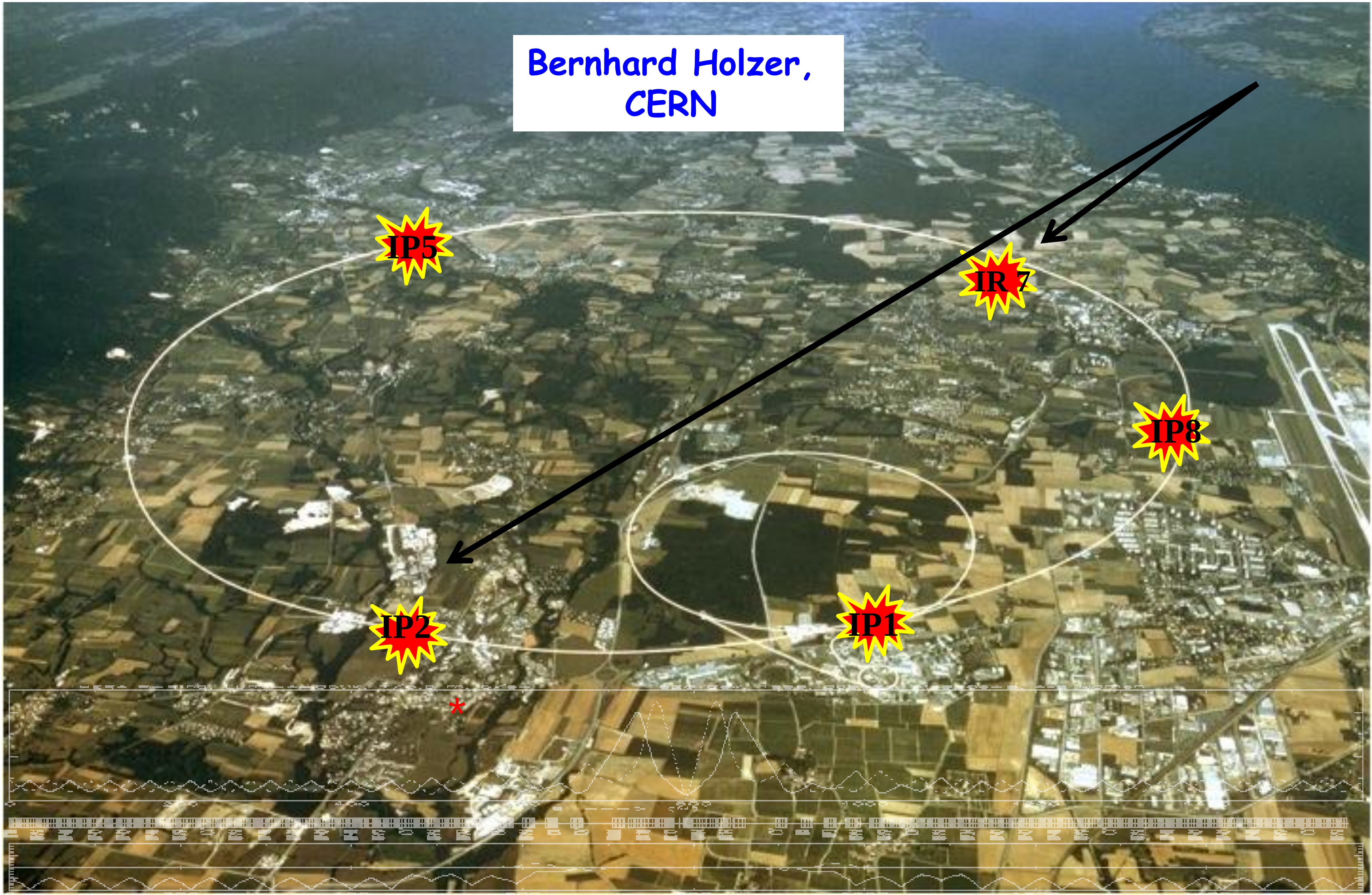
"Nb3Sn Dipoles in LHC ... a philosophical contemplation"



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

Doctor of Philosophy, abbreviated to PhD in English-speaking countries:

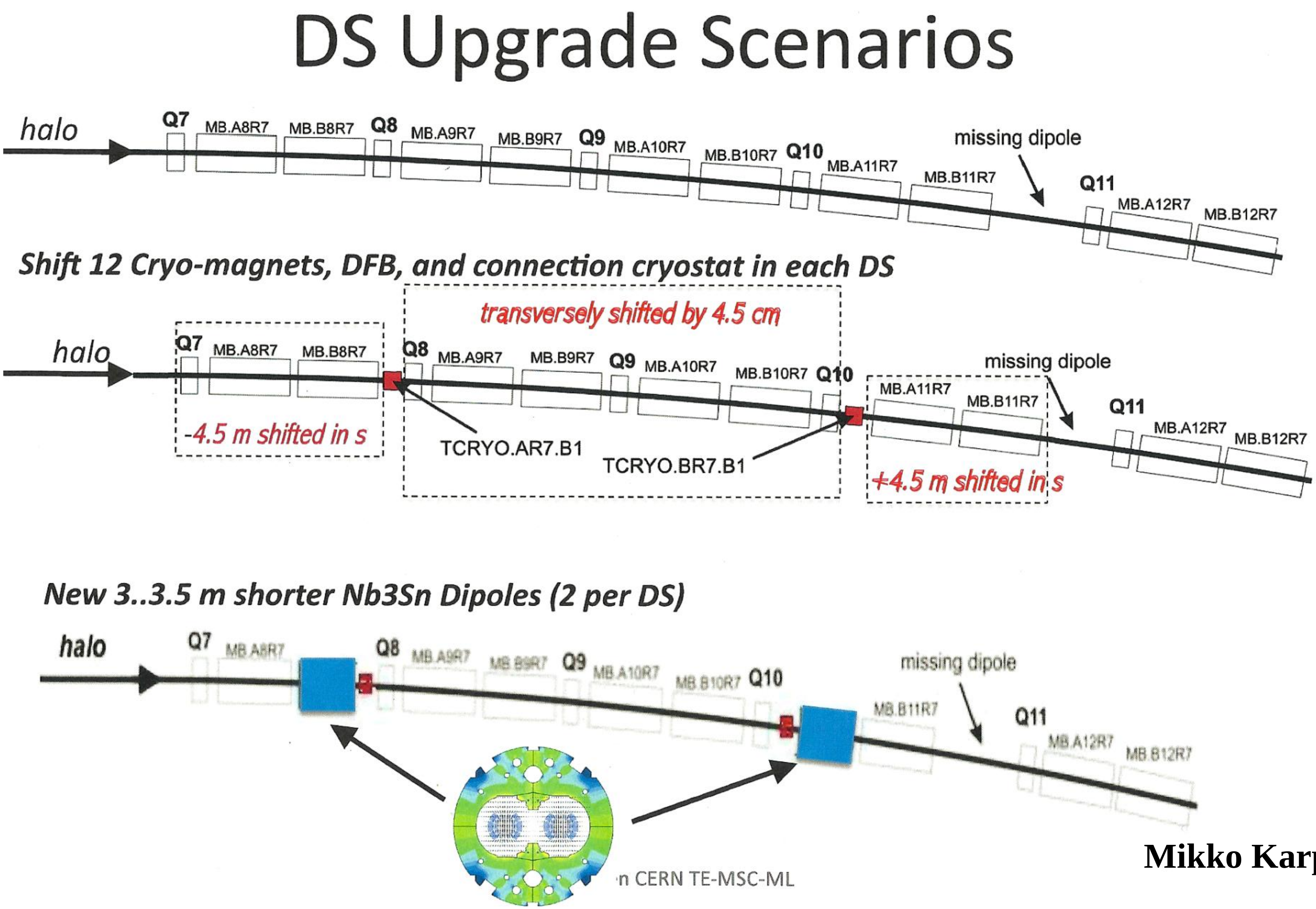
Greek *διδάκτωρ φιλοσοφίας*
Here φιλοσοφία/philosophy, literally translating to "the love of wisdom", is used in the original Greek sense, loosely meaning "the pursuit of in depth knowledge”.

in other words ....

“Nb3Sn dipoles in the LHC DS: preliminary results”

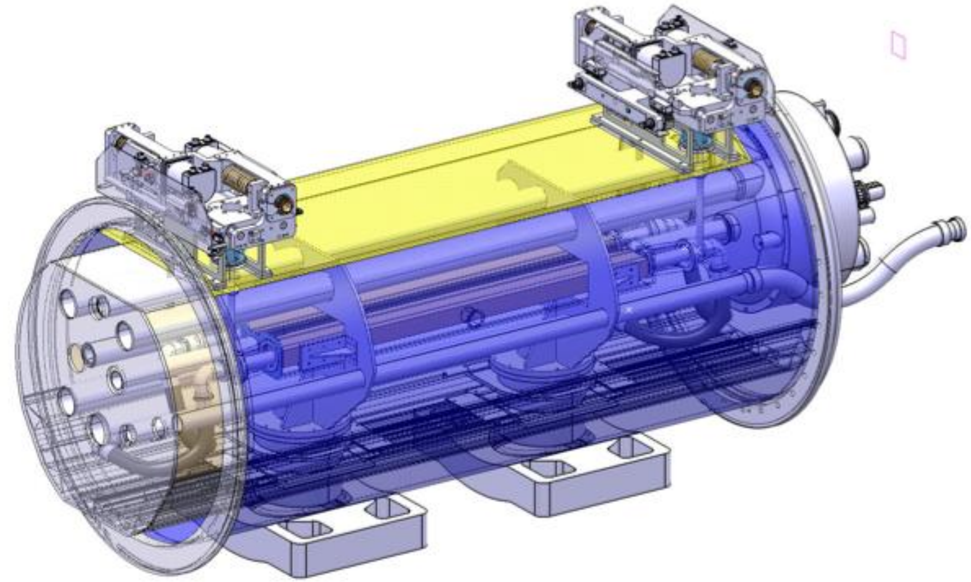
... what are we talking about ???

