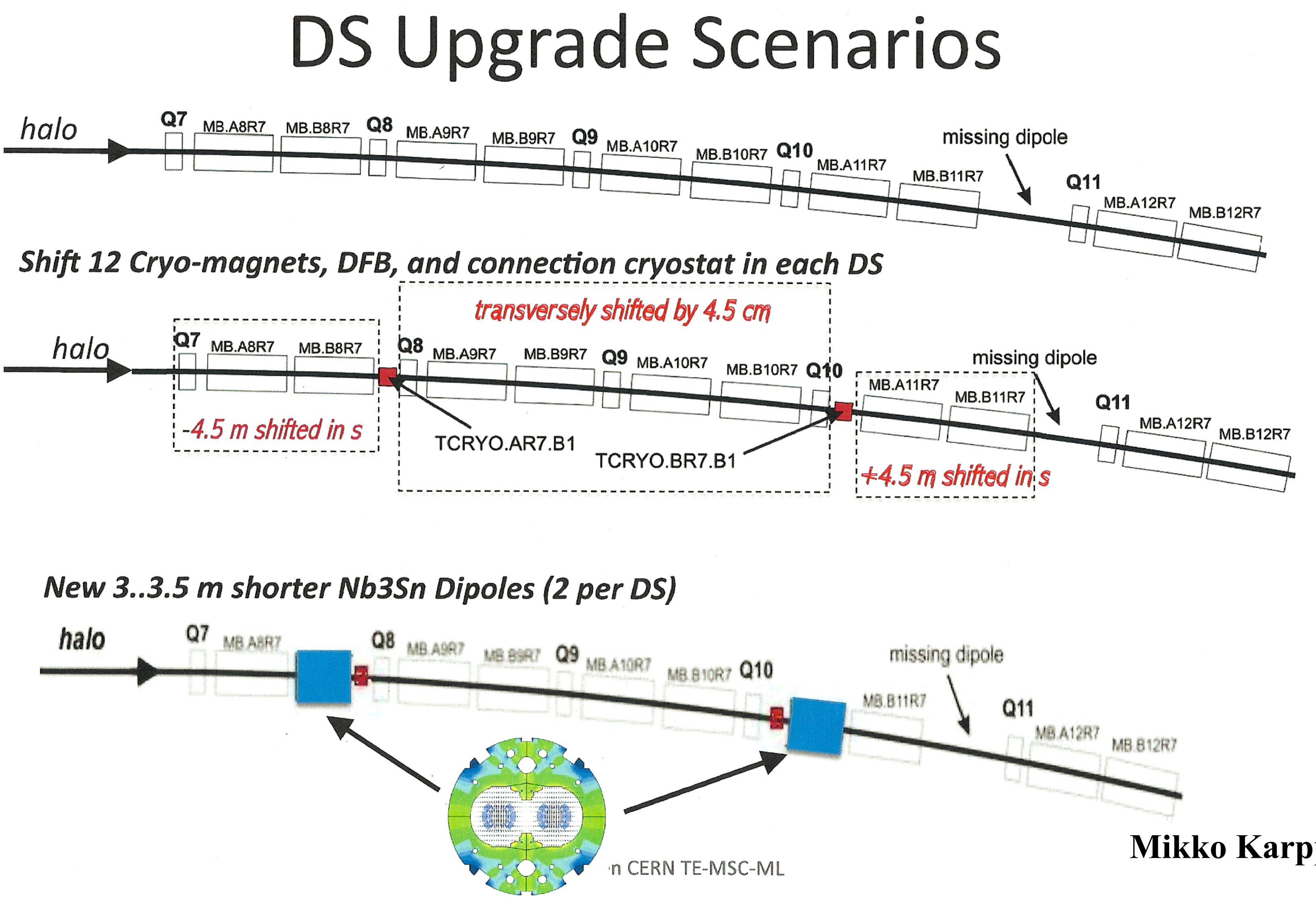
"Nb3Sn Dipoles in LHC ... a philosophical contemplation"

Bernhard Holzer,
CERN



... what are we talking about ???

replace two standard dipoles in the dispersion suppressor region by stronger ↔ shorter Nb_3Sn dipoles to gain space for Ralph

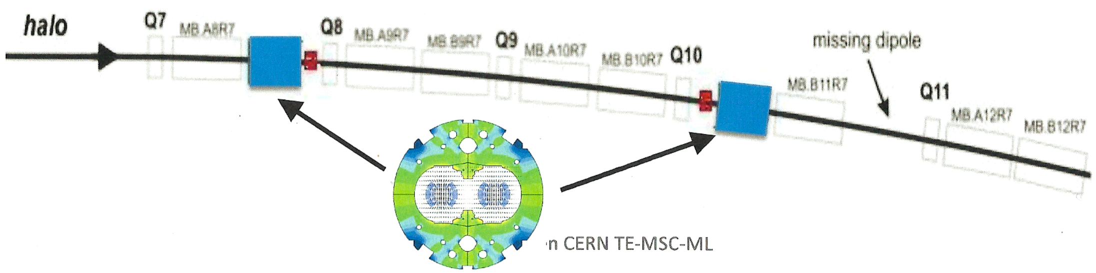


Mikko Karppinen

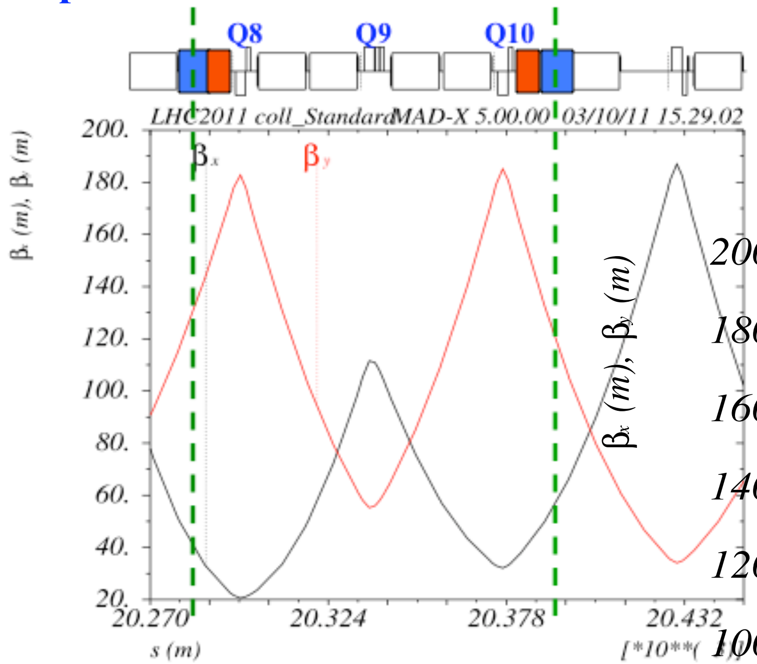
Where are we ?

IP2 & IP7

New 3..3.5 m shorter Nb3Sn Dipoles (2 per DS)

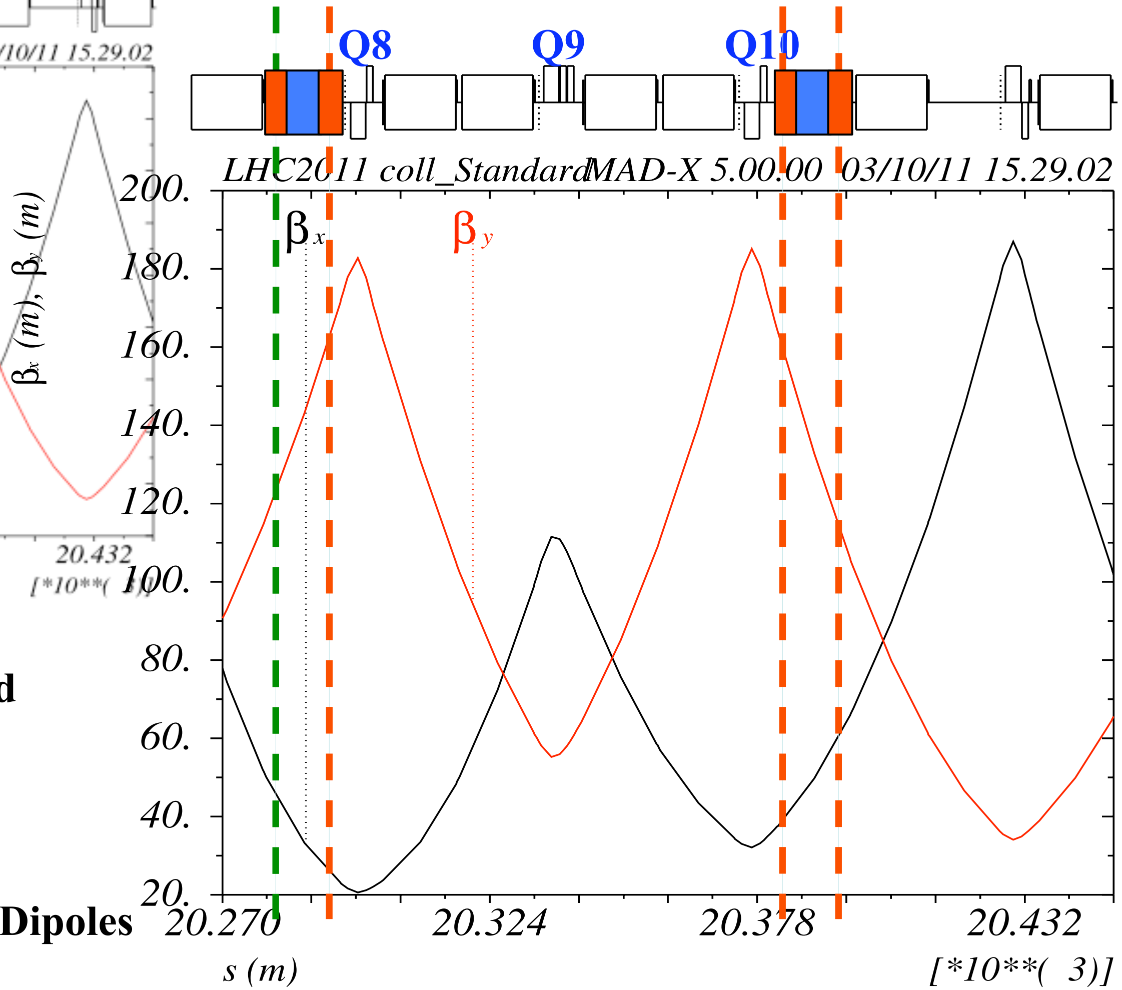


Example: IP7 R



Previous Option:

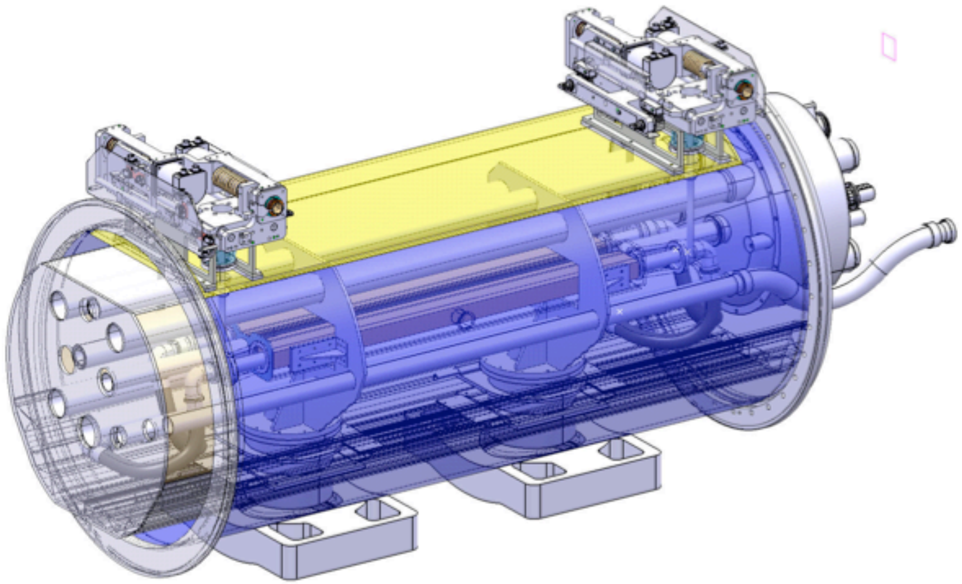
1 x 11m Nb3Sn Dipoles, shifted

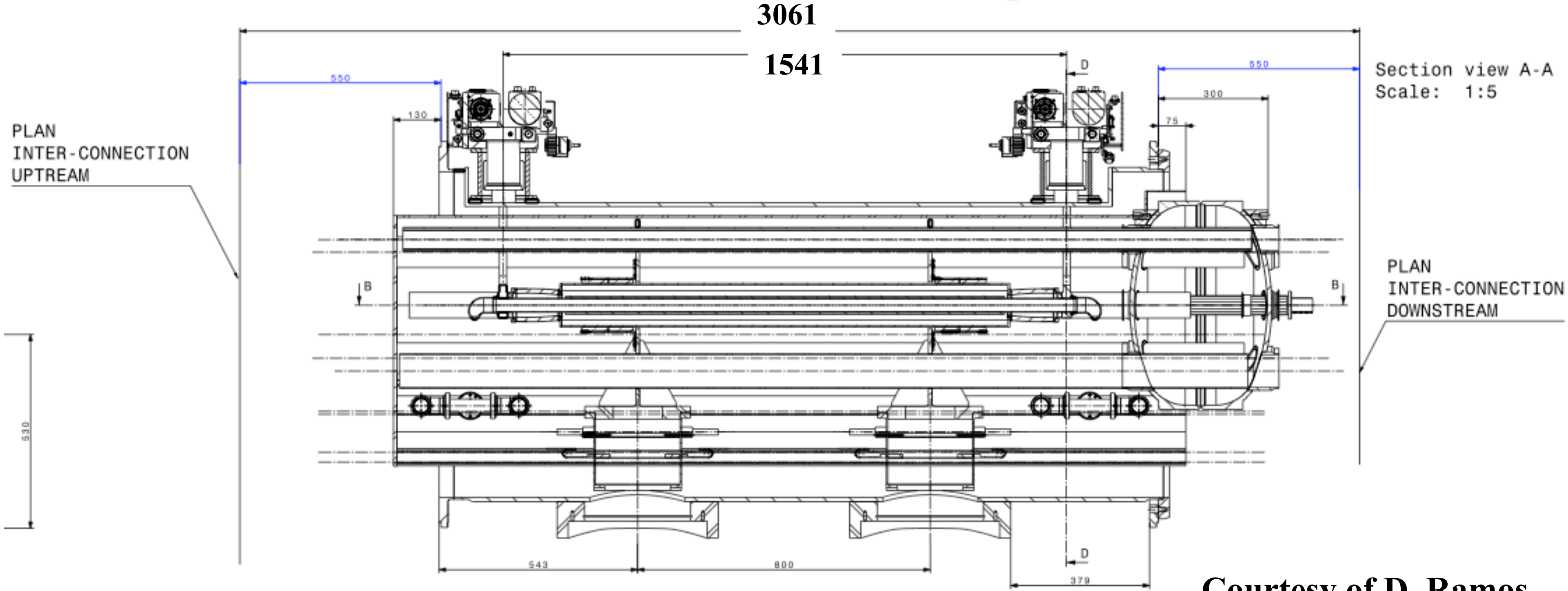


Present Option:

2 x 5.5m Nb3Sn Dipoles separated

Cryo-collimator





Courtesy of D. Ramos

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 ?

* field imperfections: effect on dynamic aperture ?

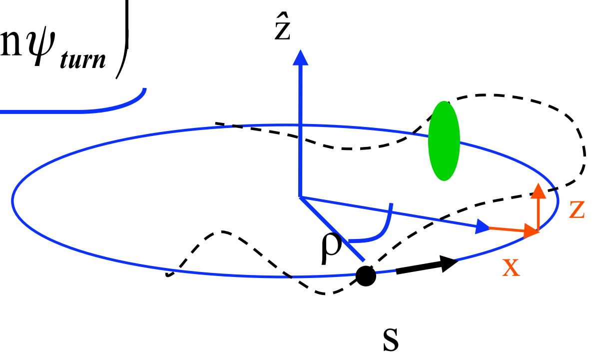
Analytical approach / Mad-X / Sixtrack Simulations

1.) R-Bernd / S-Bend: a (small) optics problem
the "edge focusing"

Quadrupole Error in the Lattice

optic perturbation described by thin lens quadrupole

$$M_{dist} = M_{\Delta k} \cdot M_0 = \underbrace{\begin{pmatrix} 1 & 0 \\ \Delta k ds & 1 \end{pmatrix}}_{\text{quad error}} \cdot \underbrace{\begin{pmatrix} \cos\psi_{turn} + \alpha \sin\psi_{turn} & \beta \sin\psi_{turn} \\ -\gamma \sin\psi_{turn} & \cos\psi_{turn} - \alpha \sin\psi_{turn} \end{pmatrix}}_{\text{ideal storage ring}}$$

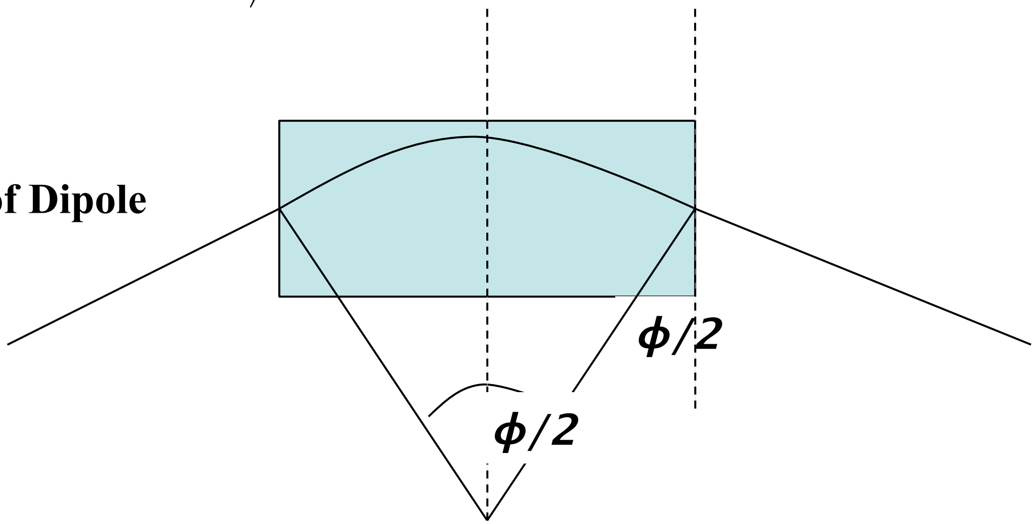


$$M_{dist} = \begin{pmatrix} \cos\psi_0 + \alpha \sin\psi_0 & \beta \sin\psi_0 \\ \Delta k ds (\cos\psi_0 + \alpha \sin\psi_0) - \gamma \sin\psi_0 & \Delta k ds\, \beta \sin\psi_0 + \cos\psi_0 - \alpha \sin\psi_0 \end{pmatrix}$$

Quadrupole Error in this case:

Edge Focusing effect of Dipole

$$M_{edge} = \begin{pmatrix} 1 & 0 \\ \frac{1}{\rho} \tan\frac{\phi}{2} & 1 \end{pmatrix}$$

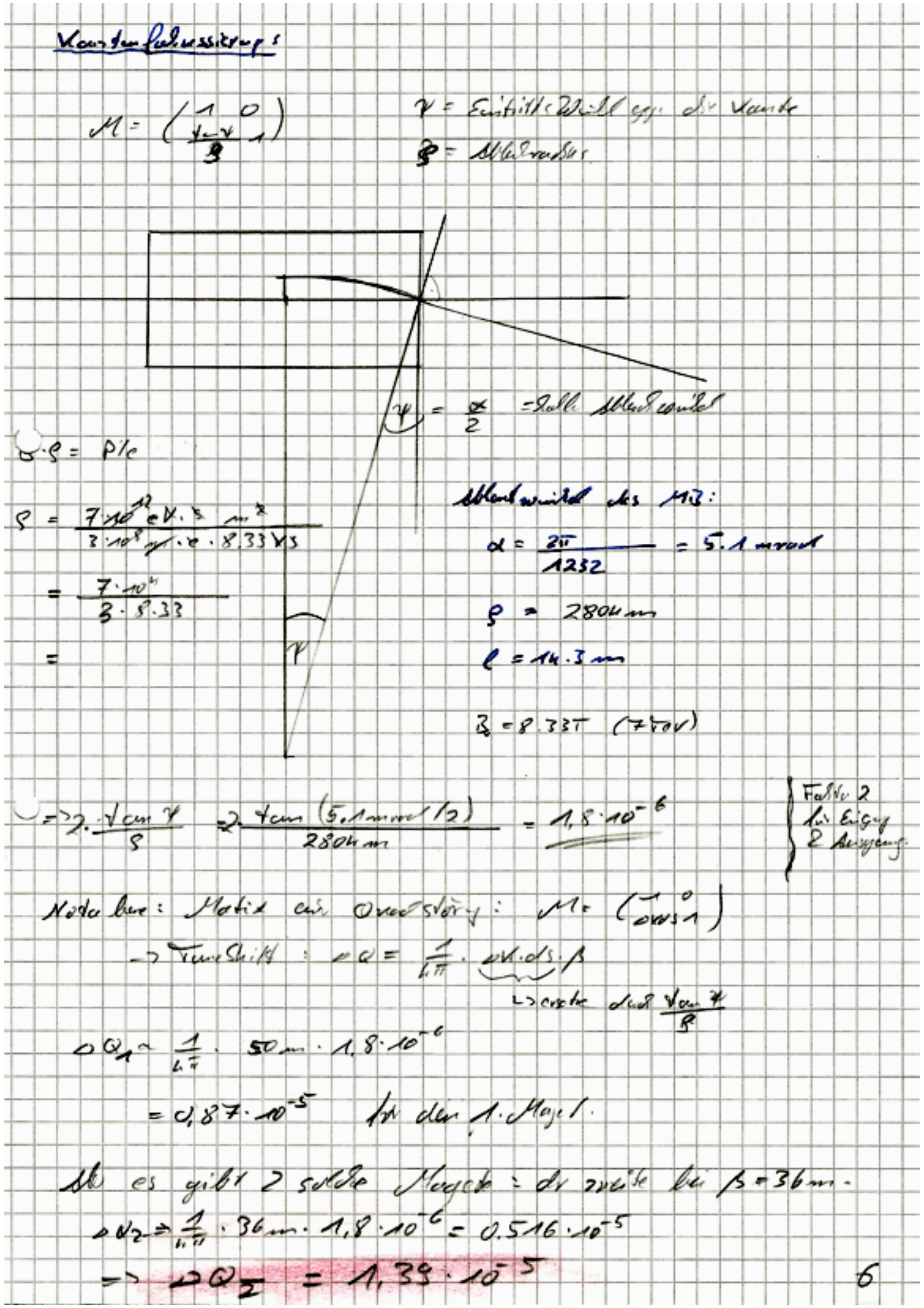


Edge Foc Effect:

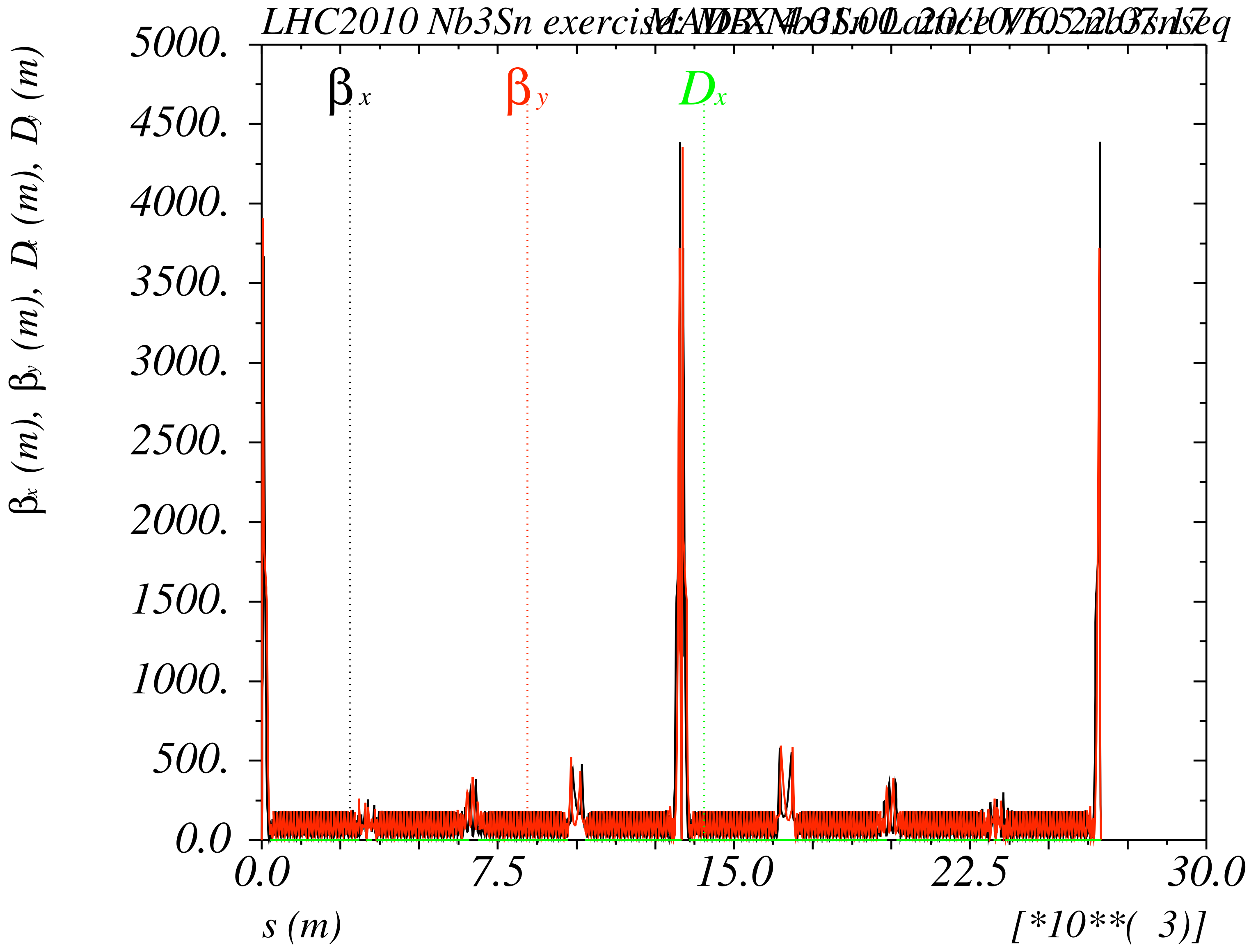
for the two effects (entrance / exit) of two dipoles we obtain ...

$$\Delta Q \approx 1.39 * 10^{-5}$$

effect on beam optics is small !!!



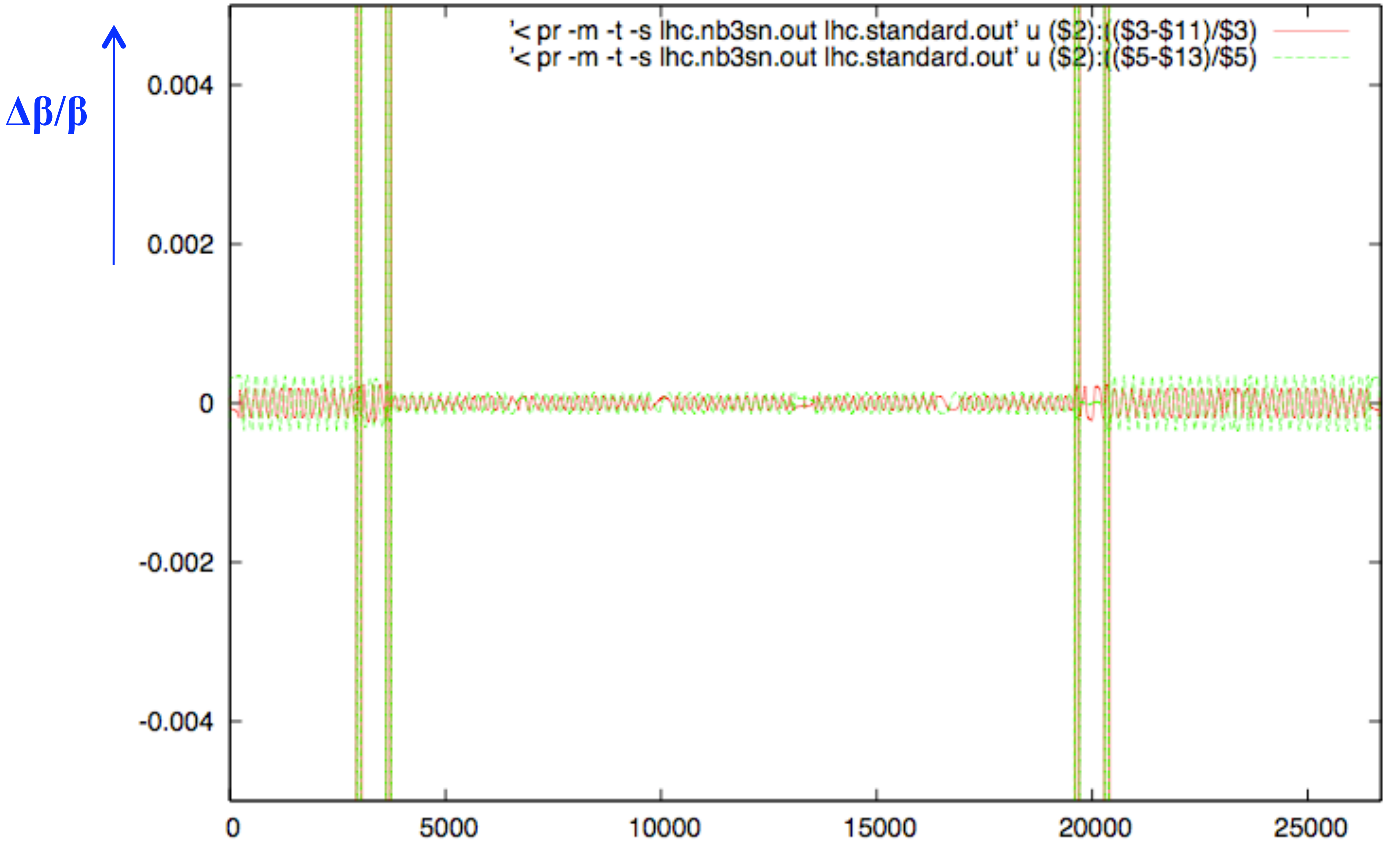
Edge Foc Effect: Optics distortion / Tune shift