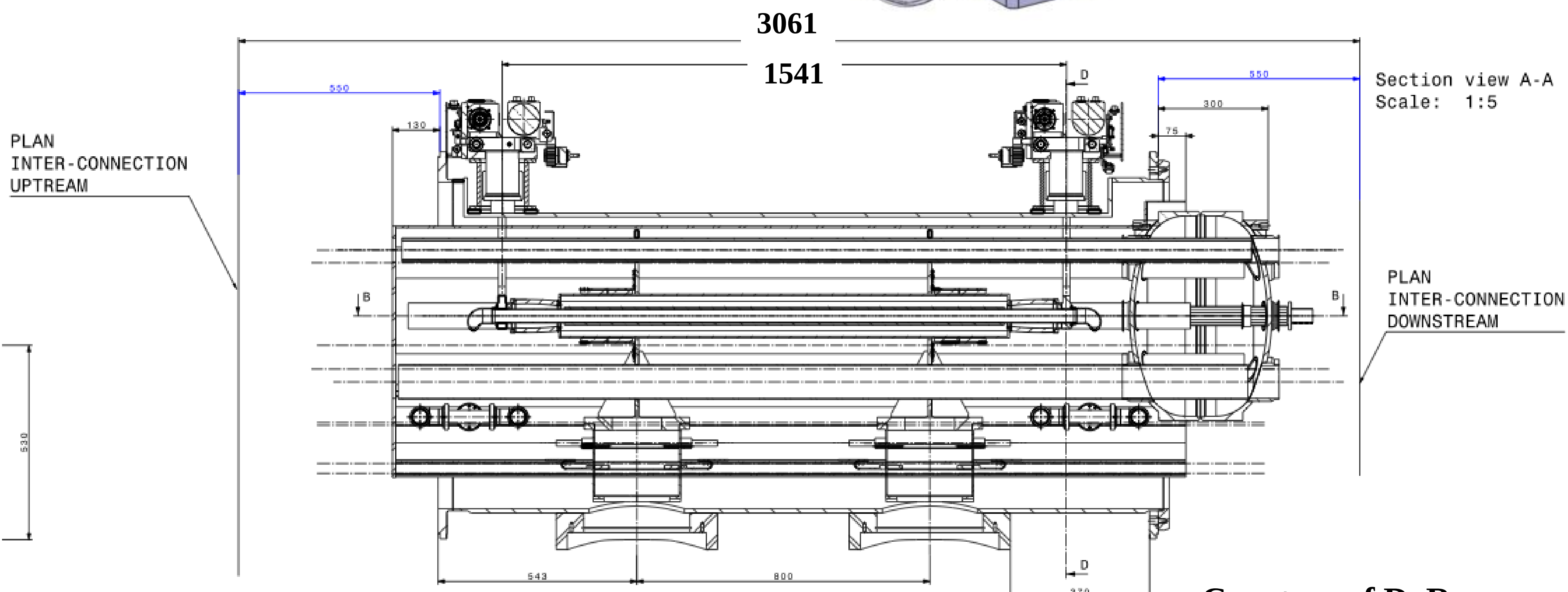
replace two standard dipoles in the dispersion suppressor region by stronger ↔ shorter Nb_3Sn dipoles to gain space for Ralph



Mikko Karppinen

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 ?
* multipole effect on dynamic aperture ?

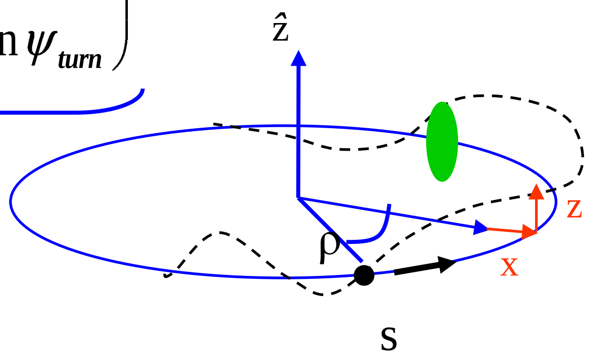
Analytical approach / Mad-X / Sixtrack Simulations

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

Quadrupole Error in the Lattice

optic perturbation described by thin lens quadrupole

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

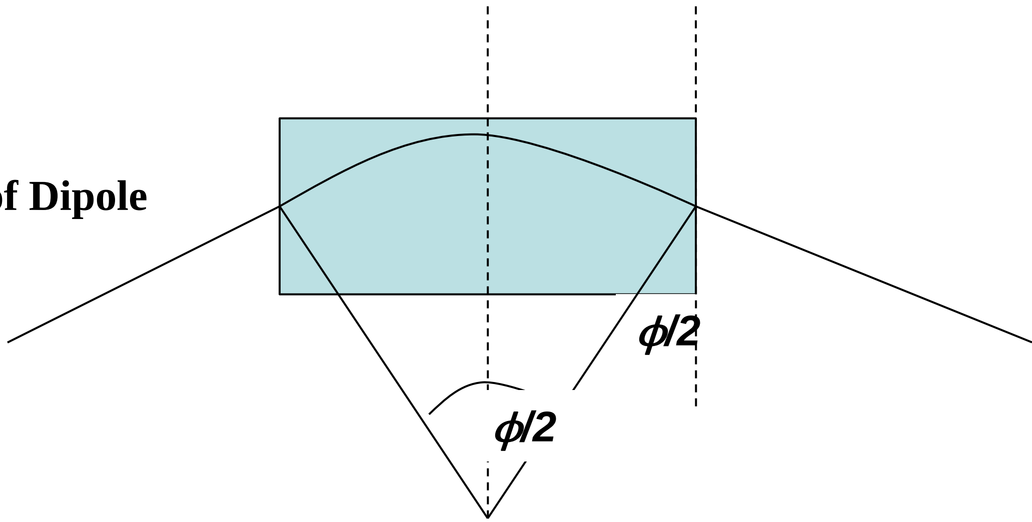


$$M_{dist} = \begin{pmatrix} \cos\psi_0 + \alpha \sin\psi_0 & \beta \sin\psi_0 \\ \Delta k ds (\cos\psi_0 + \alpha \sin\psi_0) - \gamma \sin\psi_0 & \Delta k ds \, \beta \sin\psi_0 + \cos\psi_0 - \alpha \sin\psi_0 \end{pmatrix}$$

Quadrupole Error in this case:

Edge Focusing effect of Dipole

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

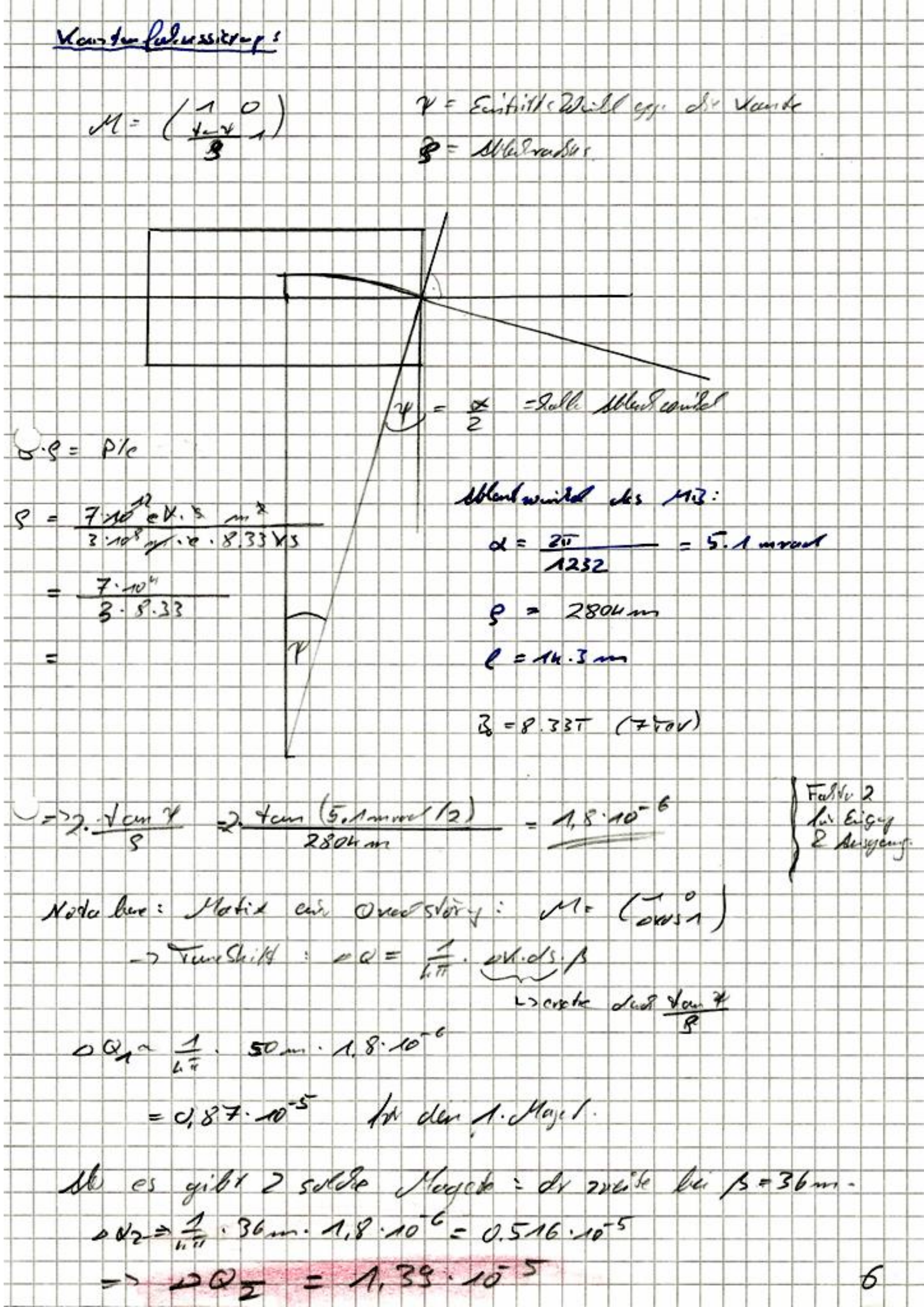


Edge Foc Effect:

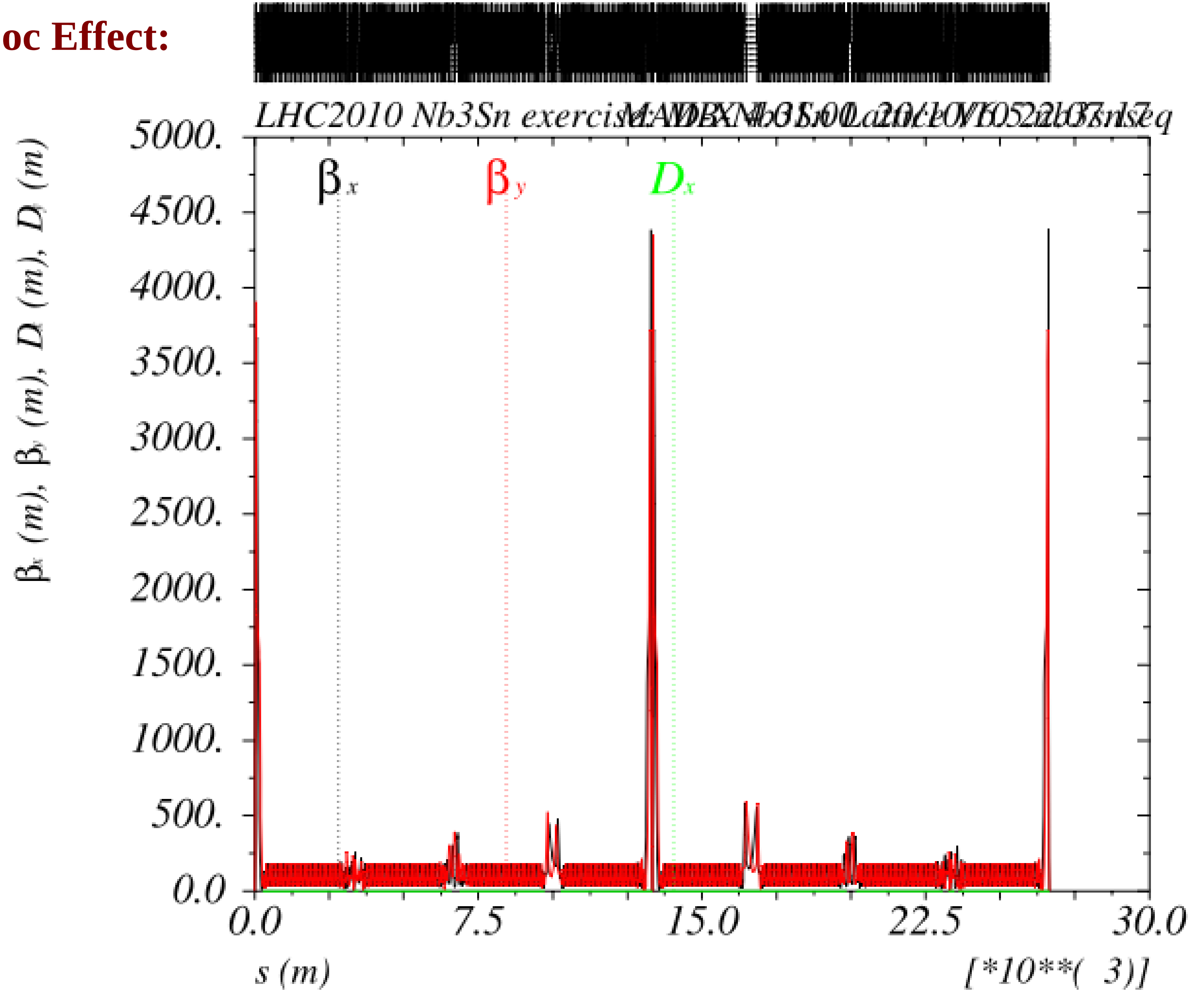
for the two effects (entrance / exit) of two dipoles we obtain ...