Edge Foc Effect: MADX calculation: optics distortion

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

tune shift: $\Delta Q_x \approx 9.05*10^{-5}$, $\Delta Q_y \approx 1.33*10^{-4}$ } **for 8 magnets**



remember
tolerance for beta beat
Δβ/β=20%

2.) Shorter Magnet: Change of Design Orbit

... global LHC geometry

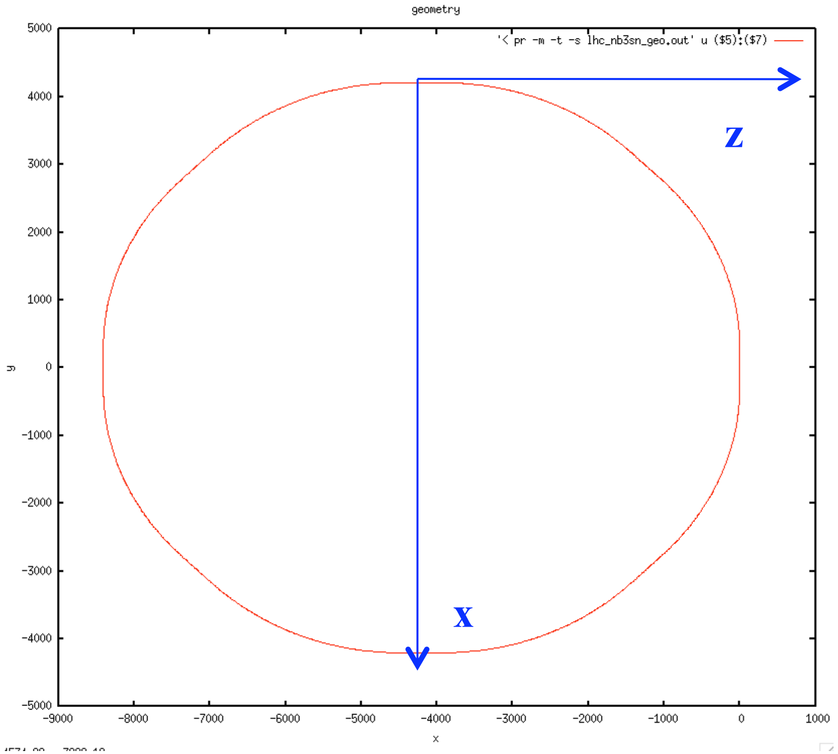
Standard LHC

$$s = 26.6588832$$
$$x = 0.1217\ mm$$
$$z = 7.97 * 10^{-5}\ mm$$
$$\theta = 6.2831$$

Nb_3Sn LHC

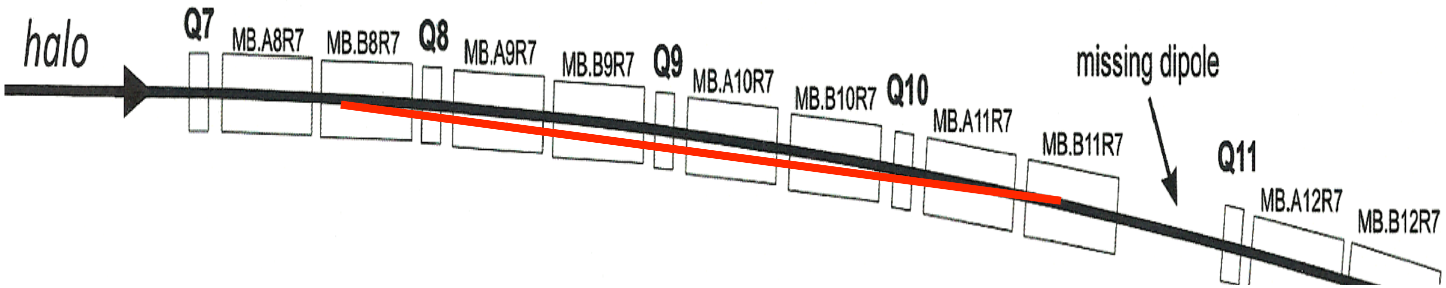
$$s = 26.65888319999$$
$$x = 0.228\ mm$$
$$z = 0.177\ mm$$
$$\theta = 6.2831$$

it's still quite a ring !!



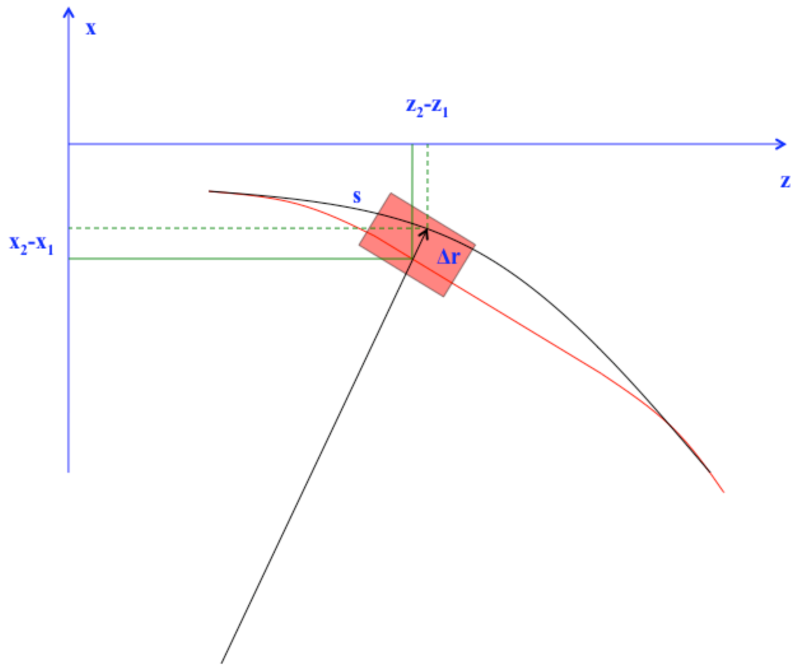
2.) Shorter Magnet: Change of Design Orbit

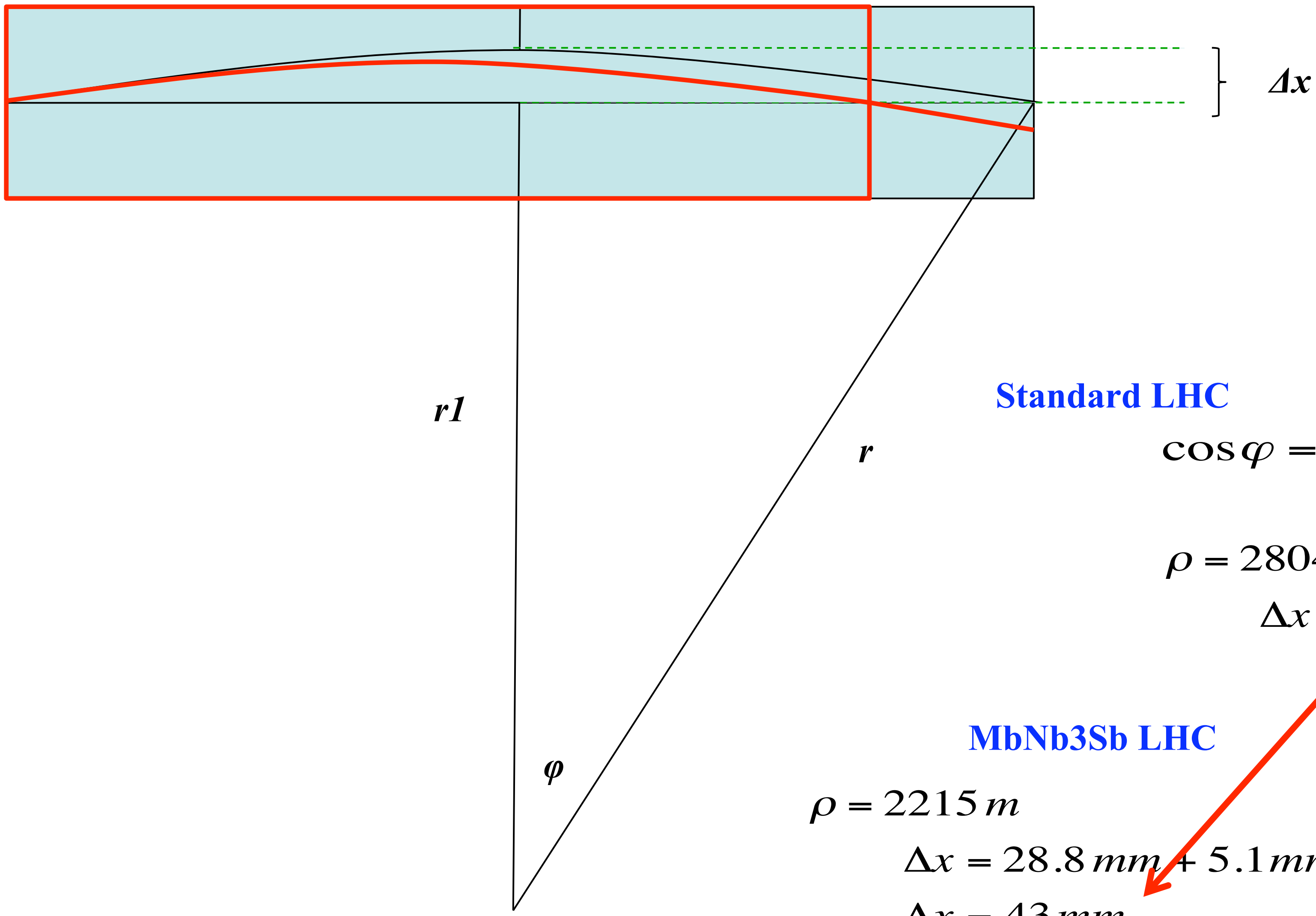
... local geometry



do we need a radial re-alignment ?

mad-x "Survey"





Standard LHC

$$\cos\varphi = \frac{r_1}{\rho}$$

$$\rho = 2804\, m$$

$$\Delta x = 36.5\, mm$$

MbNb3Sb LHC

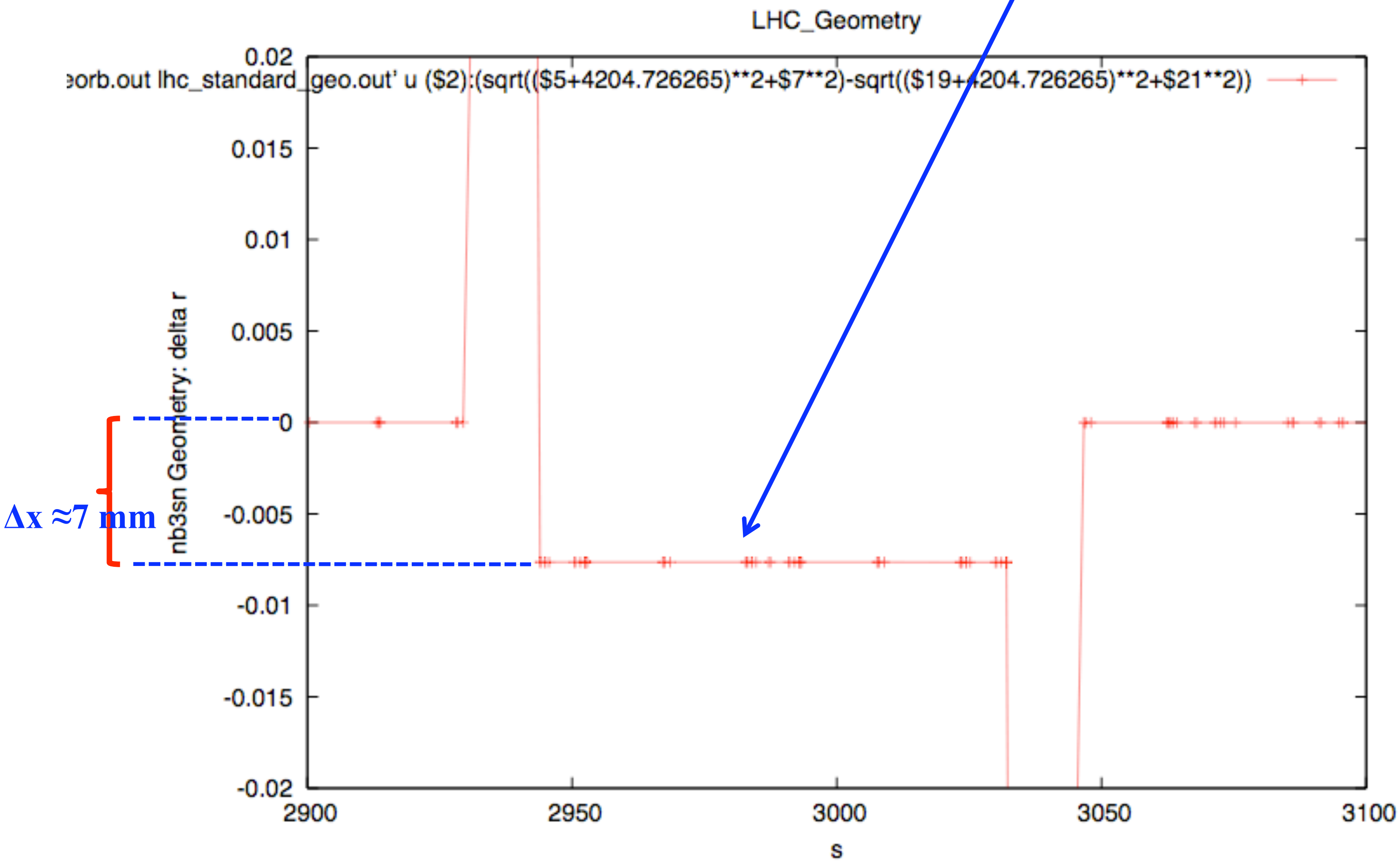
$$\rho = 2215\, m$$

$$\Delta x = 28.8\, mm + 5.1\, mrad * 3\, m$$

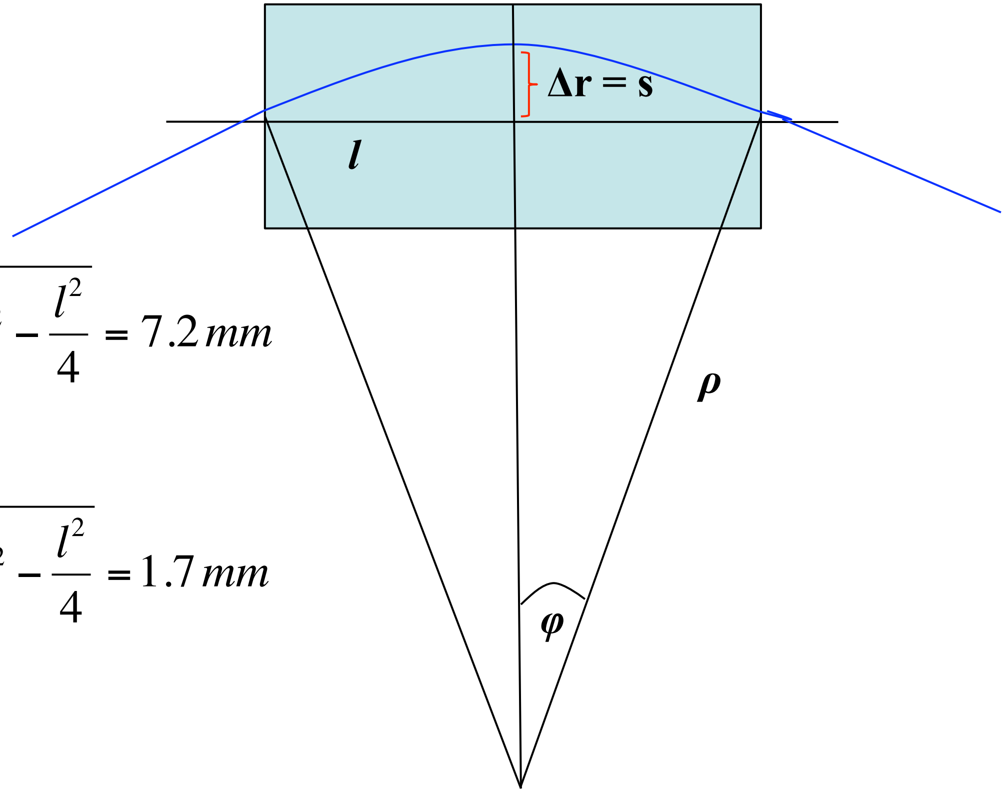
$$\Delta x = 43\, mm$$

We expect a difference of ≈ 6.5 mm !!!!

difference in radial coordinate
standard LHC – Nb3Sn LHC
local result



3.) Sagitta:



$$l = 11.3\ m$$

$$\rho = 2215\ m$$

$$\alpha = 2 * \varphi = 5.1\ mrad$$

$$s = r - \sqrt{r^2 - \frac{l^2}{4}} = 7.2\ mm$$

$$l = 5.5\ m$$

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

→ **aperture ?**

→ **feed down effects !!!**

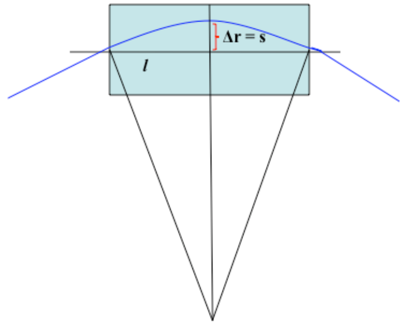
Feed Down Effects:

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

	Bdl	I	$b_{3(syst)}$	$b_{3(pc)}$	Σb_3	Bρ
450 GeV	7.7 Tm	758 A	13.96	+95.8	109.8	$1.5*10^3$ Tm
3.5 TeV	59.6 Tm	5639 A	13.99	-4.72	9.27	$1.2*10^4$ Tm
7 TeV	119.1 Tm	11517 A	13.37	+0.44	13.81	$2.3*10^4$ Tm

Feed Down Effects:

worst case l = 11.3 m
s = 7.2mm



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

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)

... considerably larger than the edge focusing story !!!

Do we have to expect problems concerning the multipoles ? YES

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

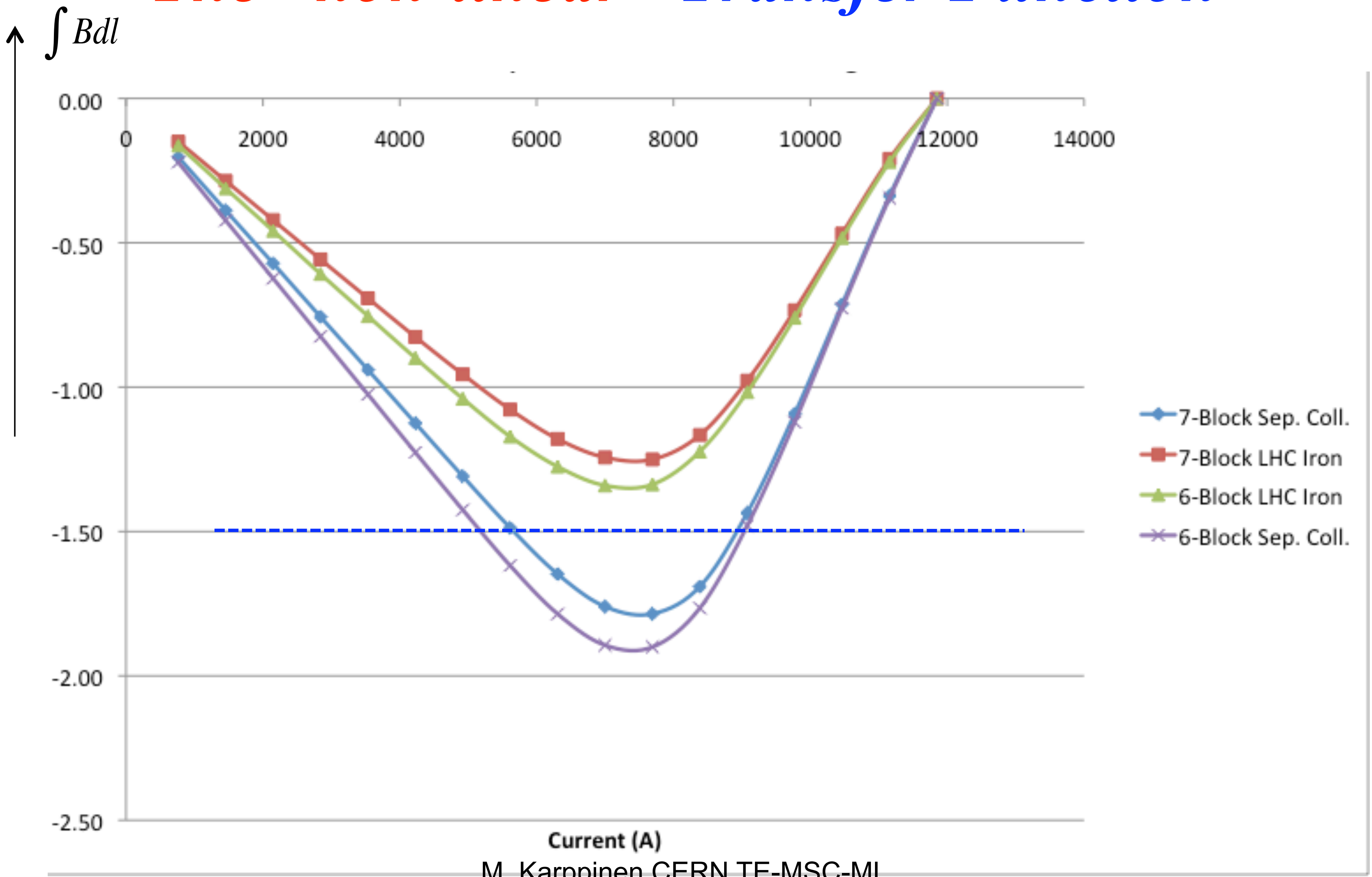
correct the orbit

plot the residual error

what are we talking about ... $\int Bdl = 1.5\,T\,m$

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

The "non-linear" Transfer Function



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again: ... 10 seconds for the contemplation:

$$E = 7\ TeV$$

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

$$N = 1232\ Magnets$$

$$\rightarrow \quad 5.1\ mrad$$

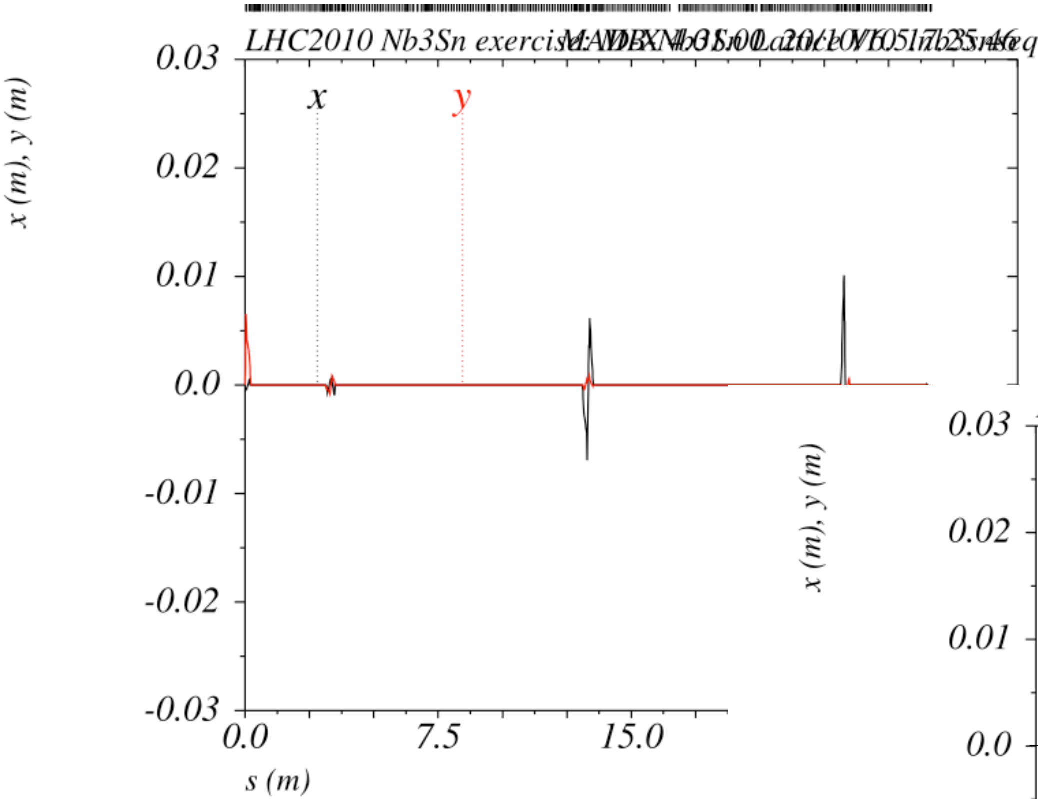
Nb3Sn Transferfunction:

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

rough estimate: → Δx ≈ 13 mm

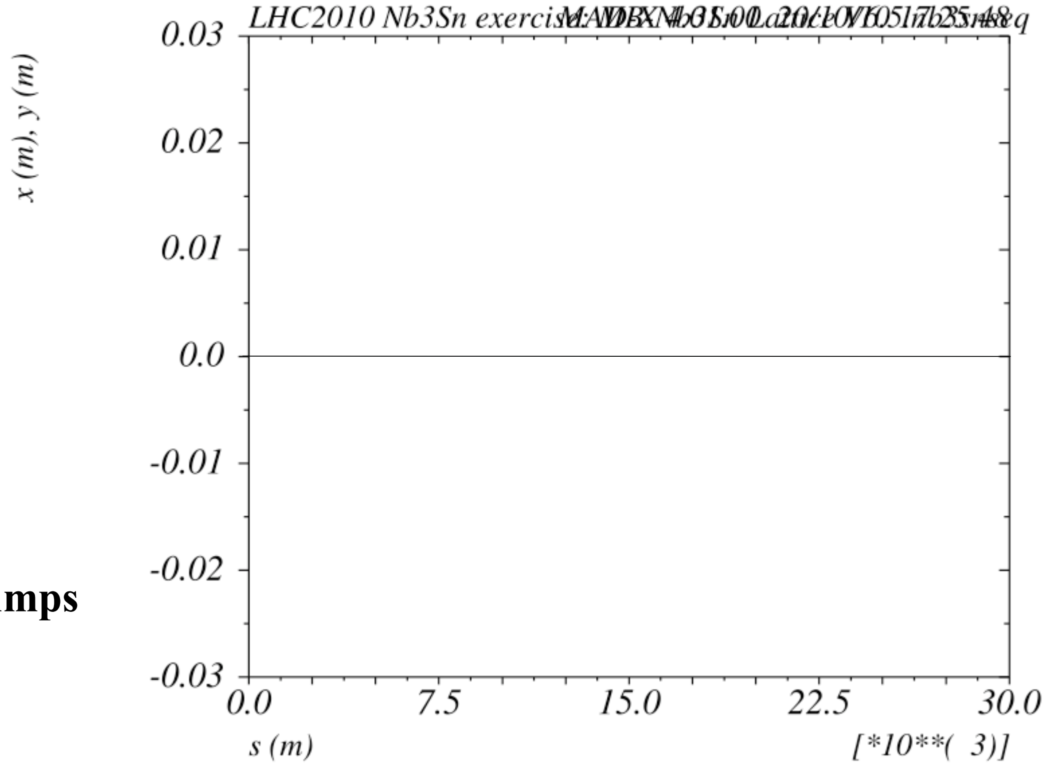
4.) The Story of the Transfer Function ...

a closed orbit problem



ideal machine

with exp bumps

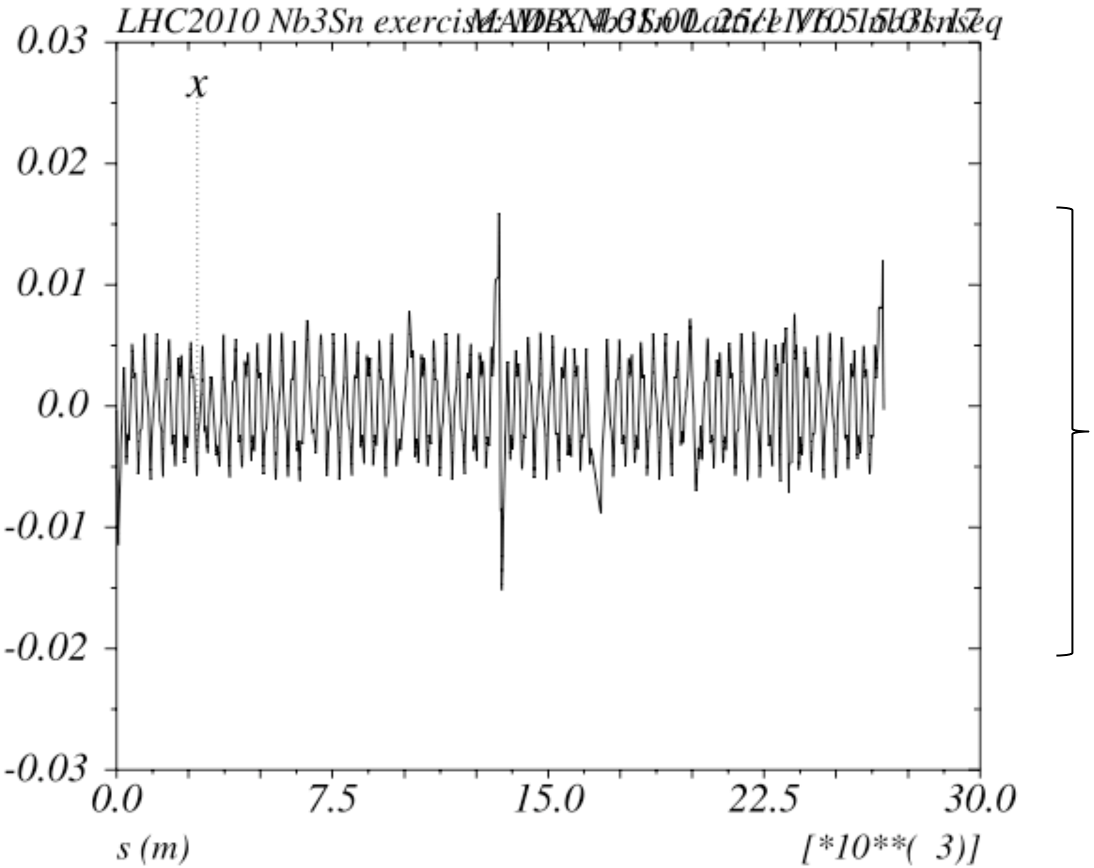


... and without exp bumps

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

a closed orbit problem

effect of nb3sn field error (1.5 Tm)
two dipoles
distorted orbit,
but partially compensated in a closed 180 degree bump
$\Delta\Phi = 4.545 \approx$ *modulo180 degree*