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

effect on beam optics is small !!!



Edge Foc Effect:



Edge Foc Effect: optics distortion

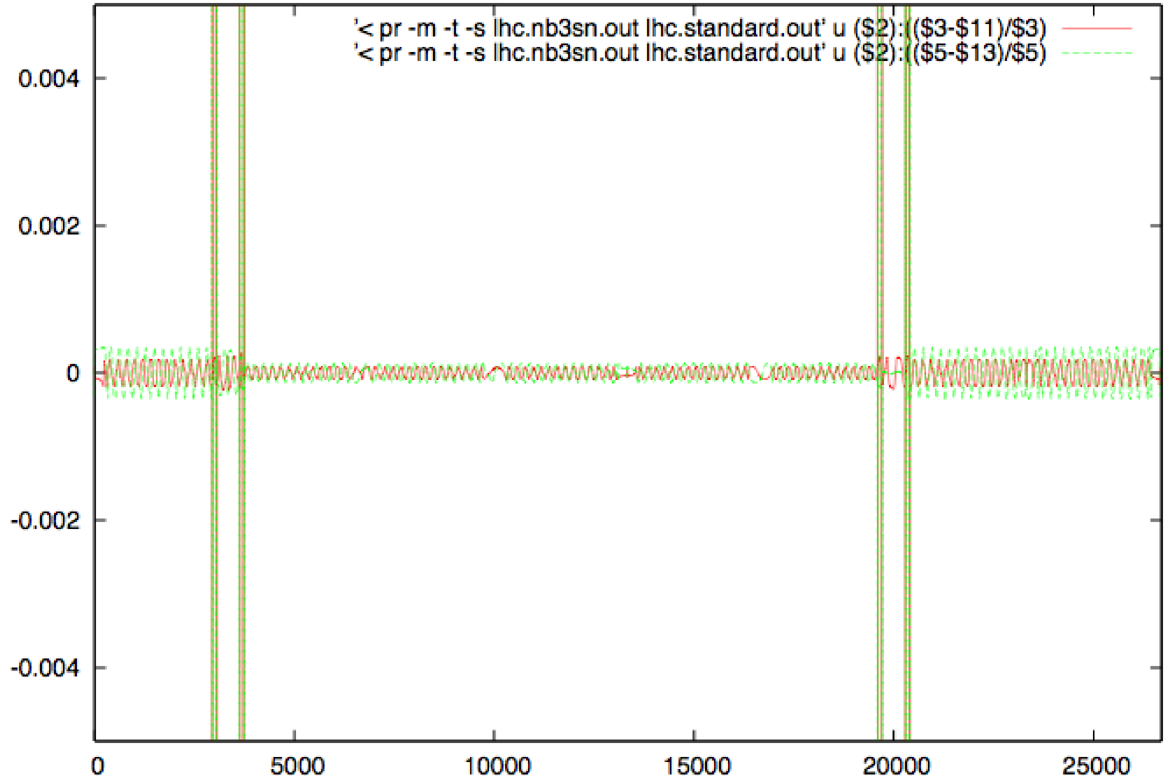
beta beat: $\Delta\beta/\beta < 1 * 10^{-3}$

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

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

remember: analyt. result per magnet: :

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



remember
tolerance for beta beat
Δβ/β=20%

2.) Shorter Magnet: Change of Design Orbit

... global LHC geometry

Standard LHC

$$s = 26.6588832$$

$$x = 0.1217\ mm$$

$$z = 7.97 * 10^{-5}\ mm$$

$$\theta = 6.2831$$

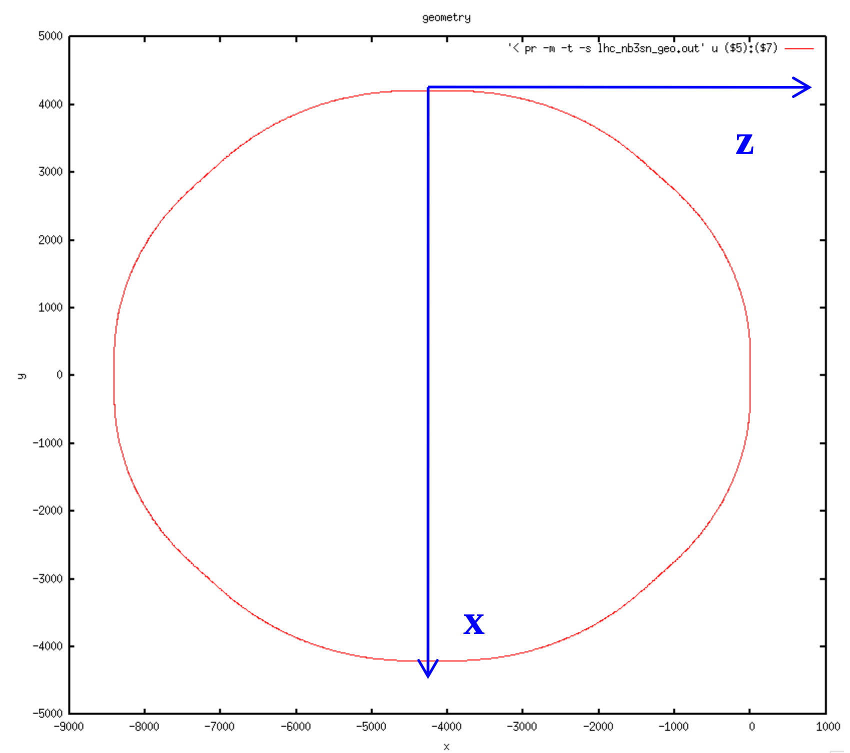
Nb_3Sn LHC

$$s = 26.65888319999$$

$$x = 0.228\ mm$$

$$z = 0.177\ mm$$

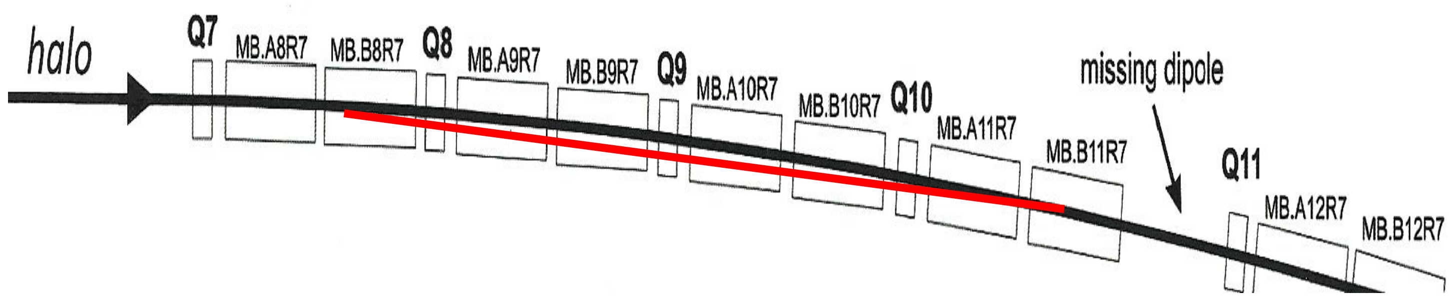
$$\theta = 6.2831$$



it's still quite a ring !!

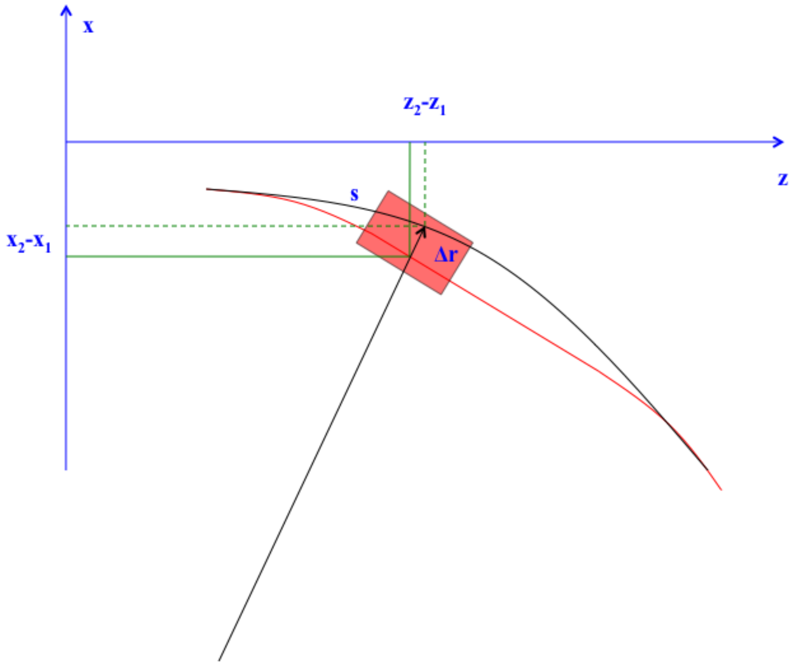
2.) Shorter Magnet: Change of Design Orbit

... local geometry

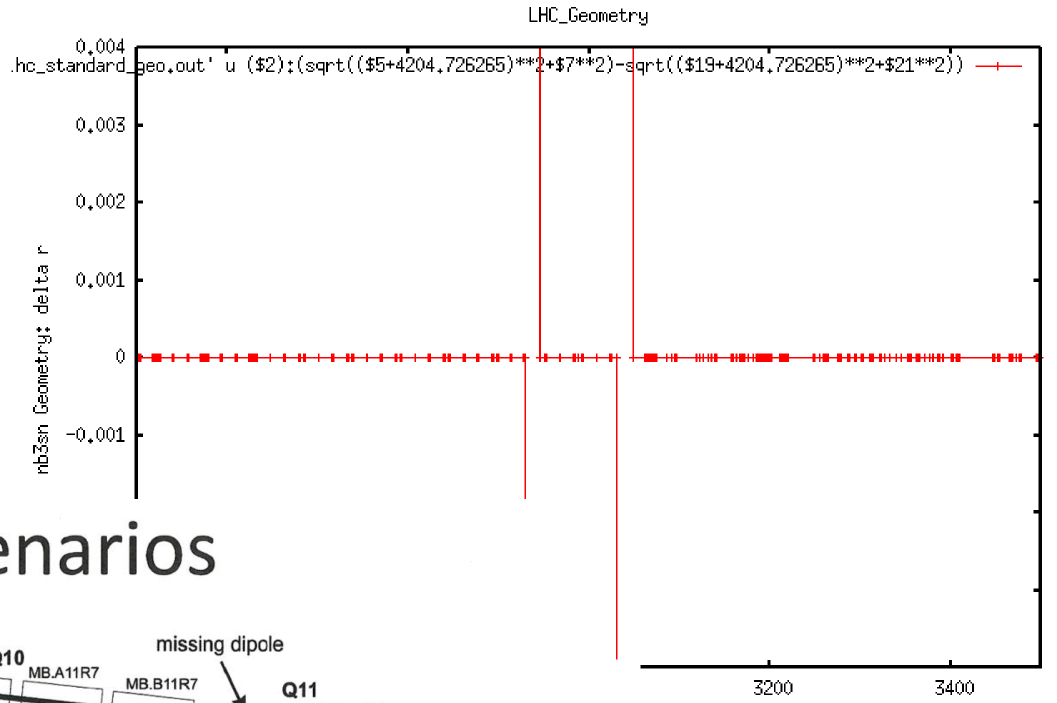


do we need a radial re-alignment ?