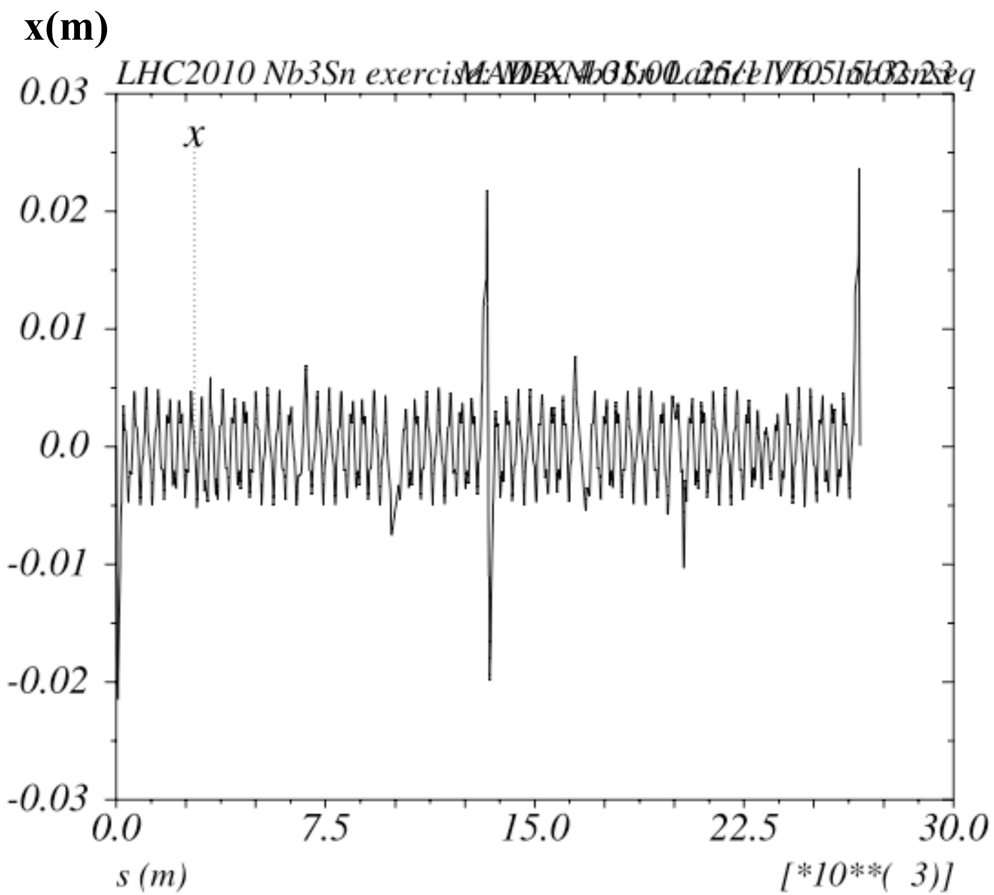
one Nb3Sn magnet

$\Delta x \approx \pm$ 15 mm

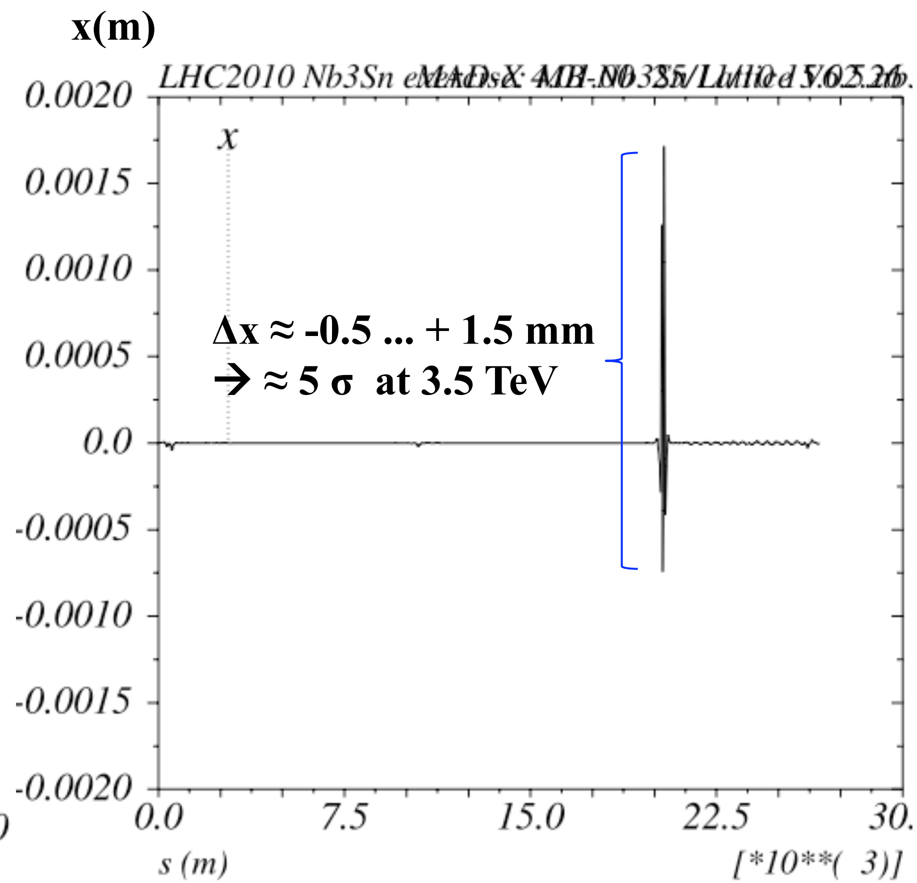
4.) The Story of the Transfer Function ...

a closed orbit problem

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



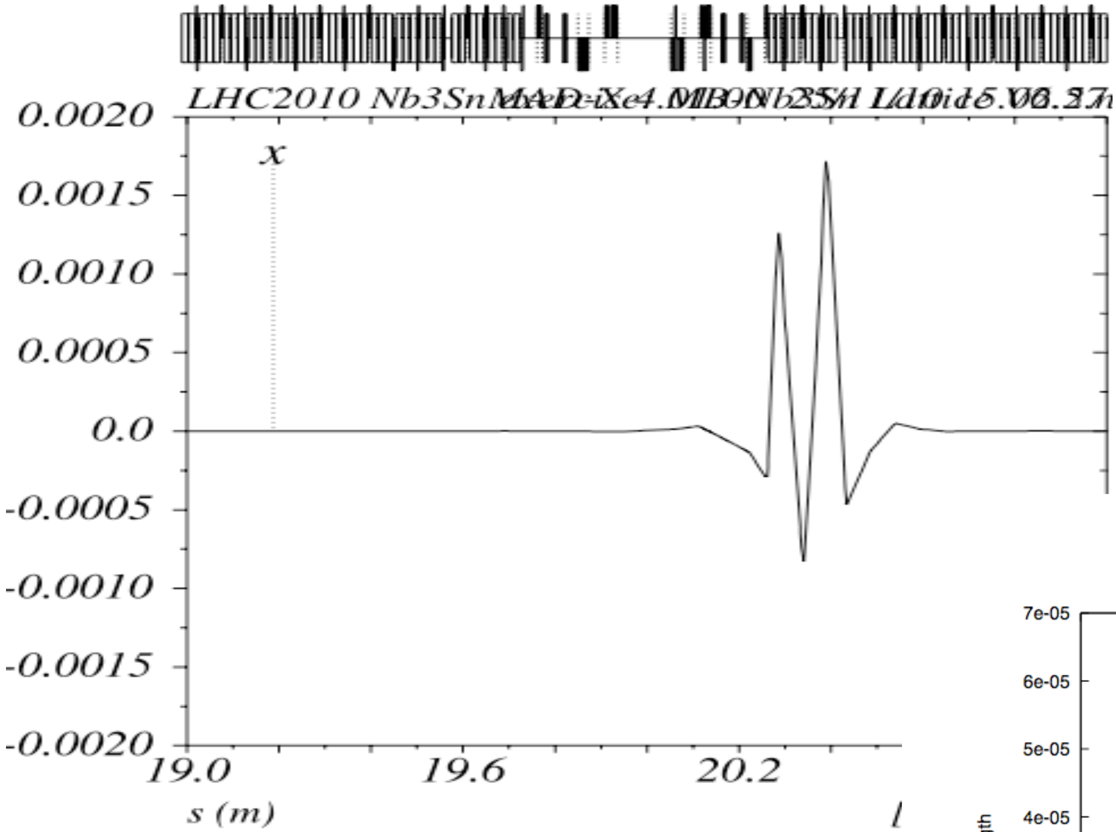
two Nb3Sn magnets



corrected by 20 orbcor dipoles

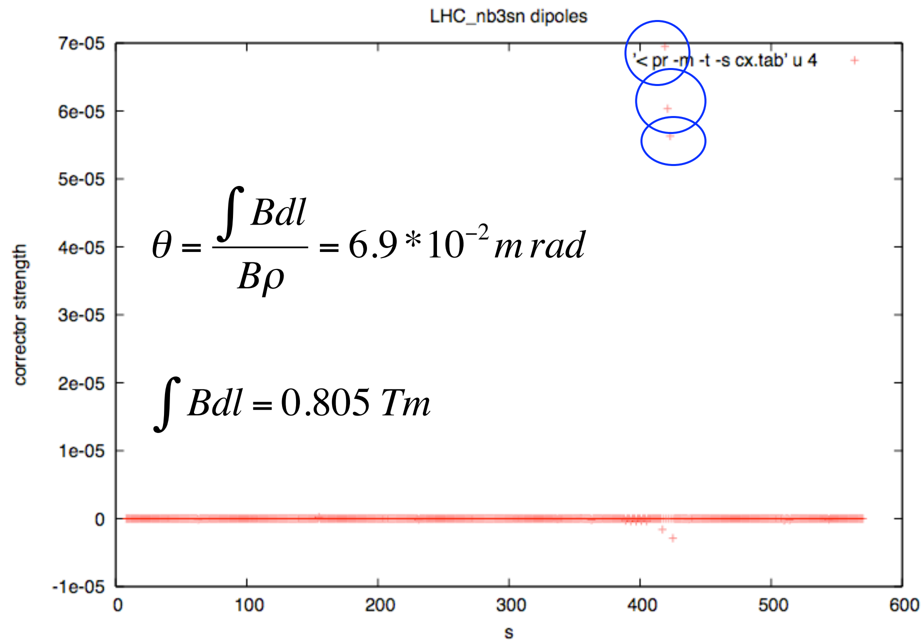
4.) The Story of the Transfer Function ...

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:

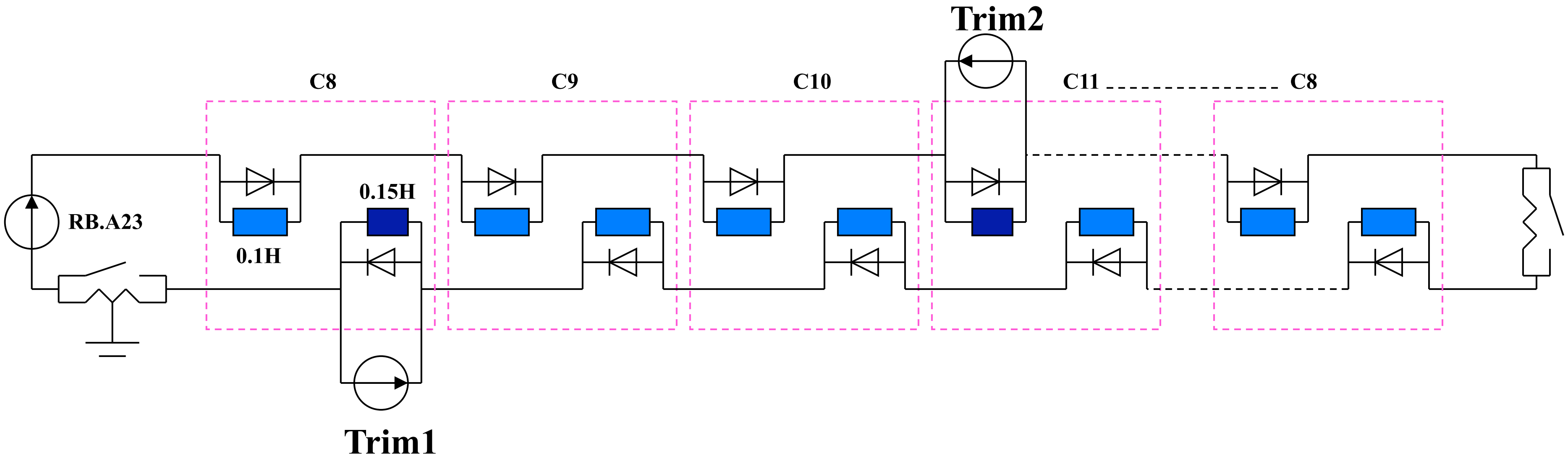
available: 1.900 Tm
needed: 0.805 Tm

!

= 42 %

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

a much better solution: additional “trim” power supply



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

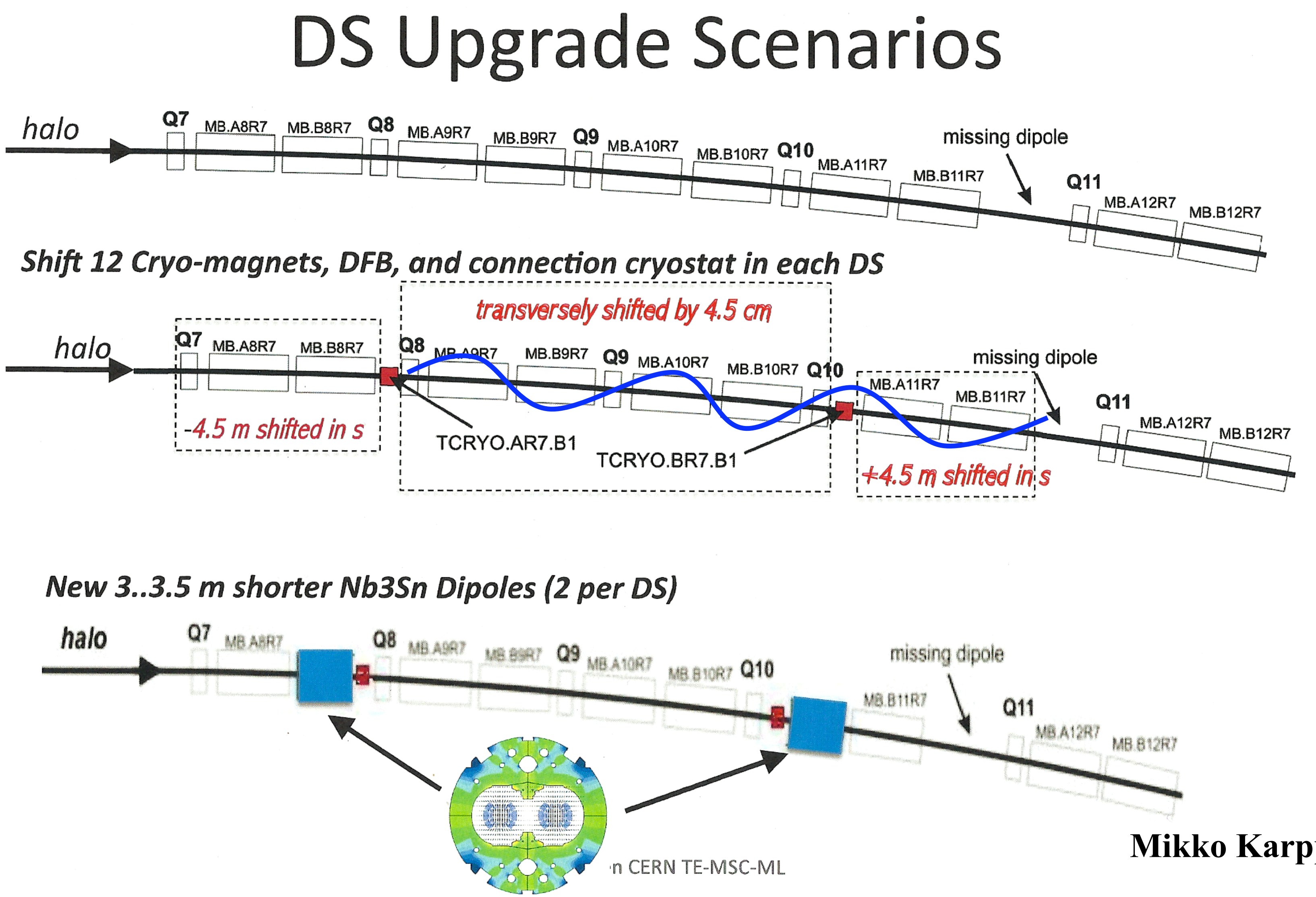
Total inductance: 0.15 H
Total resistance: 1mΩ
RB output current: ±0.6 kA
RB output voltage: ±10 V

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

Courtesy of H. Thiessen

non-local correction: **dedicated MCBH in an free part of the lattice**

does not change the picture: there will always be a inner orbit distortion in the order of several mm ... the only question is how localised we can keep the problem



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5.) Nb3Sn Dipole: Multipole Errors:

Systematic errors *scaled from the MB experience*

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

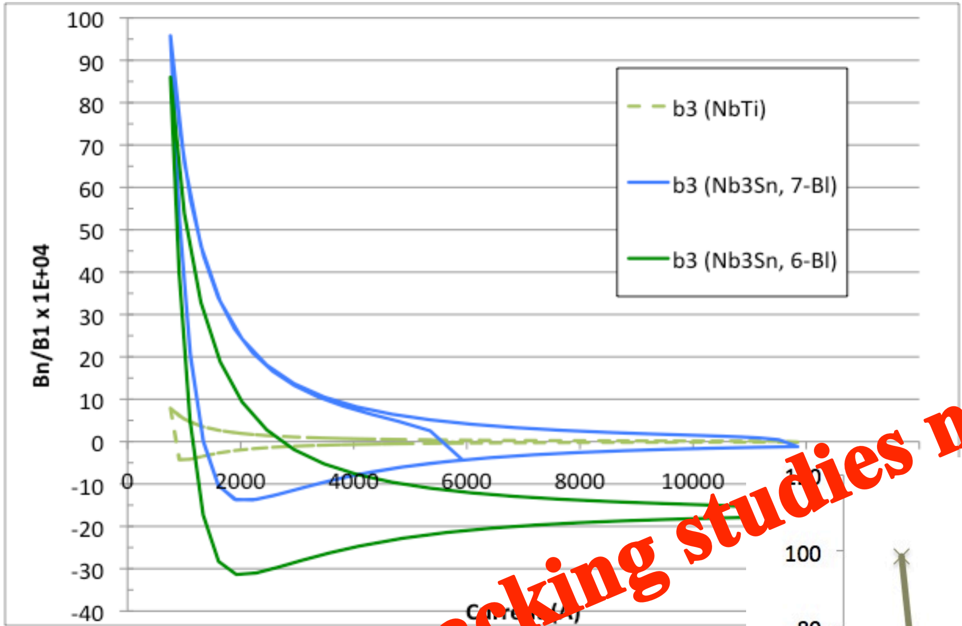
Nb3Sn Dipole: Multipole Errors:

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:

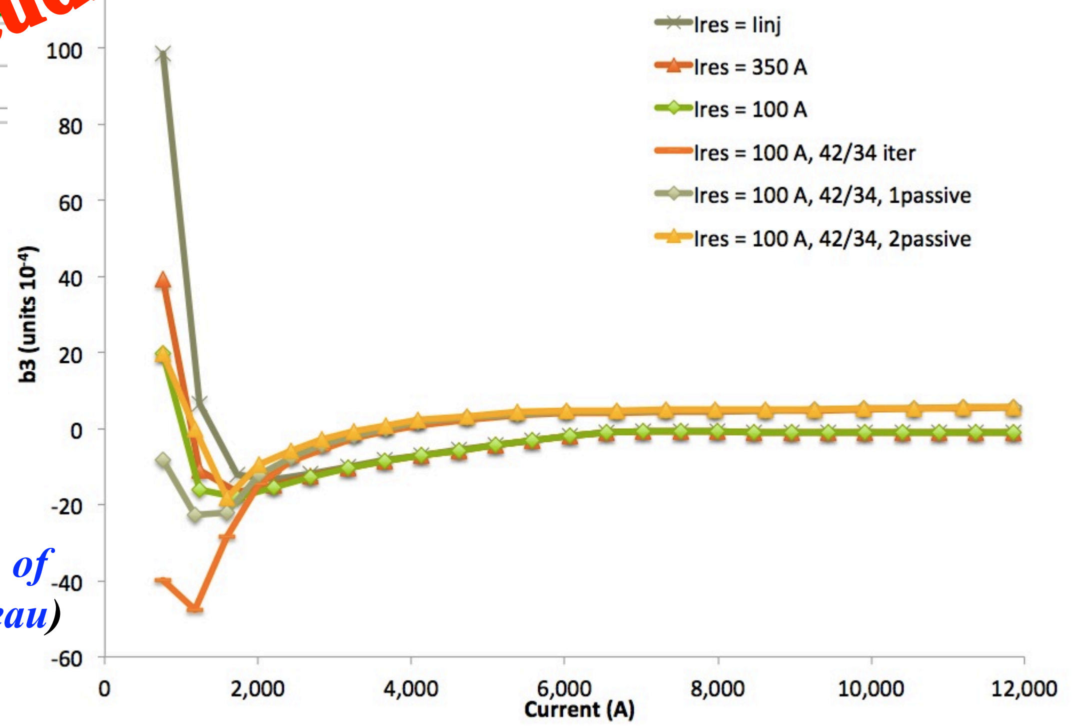
For comparison the same data for the NbTi MB coil in the same co				
Current (A)	TF (T/A), Nb	TF (NbTi)	b3 (NbTi)	b5 (NbTi)
758	-7.17E-04	-7.78E+00	7.89E+00	-7.39E-01
911	-7.16E-04	-9.34E+00	-4.26E+00	9.21E-01
1105	-7.16E-04	-1.13E+01	-4.18E+00	5.23E-01
1337	-7.16E-04	-1.37E+01	-3.45E+00	3.36E-01
1610	-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:



Comparison:
b3 Hysteresis Nb3Sn / NbTi
M. Karppinen

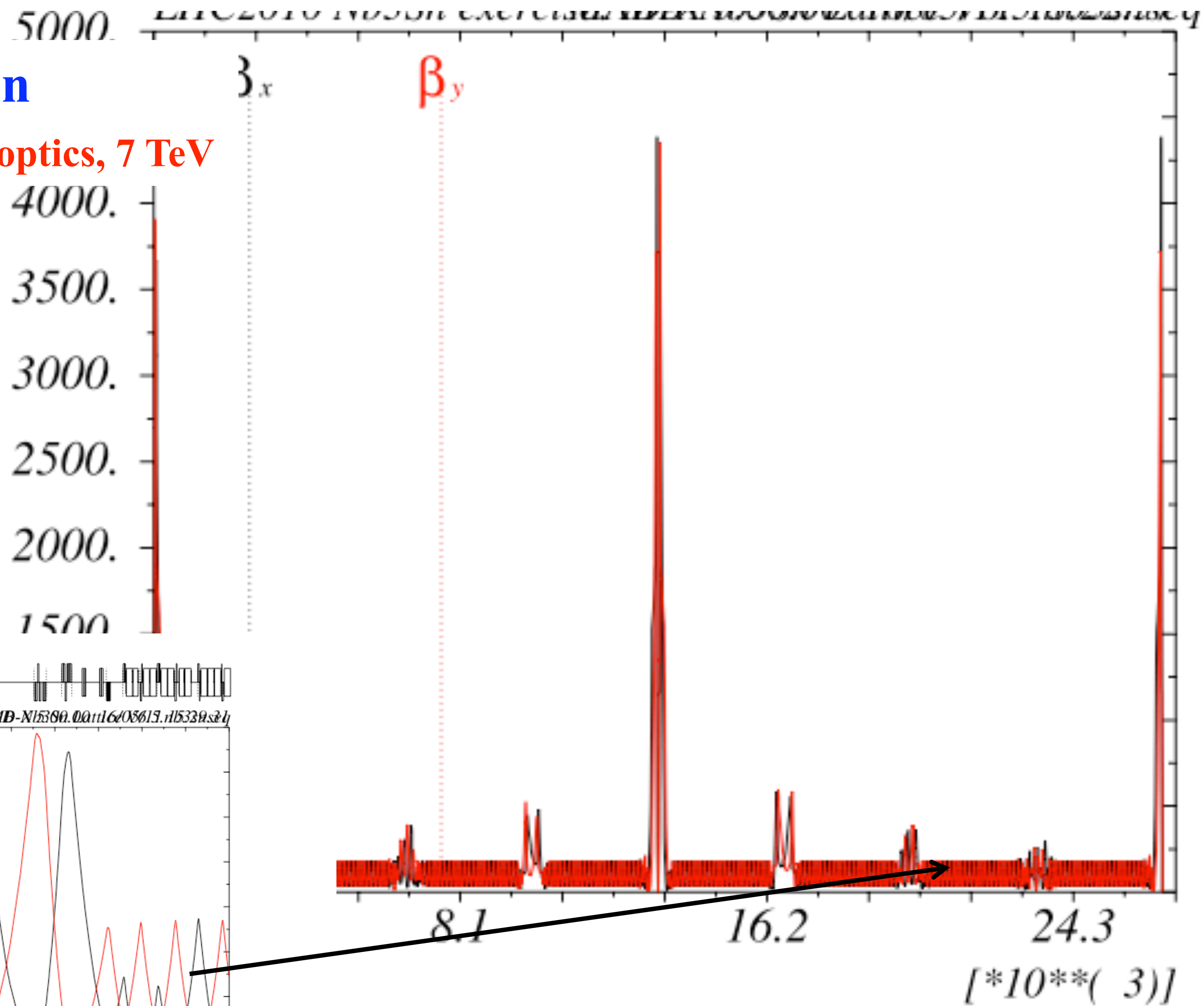
tracking studies needed

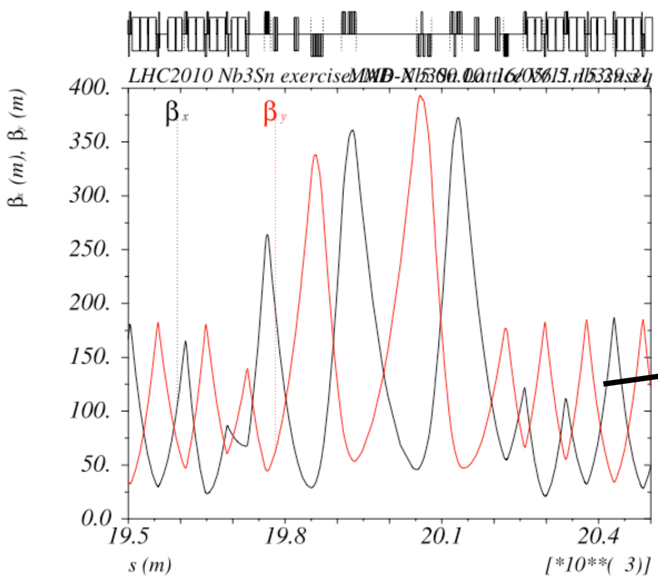


b3 remanence as a function of precycle (pre-injection plateau)
B. Auchmann

optics situation

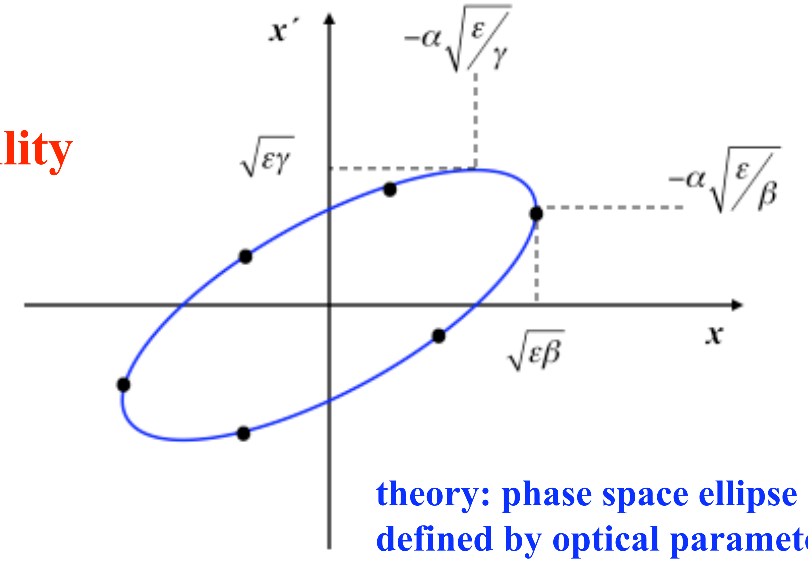
collision optics, 7 TeV



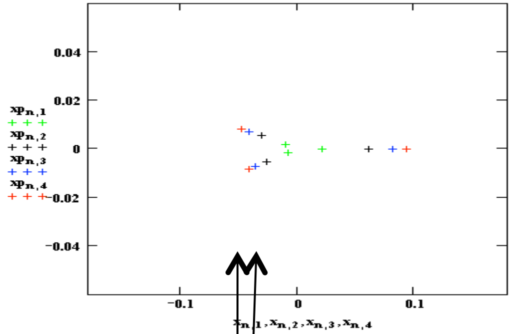


Tracking Studies:

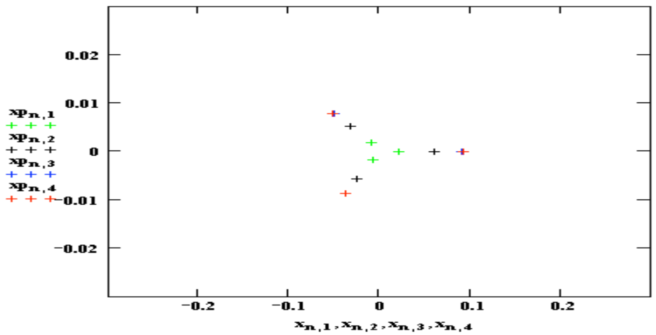
Dynamic Aperture determined via stability / survival time