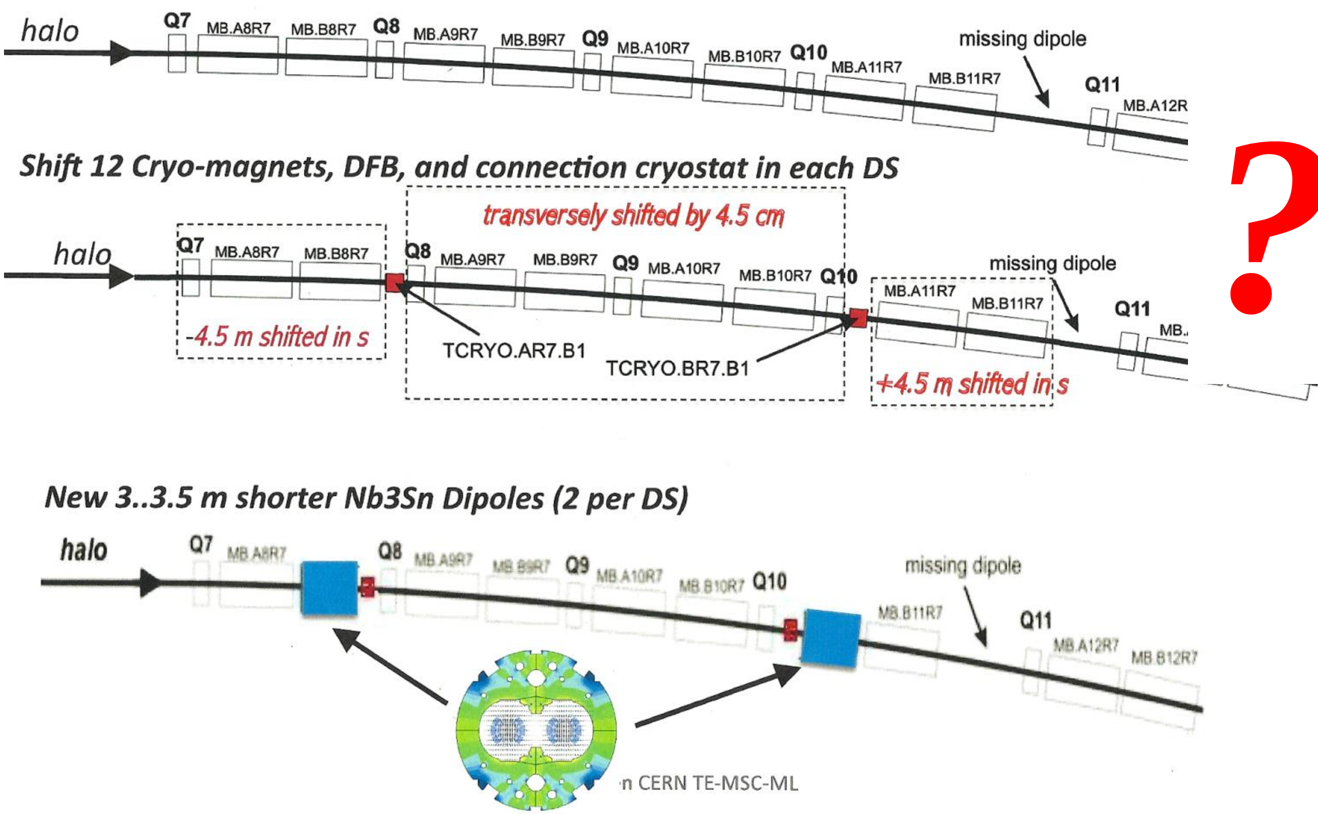
mad-x "Survey"



mad-x “Survey”

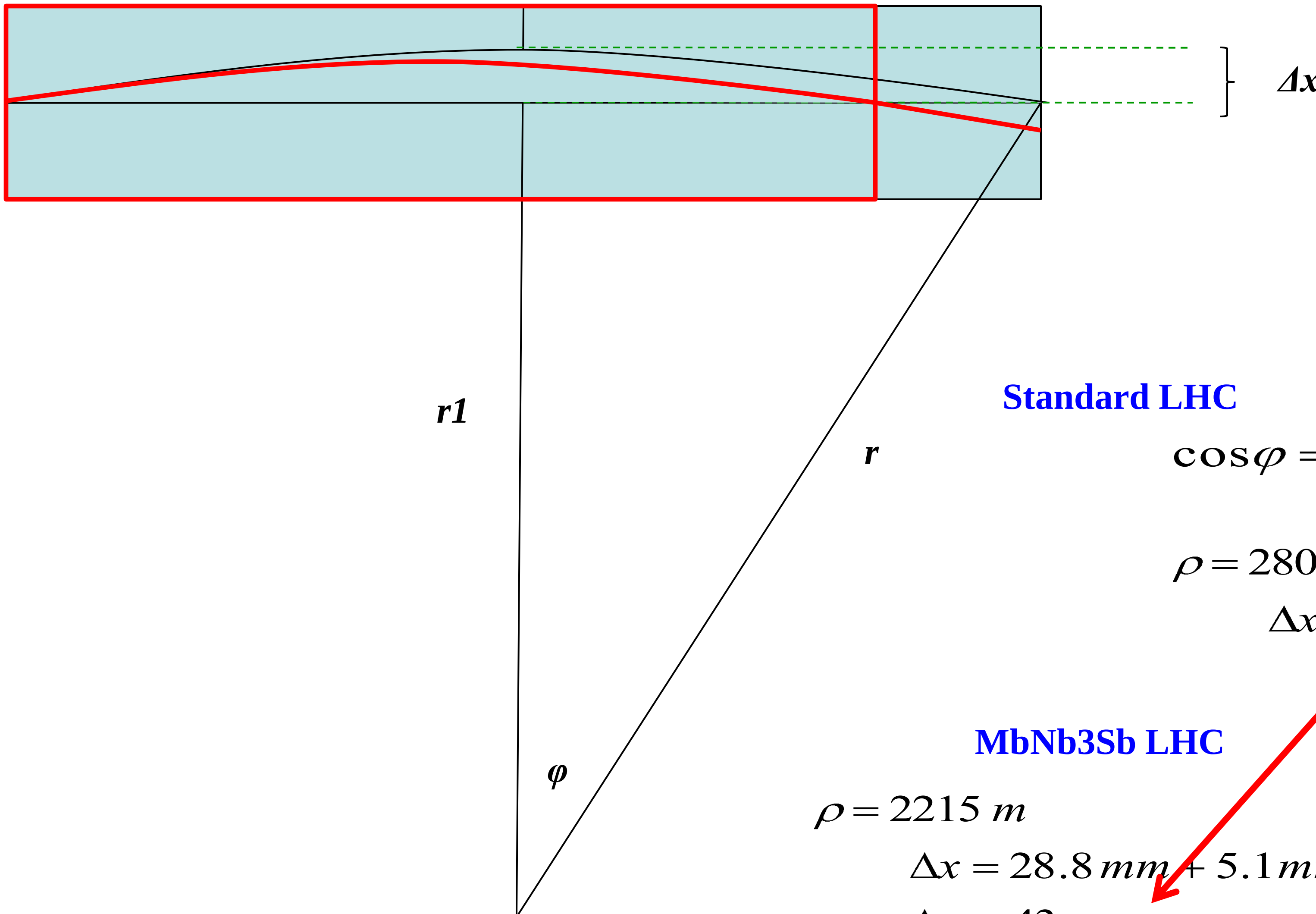


DS Upgrade Scenarios



?