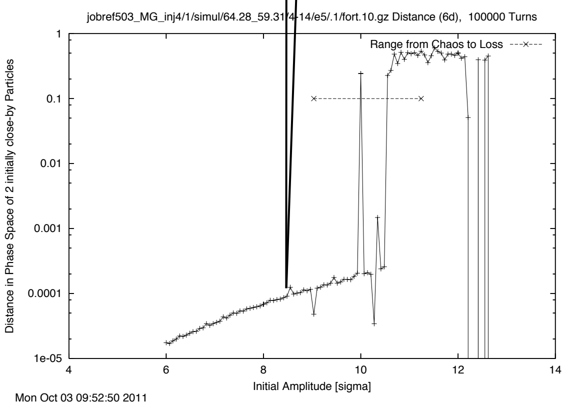
theory: phase space ellipse defined by optical parameters



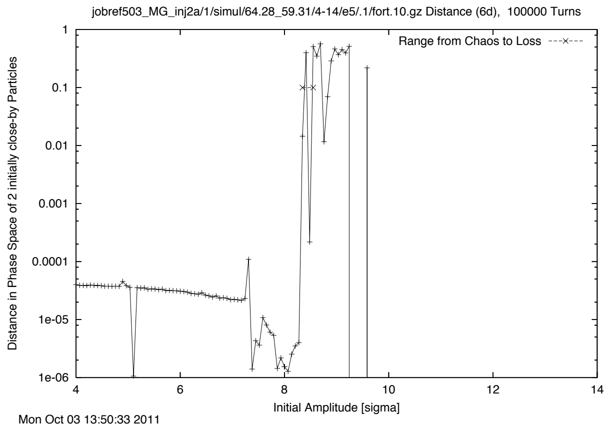
ideal, linear machine



strong b3 multipole



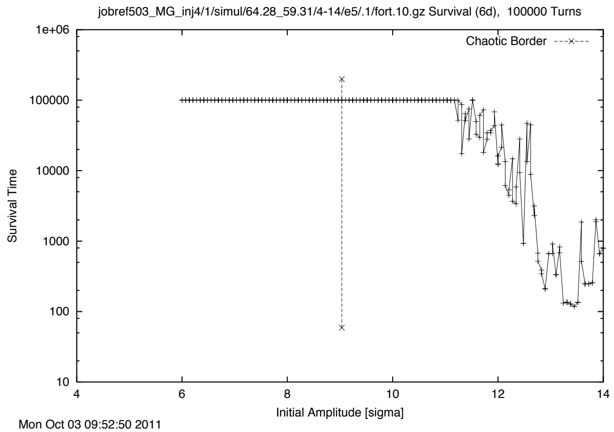
b3 = 98, full & local correction



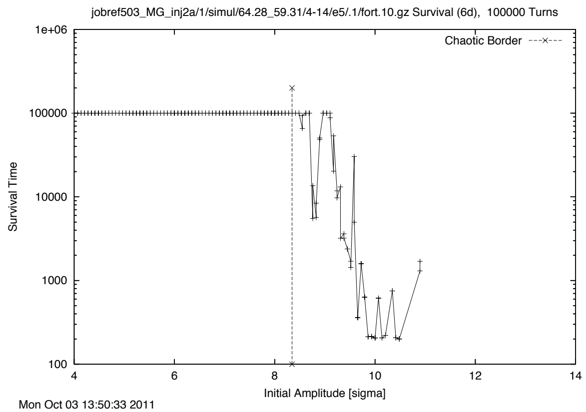
b3 = 98, no correction

Tracking Studies:

Dynamic Aperture determined via stability / survival time

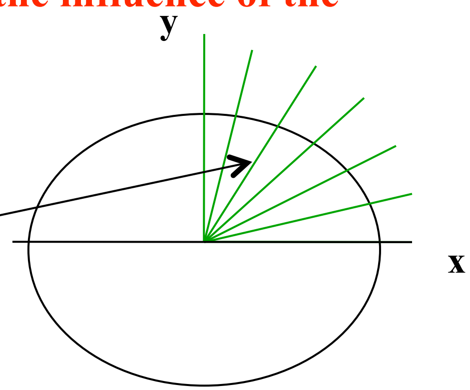


b3 = 98, full & local correction



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, 4-14 σ in units of 2,
30 particle pairs, 17 angles

Field Quality: Dynamic Aperture Studies

collision optics, 7 TeV, 2 IP's = 8 dipoles

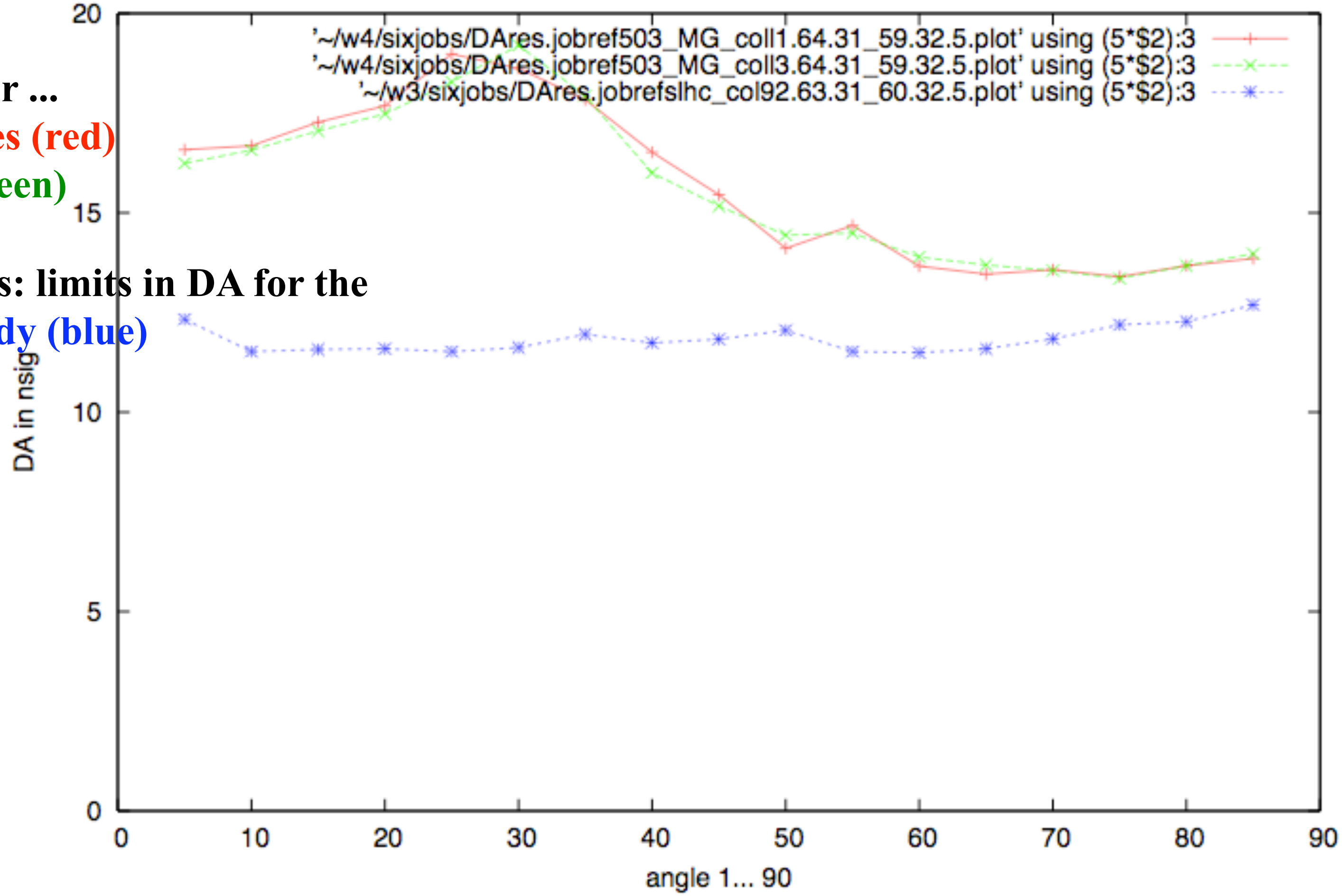
dyn aperture luminosity optics, 7 TeV, minimum of 60 seeds

dynamic aperture for ...

ideal Nb3Sn dipoles (red)

full error table (green)

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

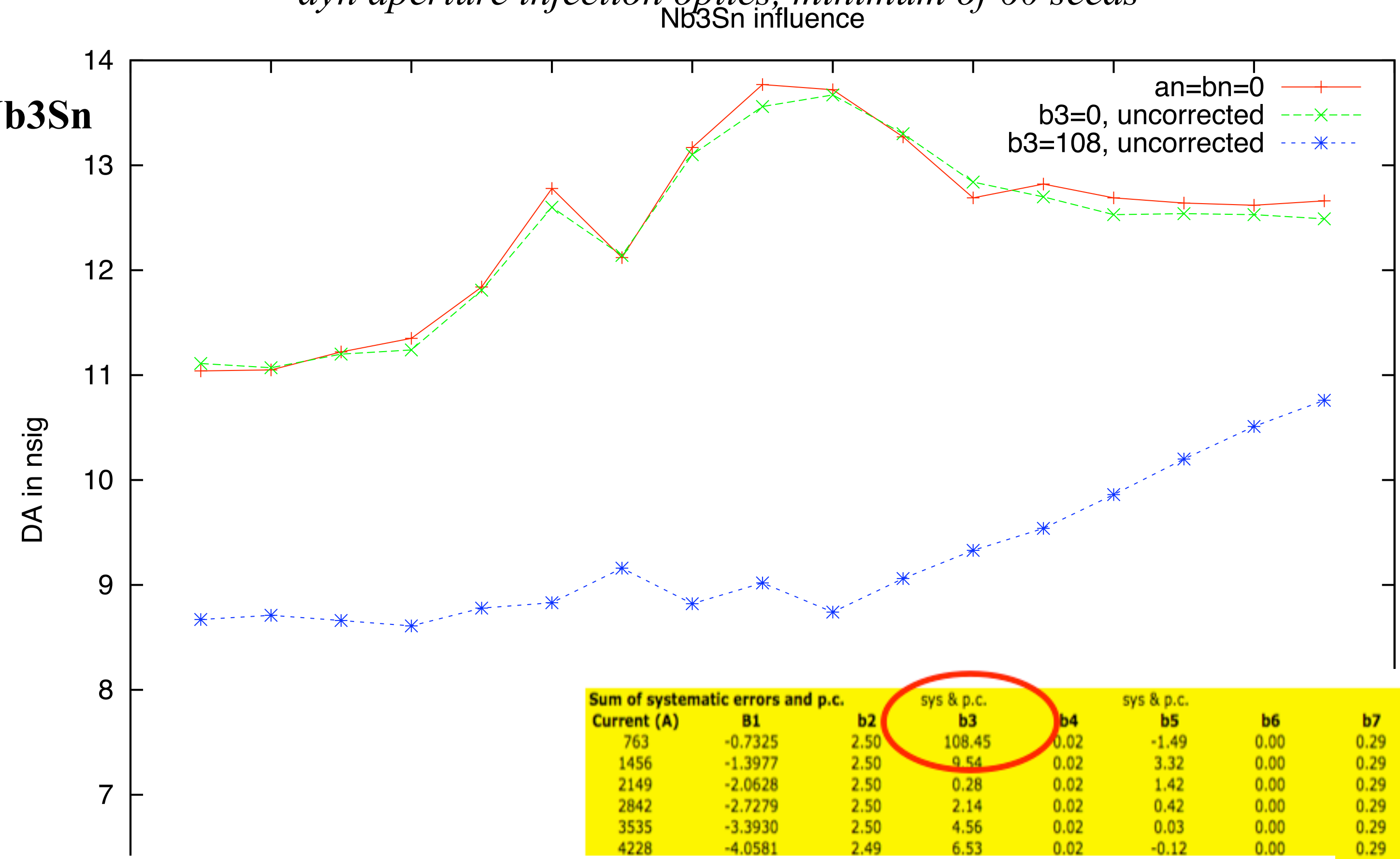


for the experts: the plot shows the minimum DA for the 60 error distribution seeds used in the tracking calculations.

Field Quality: Dynamic Aperture Studies

injection optics, 450 GeV, no special spool piece correctors
influence of b3 values, 2 IP's = 8 dipoles

dyn aperture injection optics, minimum of 60 seeds



dynamic aperture for Nb3Sn

full error table (blue)
b3 = 0
an = bn = 0

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
							0.29
							0.29
							0.29
							0.29
							0.29
							0.29
							0.29
							0.29
							0.29
							0.30
							0.30

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.

Higher order multipoles have only a very small impact on the DA.

Scan of b3 to find the tolerance limit

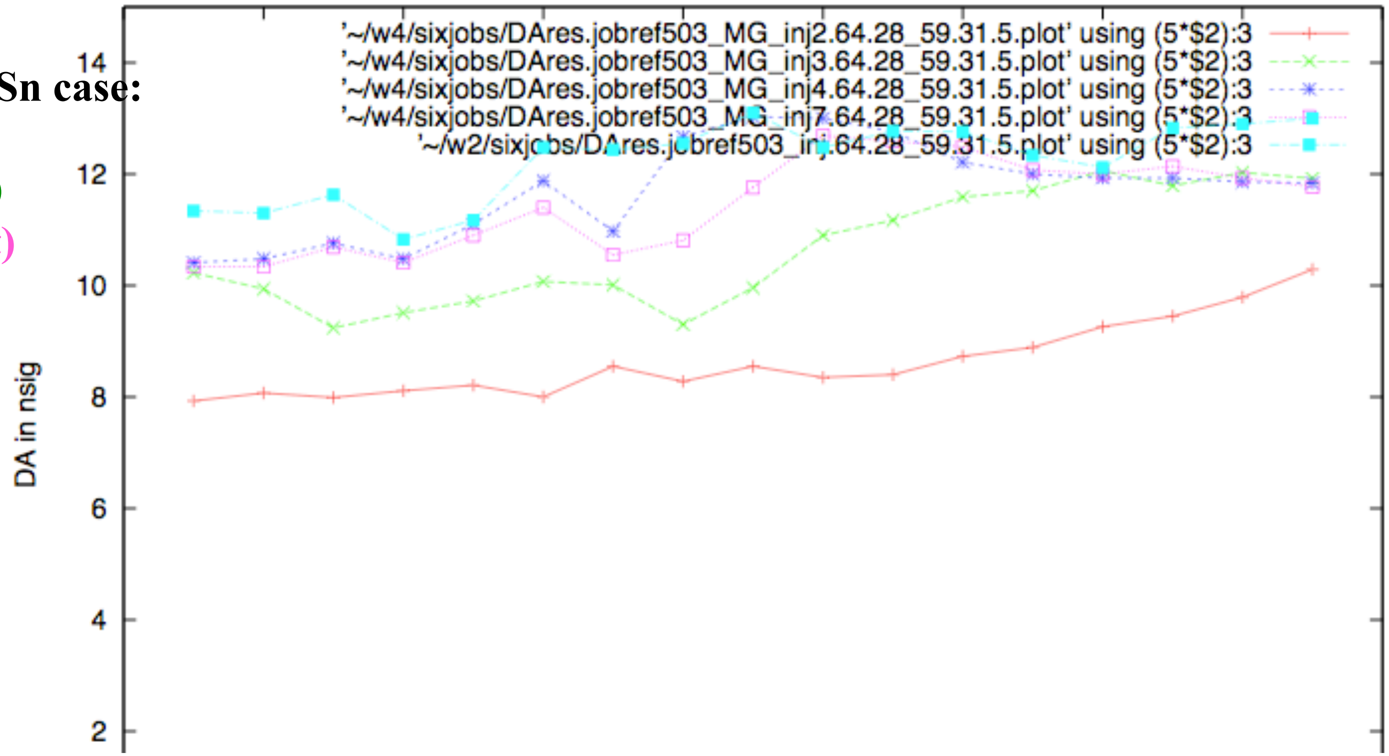
Field Quality: Dynamic Aperture Studies

injection optics, 450 GeV, no special spool piece correctors

scan of b3 values, , 2 IP's = 8 dipoles

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.
There is not much difference between b3=0 and perfect Nb_3Sn magnets !!