Attention !!!!
the exact position
of the MBNB’s has
to be defined carefully



Standard LHC

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

$$\rho = 2804\ m$$

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

MbNb3Sb LHC

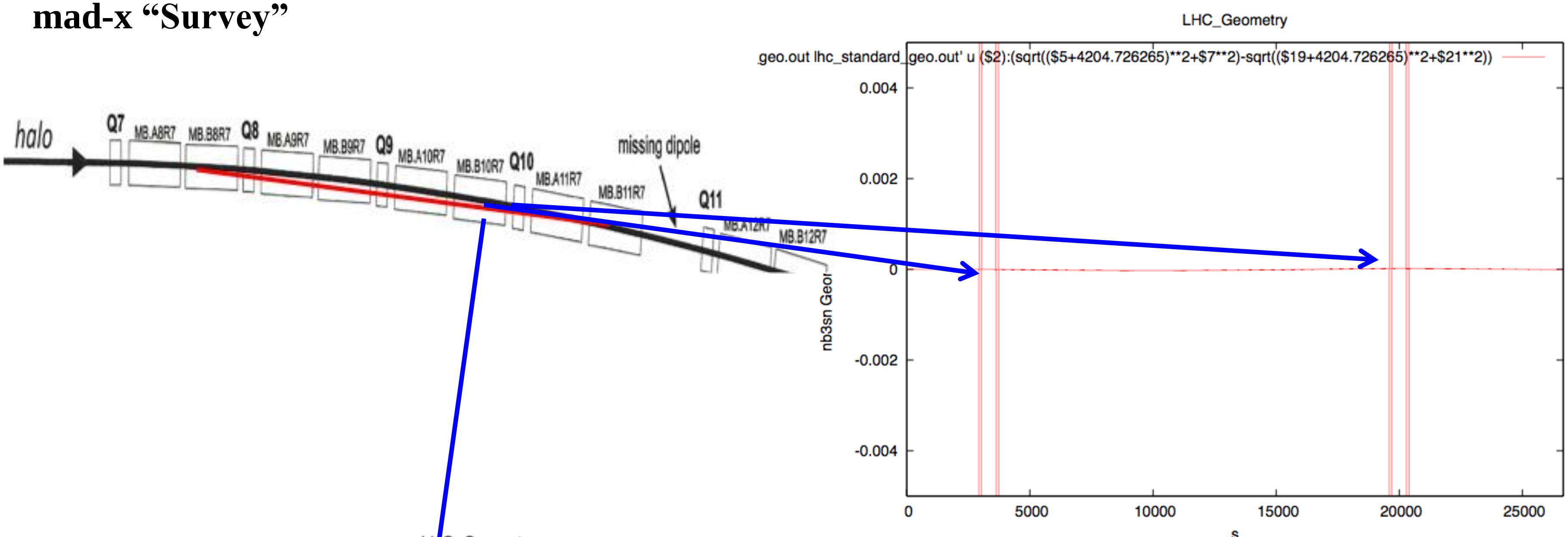
$$\rho = 2215\ m$$

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

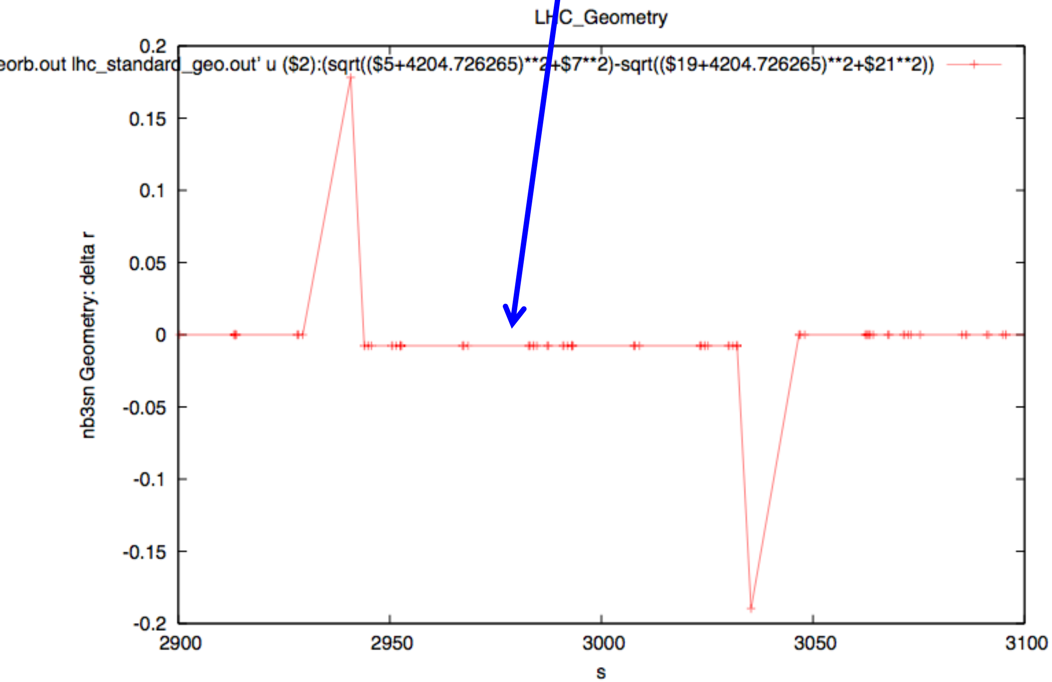
$$\Delta x = 43\, mm$$

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

mad-x “Survey”

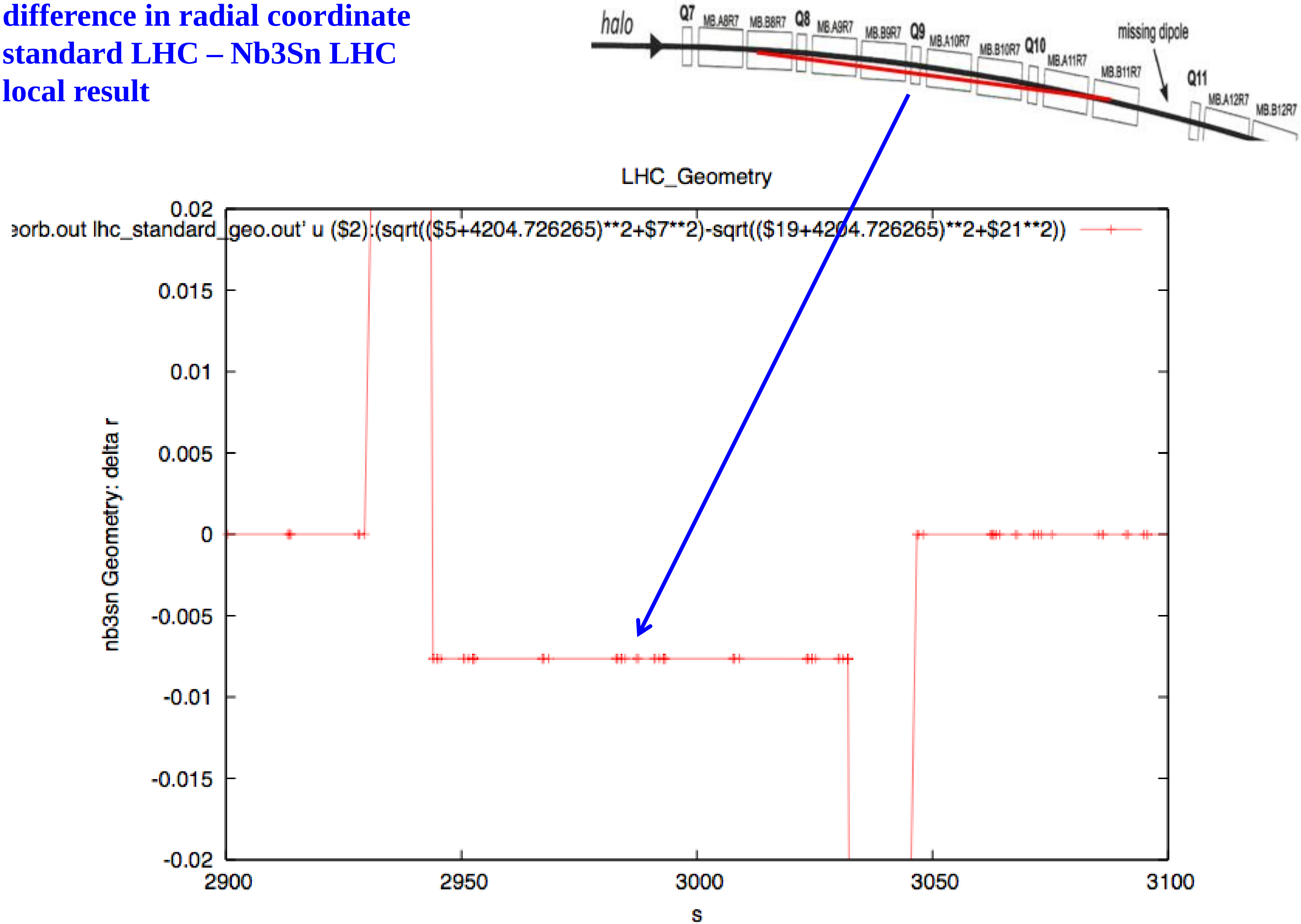


difference in radial coordinate standard LHC – Nb3Sn LHC global result

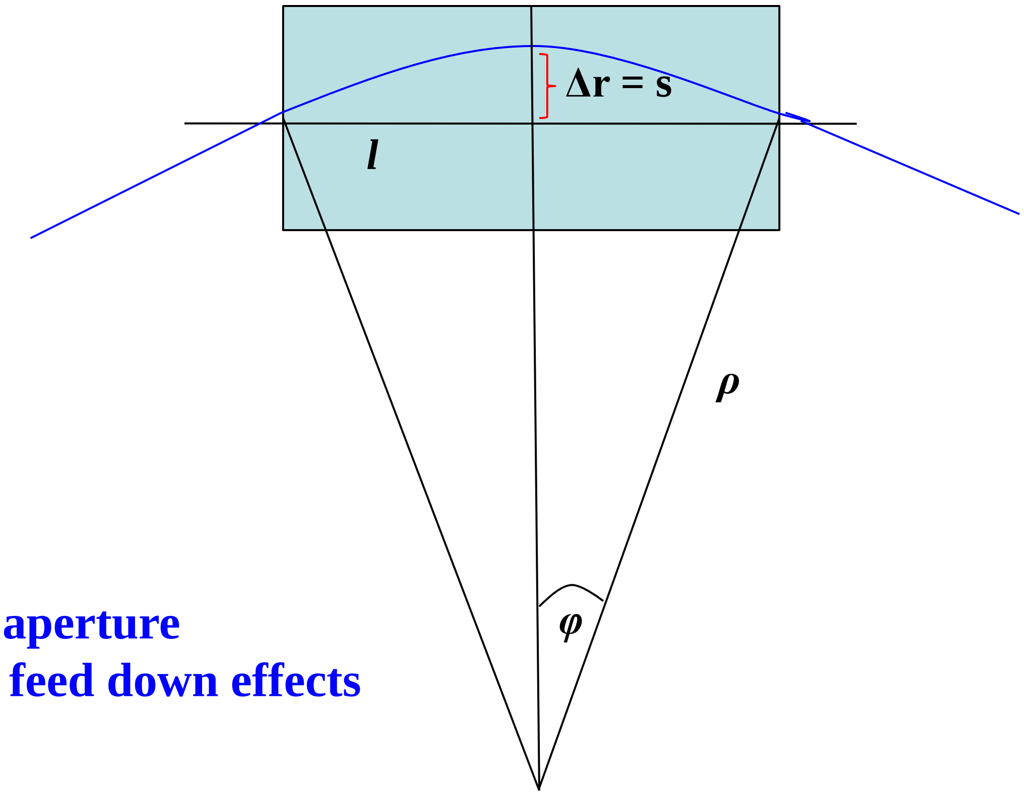


difference in radial coordinate standard LHC – Nb3Sn LHC local at IP2

difference in radial coordinate
standard LHC – Nb3Sn LHC
local result



3.) Sagitta:



$$l = 11.3\ m$$

$$\rho = 2215\ m$$

$$\alpha = 2 * \varphi = 5.1\ m\,rad$$

$$s = r - \sqrt{r^2 - \frac{l^2}{4}} = 7\,mm$$

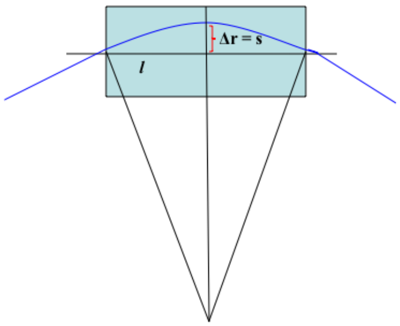
→ **aperture**

→ **feed down effects**

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

	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:



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%

← considered as tolerance limit (DA)

per Magnet

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

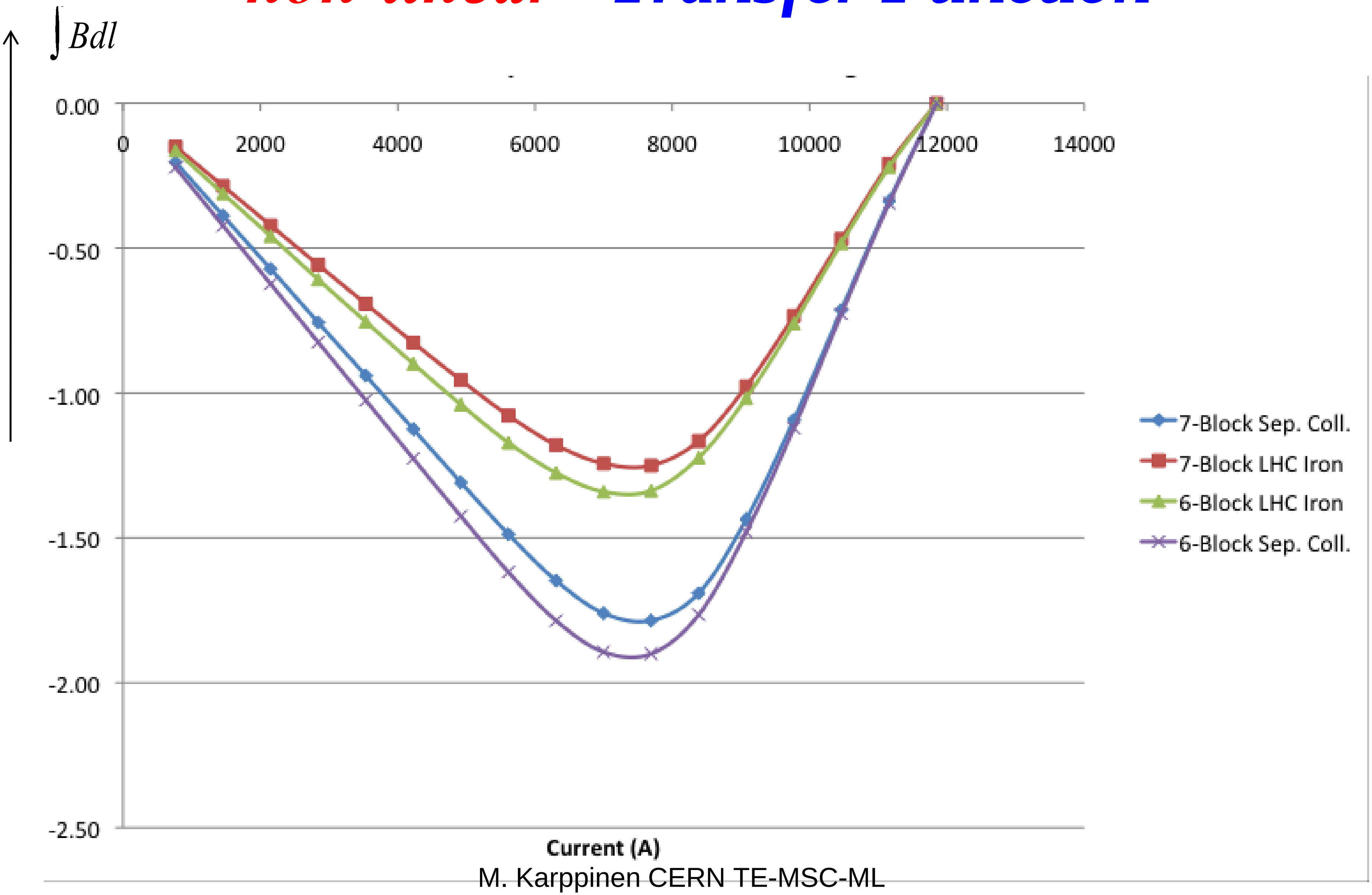
correct the orbit

plot the residual error

what are we talking about ... $\int Bdl = 1.5\ Tm$

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

“non-linear” Transfer Function



again: ... 10 seconds for the contemplation:

$$E = 7\ TeV$$

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

$$N = 1232\ Magnets$$

$$\rightarrow \quad 5.1\ mrad$$

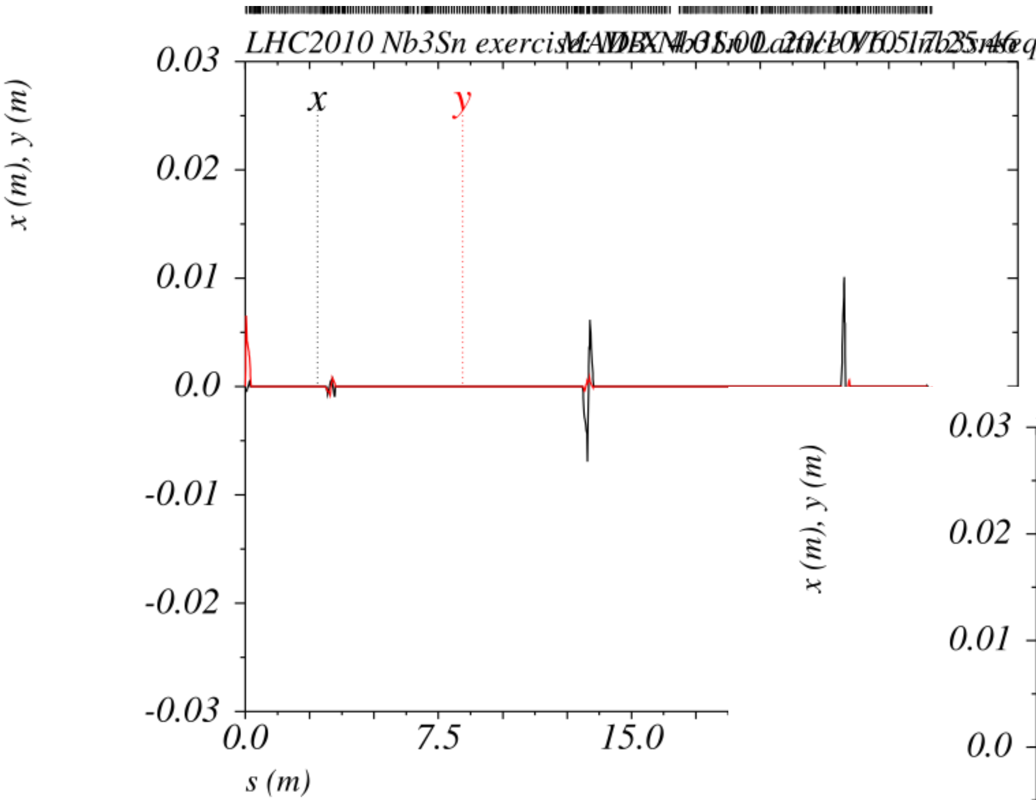
Nb3Sn Transferfunction:

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

rough estimate: → Δx ≈ 13 mm

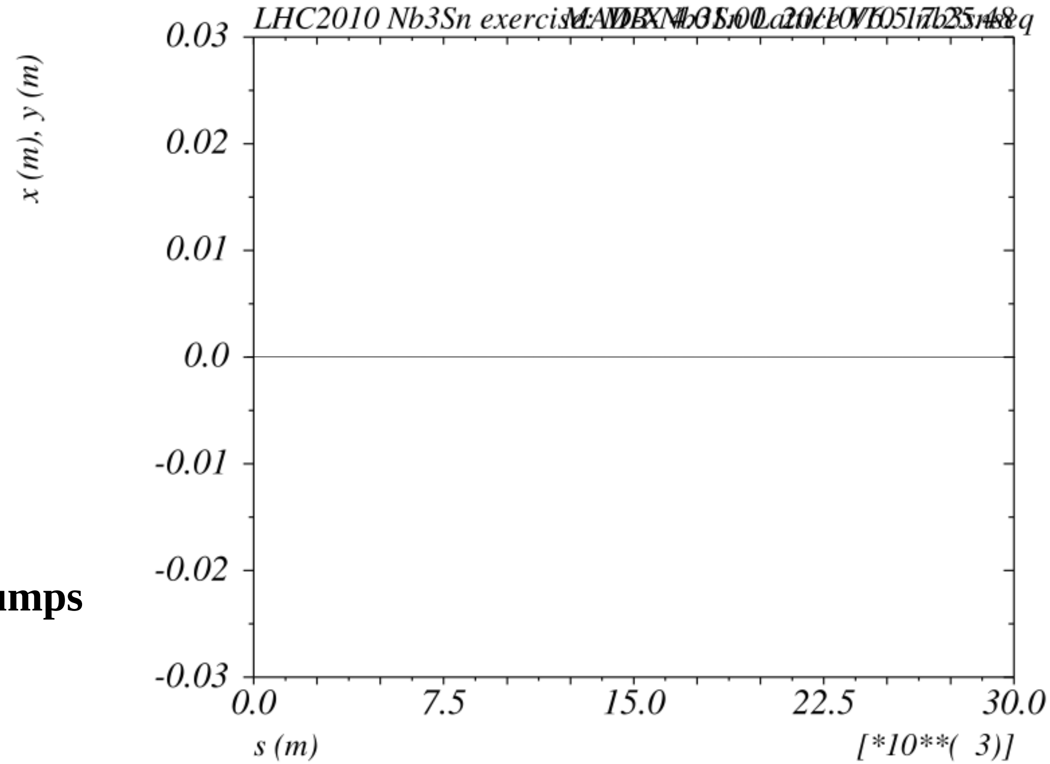
4.) The Story of the Transfer Function ...