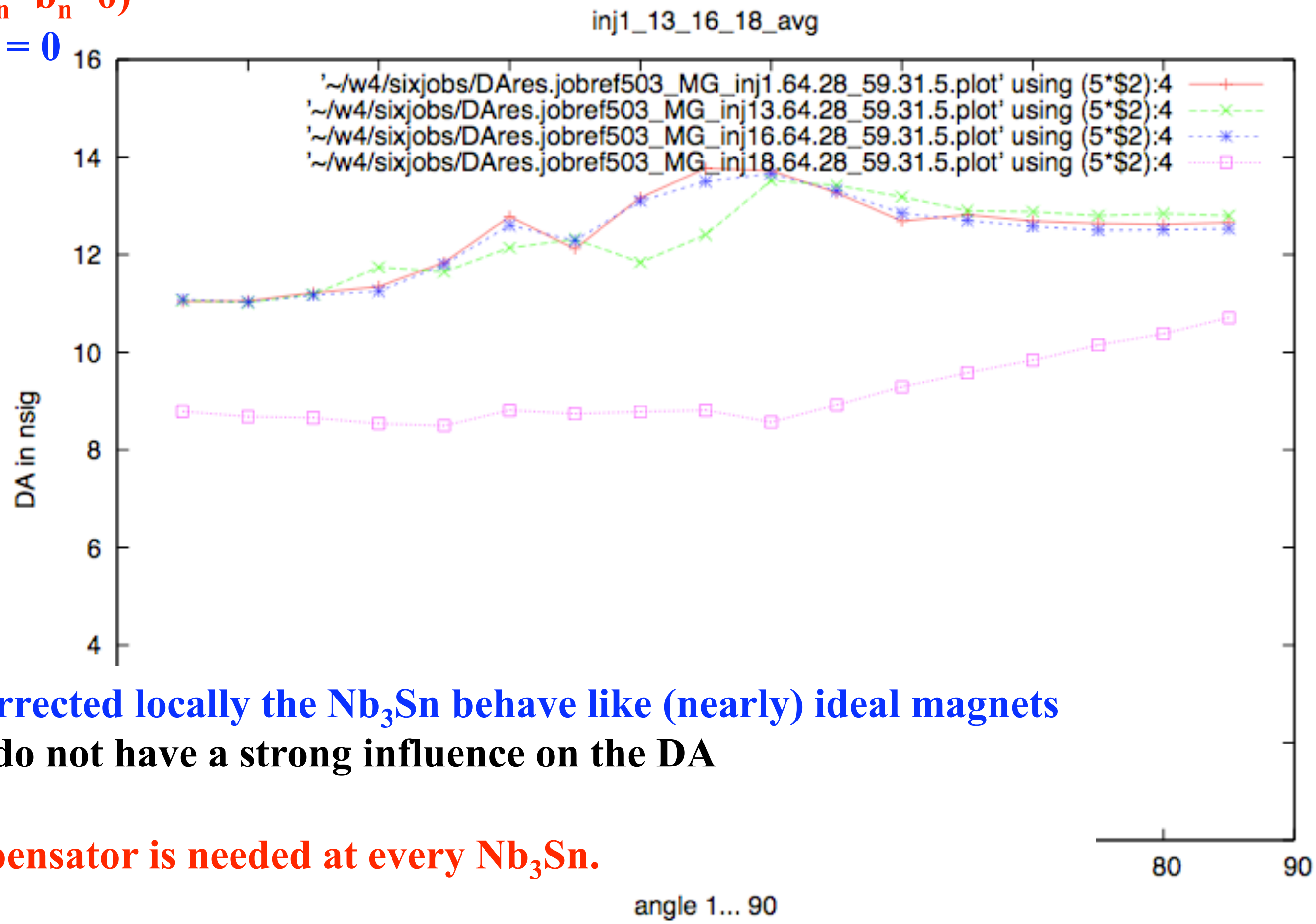
Alternative solution: strong local spool piece corrector ...

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 (all 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

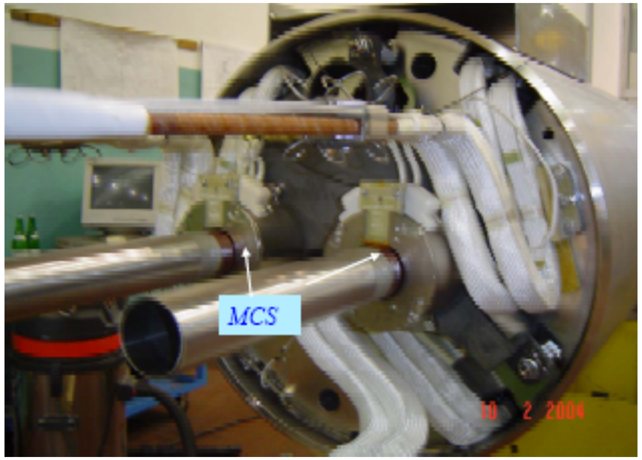


for the experts: if b_3 is corrected locally the Nb_3Sn behave like (nearly) ideal magnets
Higher order multipoles do not have a strong influence on the DA

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

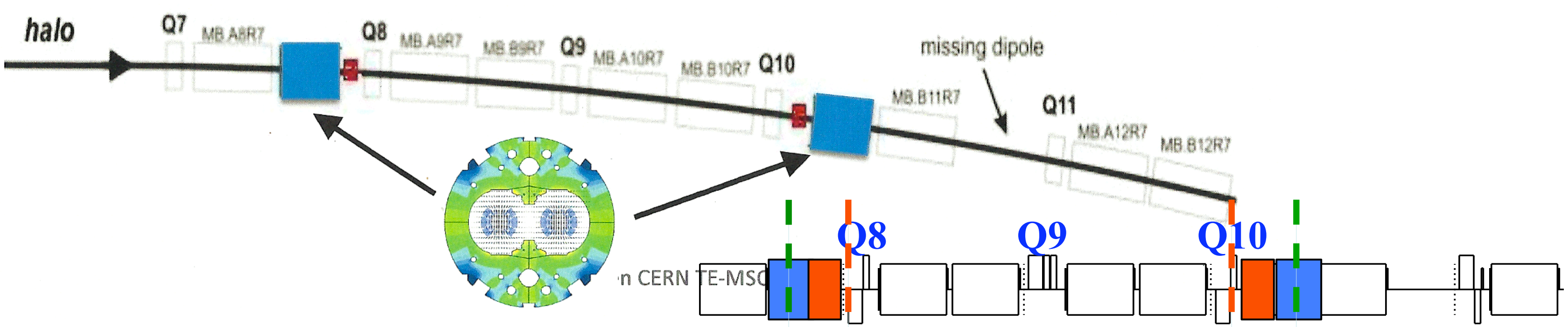
? what about higher multipoles

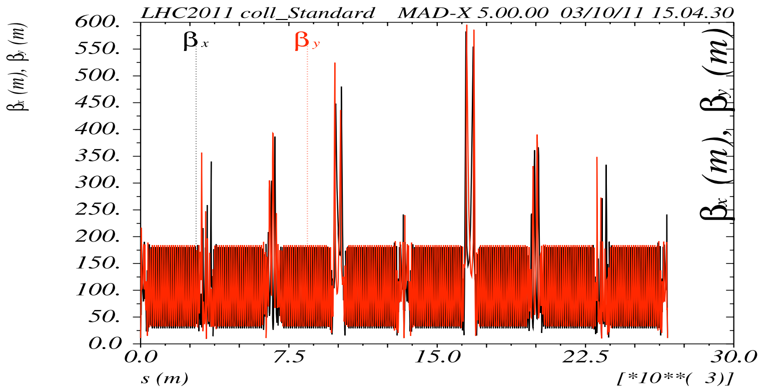
?? what about the skews

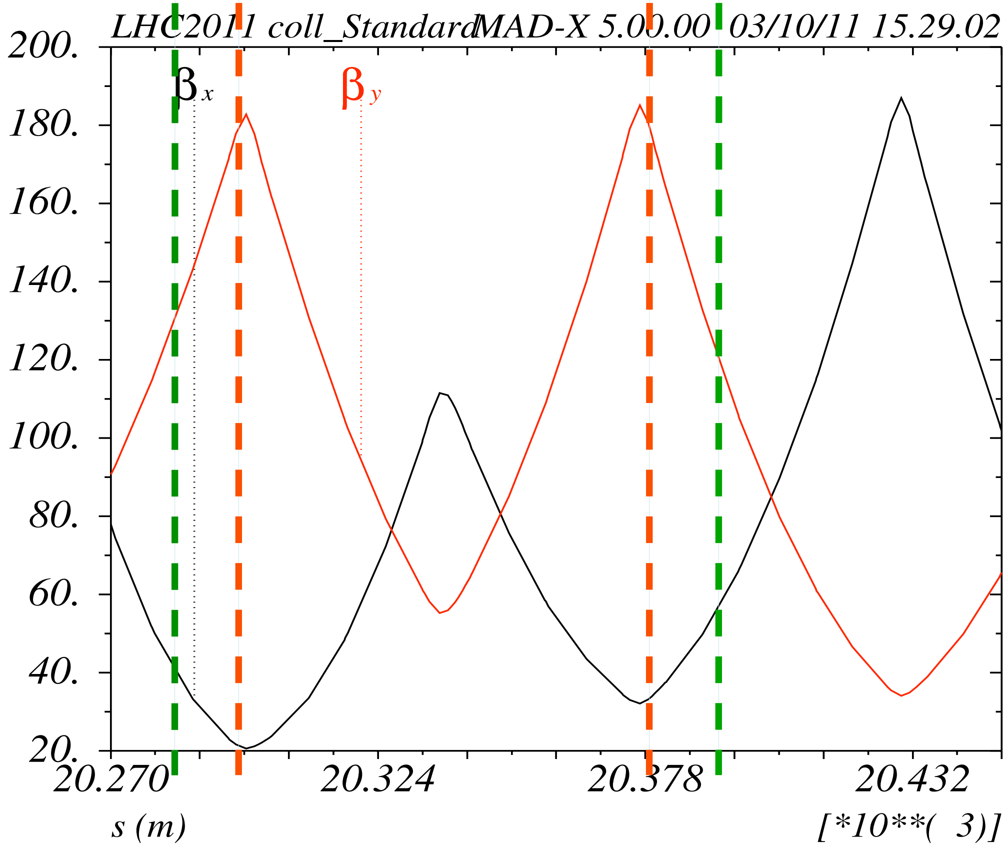
??? what about reality

Field Quality: non-local b_3 correction

New 3..3.5 m shorter Nb3Sn Dipoles (2 per DS)







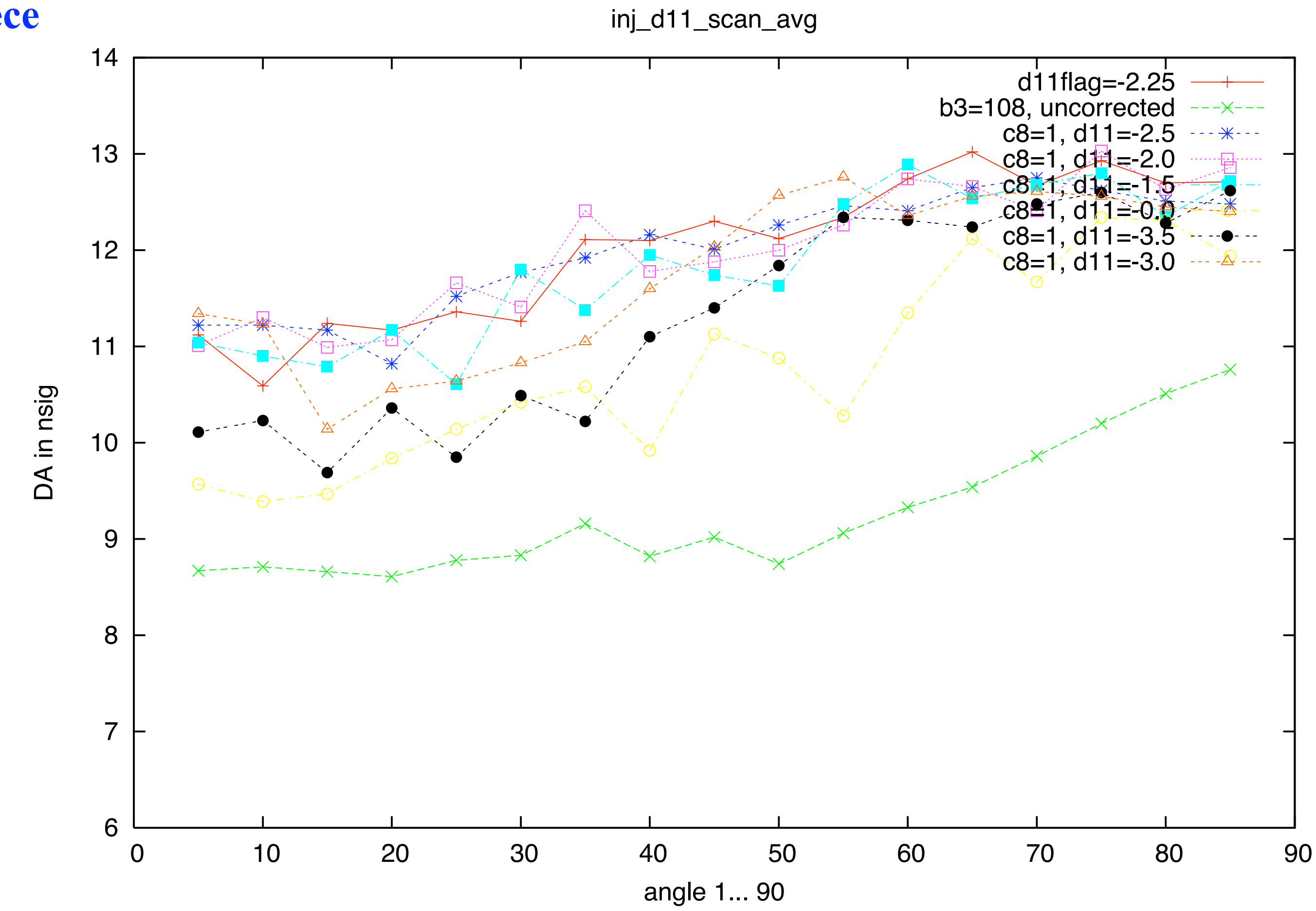
spool piece correctors at the quads

Field Quality: non-local b_3 correction

injection optics, 450 GeV, special spool piece correctors placed at the quads

local correction of b3 at B8

scan of non-local spool piece corrector, located at Q10



Resume Nb3Sn dipoles

have (nearly) no effect on the linear 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 but a 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.

To be done:

Repeat the DA calculations & local compensation for the actual Dipole option (1 * 11m, 2 * 5.5m .... 3 * 4711 m)

... and the number of IP's

Follow up of actual multipoles

Bernhard Auchmanns improved precycle,
results of first actual magnet measurements
uncertainties / systematics
pc contributions

Summarise all this in a HL-LHC report
in progress