a closed orbit problem



ideal machine

with exp bumps

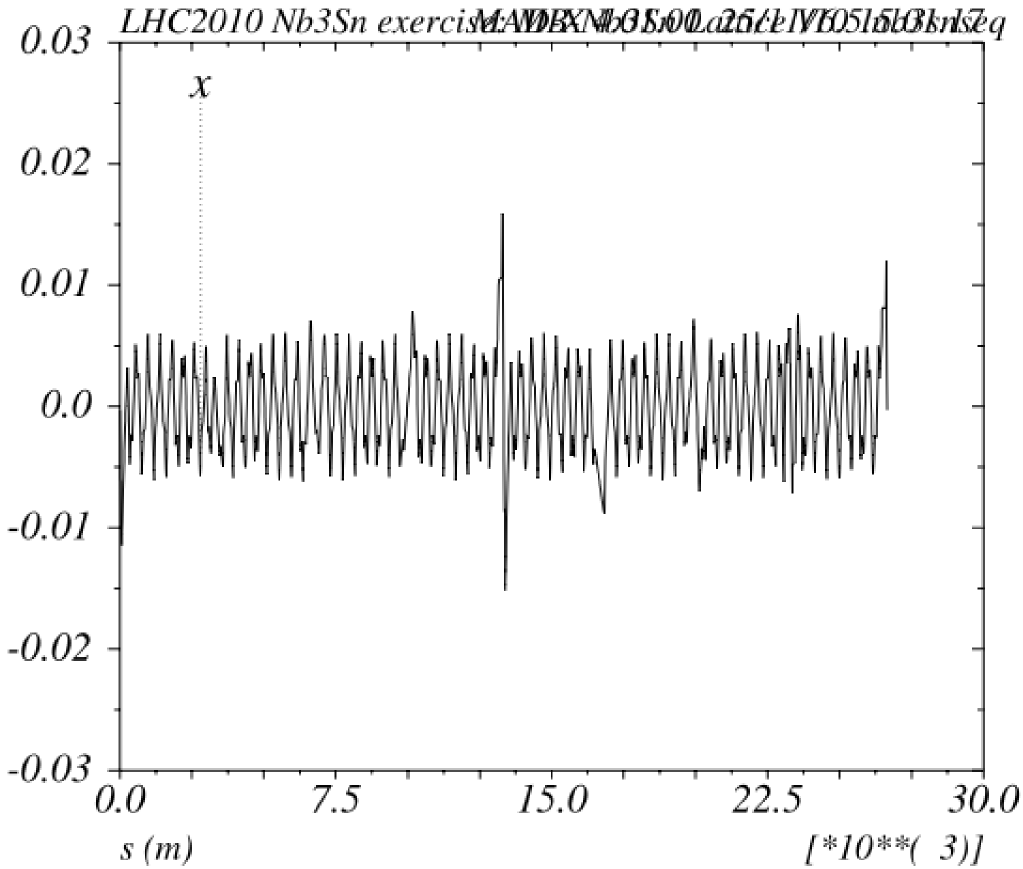


... and without exp bumps

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 ≈ *modulo180 degree*



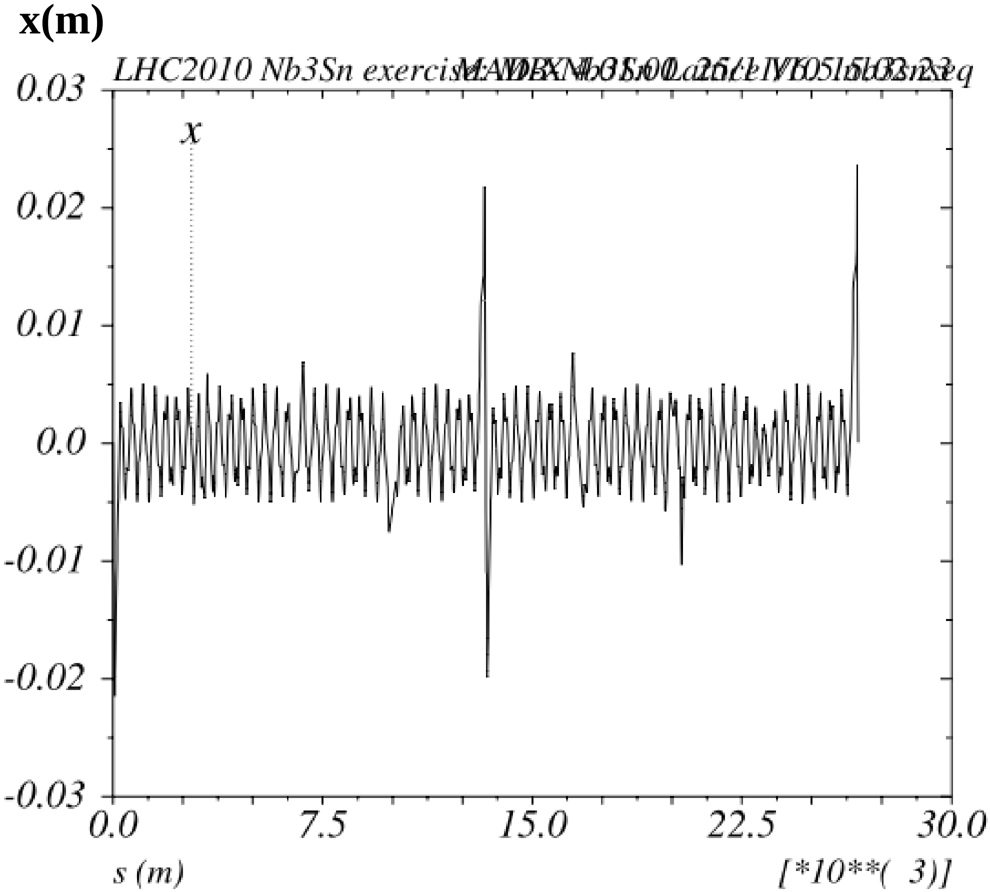
one Nb3Sn magnet

$\Delta x \approx \pm$ 15 mm

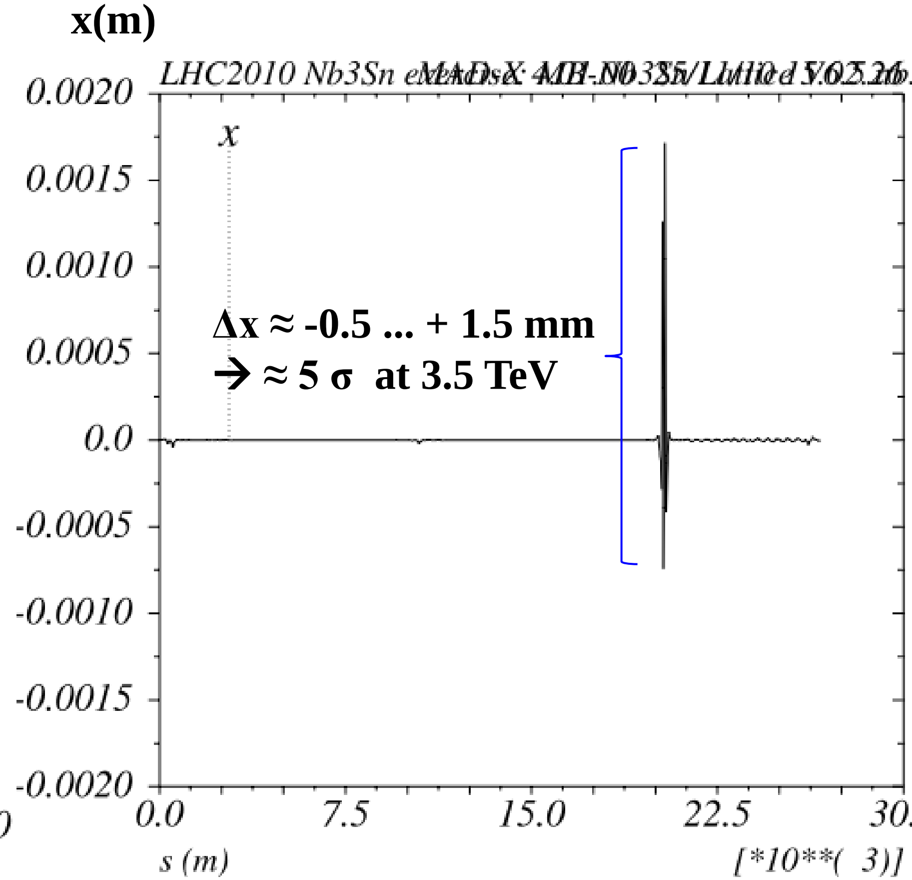
4.) The Story of the Transfer Function ...

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



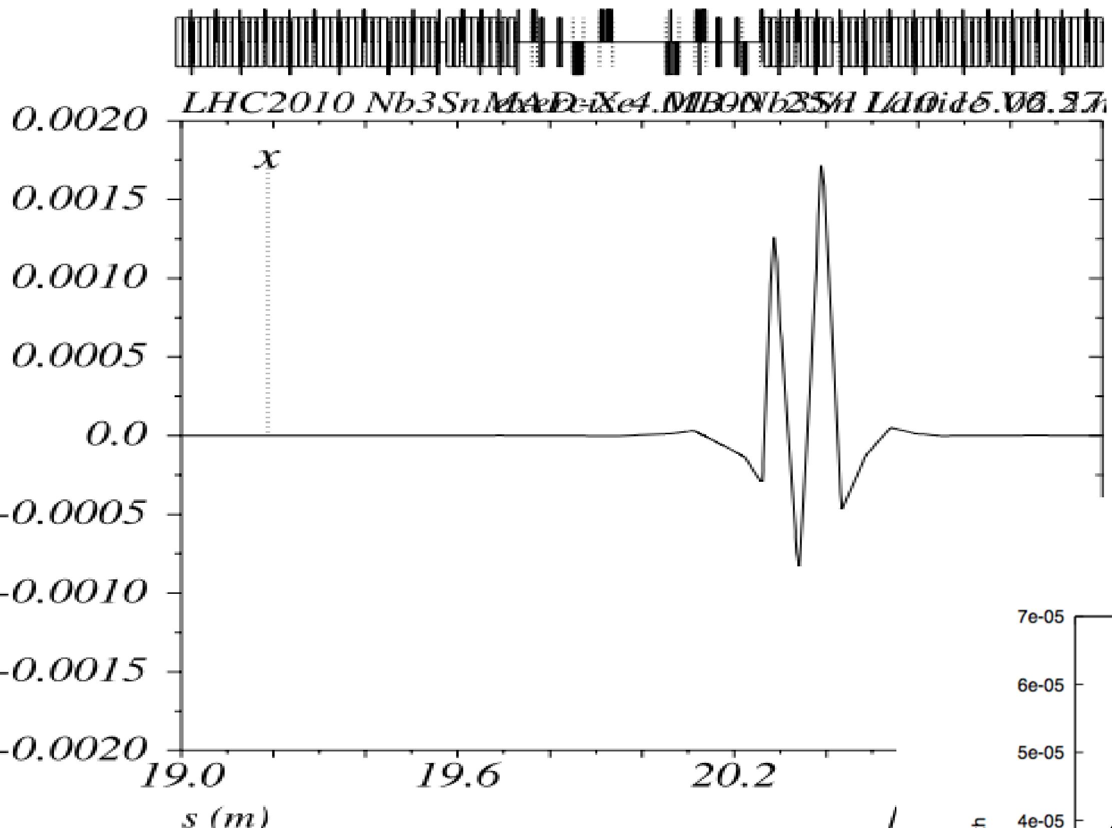
corrected by 20 orbcor dipoles

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
Δφ ≈ 4.545 phase relation,
closed by MCBH correctors

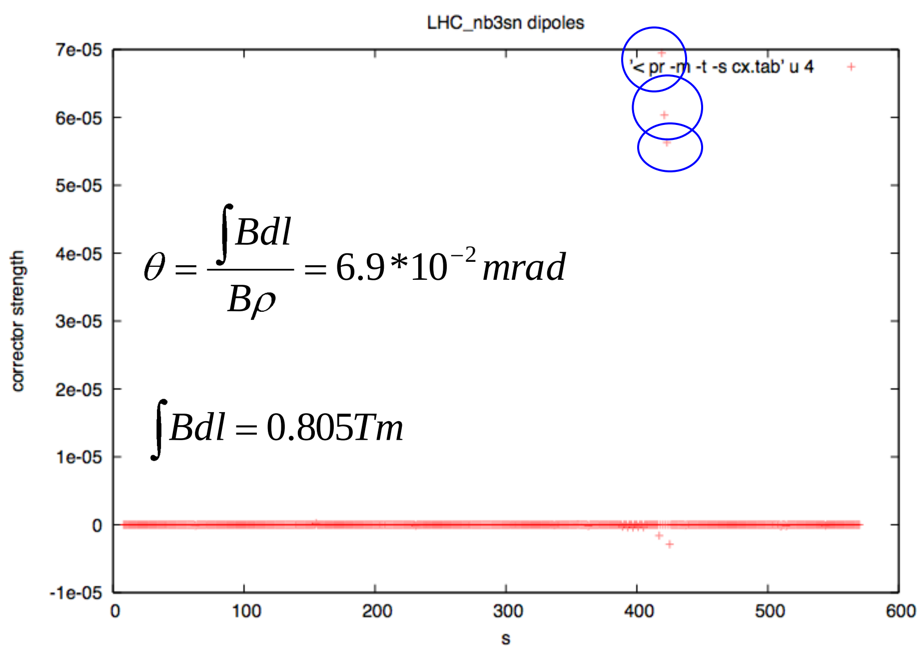


MCBH corrector strength:

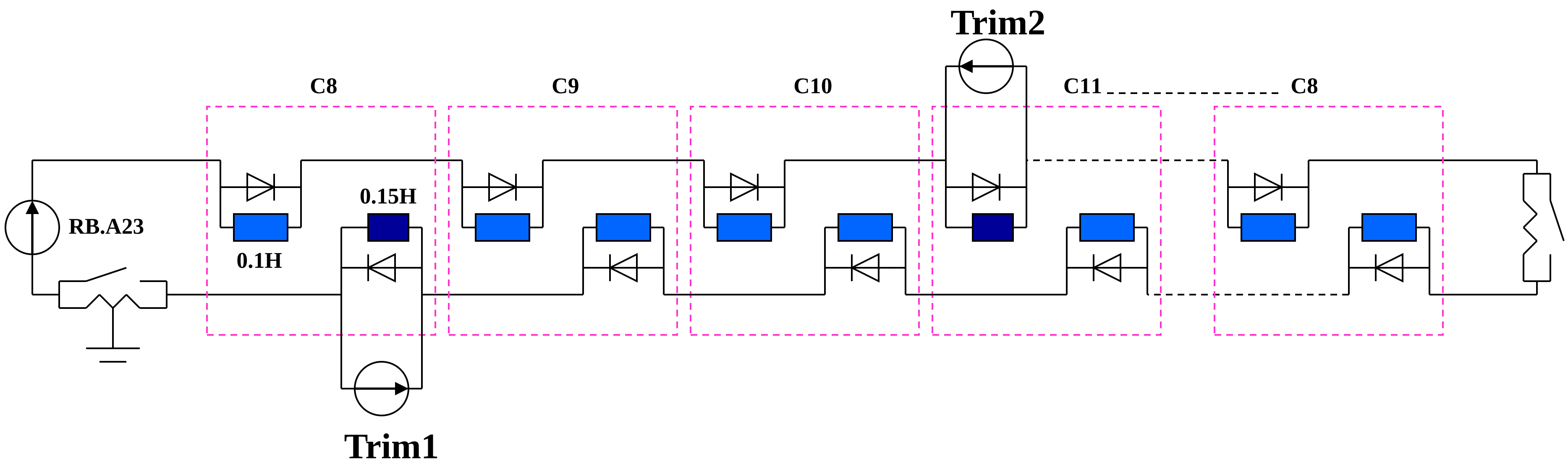
available: 1.900 Tm
needed: 0.805 Tm

!

= 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

(+)

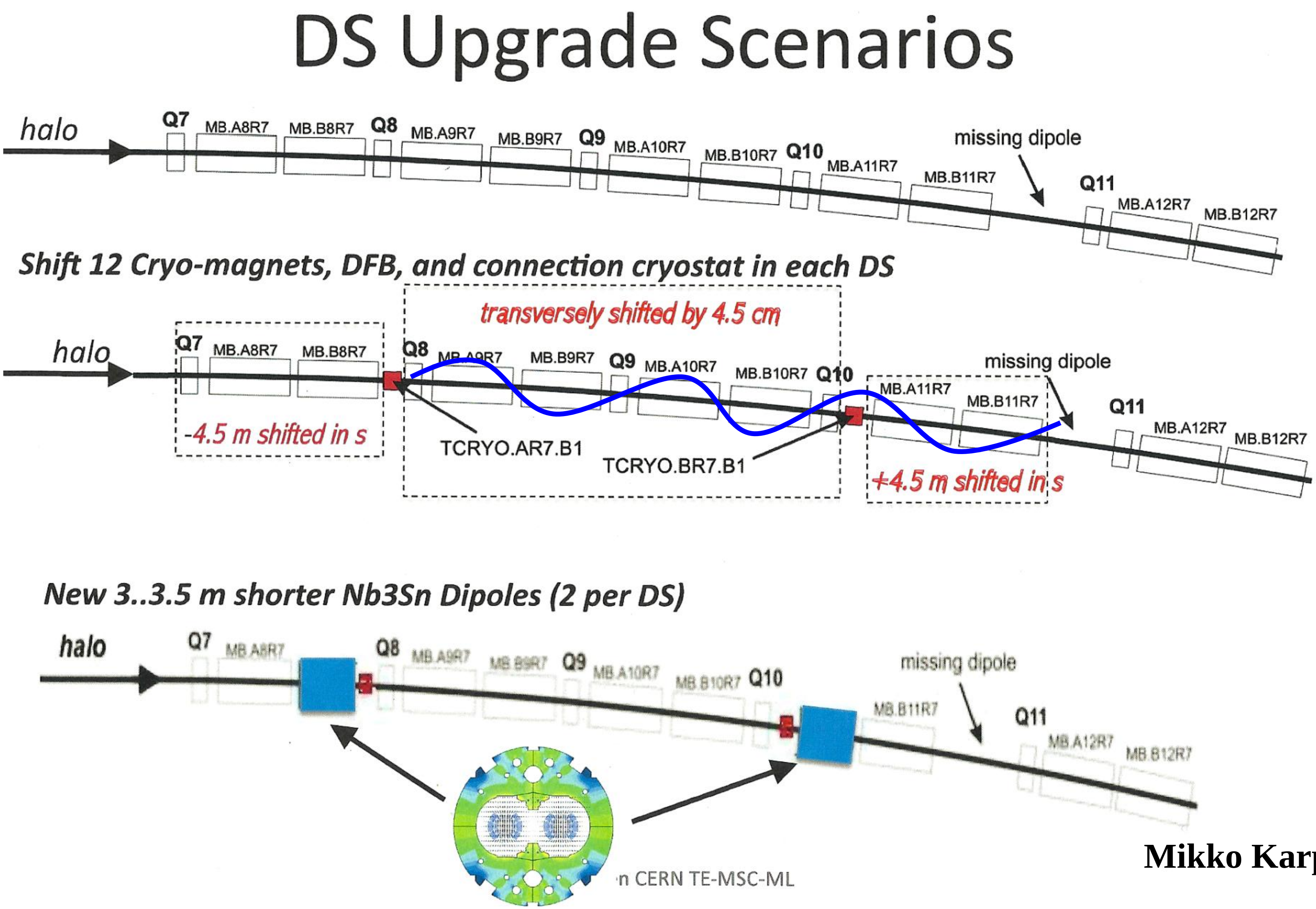
- Low current CL for the trim circuits
- Size of Trim power converters

(-)

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

Courtesy of H. Thiessen

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



Mikko Karppinen

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

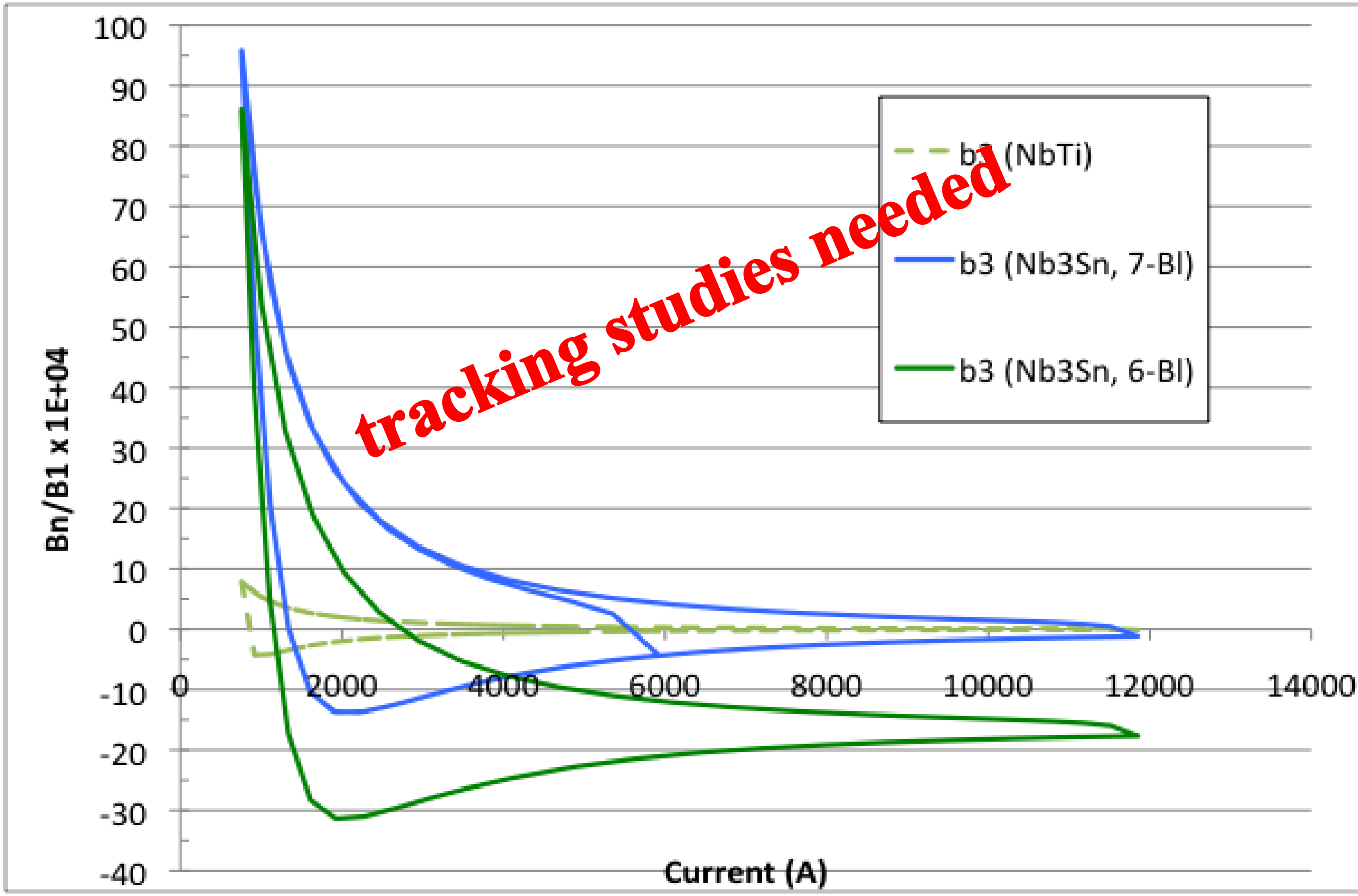
Nb3Sn Dipole: Multipole Errors:

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:



M. Karppinen CERN TE-MSC-ML

11T Dipole Project

1. **Project definition** **(Sep ‘10-Feb ’11)**
   - Schedule
   - Responsibilities and contributions, available resources
   - Funding
2. **Study phase** **(Sep ’10-Mar ’11)**
   - Impact on the LHC
   - Definition of the parameters and boundary conditions
   - Conceptual design
3. **D&D-phase** **(Mar '11-Dec '13)**
   - Magnet design
   - Supporting studies
   - Model Program
   - *Go/No-Go Decision* *(Jan ‘13)*
4. **Production phase** **(Jun ’13-Dec ‘16)**

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 and have to be studied
for injection energy, flat top, 3.5 TeV ??